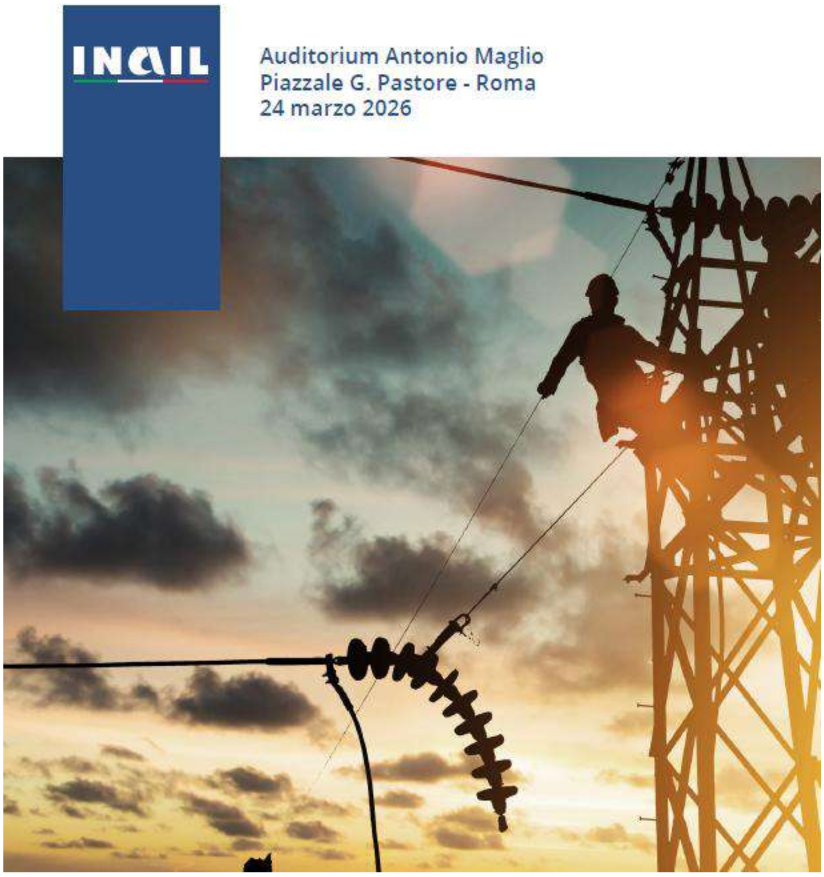
WORKLIMATE 2.0 – TEMPERATURE ESTREME E IMPATTI SU SALUTE, SICUREZZA E PRODUTTIVITÀ AZIENDALE

Articoli scientifici prodotti nell’ambito dei progetti Worklimate e Worklimate 2.0 o su temi di ricerca attinenti.

WORKLIMATE2.0
CLIMA LAVORO PREVENZIONE



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Consiglio Nazionale delle Ricerche
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PRESENTAZIONE

I progetti WORKLIMATE e WORKLIMATE 2.0 hanno sviluppato negli ultimi anni un ampio programma di ricerca volto a comprendere e gestire gli effetti del cambiamento climatico sulla salute e sicurezza dei lavoratori in Italia. Le attività svolte hanno permesso di analizzare in profondità come le temperature estreme incidano sul rischio di infortunio, sulla produttività e sul benessere delle persone esposte in diversi contesti occupazionali. Attraverso studi epidemiologici condotti su scala nazionale e in settori specifici, come edilizia e agricoltura, è stato possibile quantificare l'aumento degli infortuni nelle giornate caratterizzate da condizioni climatiche più critiche, delineando anche le ricadute economiche e organizzative associate allo stress termico.

Parallelamente, i progetti hanno esaminato le strategie di adattamento adottate da lavoratori e imprese per far fronte al caldo crescente, sviluppando tra l'altro uno strumento geospaziale innovativo che stima la perdita di capacità lavorativa dovuta alle alte temperature e supporta la gestione delle attività in condizioni avverse. Le ricerche hanno inoltre valutato l'efficacia di diverse misure di prevenzione, mostrando come interventi mirati possano ridurre l'esposizione e mitigare gli effetti negativi del caldo.

Accanto agli studi epidemiologici, grande attenzione è stata dedicata agli aspetti comportamentali e percettivi, oggetto di un nuovo lavoro attualmente in pubblicazione. Un ulteriore contributo innovativo è rappresentato dal prototipo di osservatorio nazionale sugli eventi da caldo, basato sulla raccolta sistematica di informazioni provenienti dai media, che offre un quadro immediato delle criticità emergenti sul territorio.

Il progetto ha inoltre approfondito la dimensione microclimatica e tecnologica, conducendo monitoraggi ambientali in un campione di aziende e valutando, sia sul campo sia in camera climatica, l'efficacia di dispositivi per la mitigazione del caldo come le giacche ventilate. I risultati hanno evidenziato il potenziale di soluzioni tecniche innovative nel ridurre lo stress termico e migliorare sicurezza e comfort dei lavoratori.

Le attività hanno prodotto una raccolta ampia e solida di articoli scientifici pubblicati su riviste *peer-reviewed*, spesso in *open access*, contribuendo in modo significativo alla diffusione delle conoscenze sui rischi climatici e sulle strategie di prevenzione nel mondo del lavoro.

INDICE

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Original Article

Nationwide heat-related workability loss and adaptation measures: development of a geospatial tool to support work management in heat conditions

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Abstract: Heat reduces labor productivity, leading employers to adjust work schedules. However, no international climate service exists for managing heat-related productivity losses. This study estimated summer workability loss (WL) across Italy for various 8-h work shifts and integrated the data into a WebGIS tool providing municipal-level insights. Global ERA5 climatological data (2009–2017) was downscaled to a 2.5 km grid over Italy and the workability equation calculated WL for different shifts (5am–1pm, 6am–2pm, 7am–3pm, 8am–4pm, 9am–5pm). The data was integrated into the Google Earth Engine (GEE) App for improved visualization. Compared to WL for workers performing high metabolic rate tasks in the sun, WL decreased significantly ($p<0.01$) for moderate metabolic rate tasks in the sun (60%) and for high metabolic rate tasks in the shade (over 90%). Starting shifts earlier than 9am reduced WL: by 4% starting 1 h earlier and nearly halving WL starting 4 h earlier (5am). The GEE "Worklimate 2.0 App" (https://ee-worklimate.projects.earthengine.app/view/workabilityloss) visualizes these findings. This study shows that rescheduling work hours and providing shade can significantly reduce WL in Italy, though additional heat adaptation strategies are needed to fully mitigate WL. The GEE App is the first international climate service for analyzing heat-related WL across working shifts.

Key words: Early morning shifts, Heat-related productivity loss, Heat safety policies, Rescheduling working hours, Wet Bulb Globe Temperature

Introduction

Heat exposure increases the risk of occupational injuries and reduced productivity globally[1]. Studies, including those sector-specific focused on Italy, have quantified these impacts[2, 3], with the largest study (2014–2019) estimating over 4,000 annual heat-related injuries from over 2 million cases[4]. Heat-related injuries pose public health, social, and economic challenges, causing labour productivity losses due to health impairments, absenteeism, and reduced quality of life, conditions representing a growing global concern in a warmer world[5, 6]. Productivity often

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declines as workers adapt to heat by slowing work or taking more breaks7), a phenomenon called presenteeism7), which is often the first sign of heat's impact8) and leads to greater losses than absenteeism9). Heat-related productivity or work capacity has been estimated by using models based on work intensity10–14), with the Wet Bulb Globe Temperature (WBGT) as the international standard indicator15, 16). Equations converting WBGT into percentage productivity loss or workability were used to quantify productivity loss across various scales17–19). Workplace heat adaptation strategies also include shifting work to cooler hours, reorganizing tasks, and adding shaded breaks. Globally and in Italy, employers have started arbitrarily adjusting schedules to reduce worker's heat exposure, without quantitative data on optimal strategies19). Currently, there is no international climate service for managing heat-related productivity losses. Since 2020, the Italian Worklimate project (Worklimate 2.0 is currently underway, https://www.worklimate.it/en/home-english/) has aimed to evaluate heat stress impacts on workers' health and productivity. Key goals also include estimating productivity loss through weather-climate monitoring and providing tools for workplace planning. This study aimed to estimate the average workability loss (WL) across Italy using a high-spatial resolution WBGT dataset (2009–2017) applied on monthly summer decades for different 8-h work shifts. This information was implemented in a WebGIS information tool developed by using the Google Earth Engine platform. This tool provides detailed municipal-level WL data for various time slots, focusing on an unacclimatized worker and factoring in sun/shade exposures and metabolic rates. This information is potentially valuable for companies, employers, and health and safety officers, as it can help improve the planning and organization of work activities, as well as the management of the workforce across various industries.

Subjects and Methods

The study area and workflow

The study area is Italy with an extension of 301,340 km^2, a population of 58,989,749 inhabitants, and about 7,980 municipalities (https://demo.istat.it). According to the Köppen–Geiger Classification20) a temperate climate with dry and hot summers (Csa class) mainly occurs in Italy, as well as a temperate climate with no dry season in the northern and eastern part (Cfa class).

The final study area included about 4,337 Italian municipalities, focusing only on those below 300 m a.s.l., as outlined in the methodological workflow (Fig. 1).

Meteorological data and workability loss calculation

ERA5 data21), a global dataset with a resolution of around 31 km, was downloaded for the period 2009–2017. To achieve a finer resolution suitable for our research, we downscaled this data using a two-step hindcast

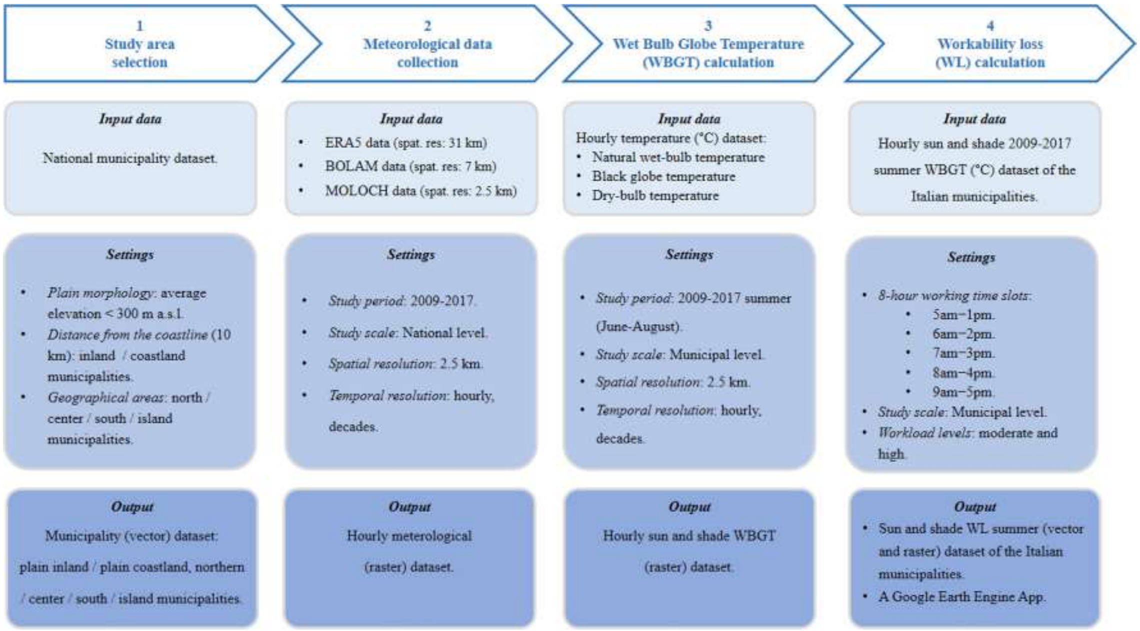

Fig. 1. The methodological workflow of the study.

modeling chain. This involved the use of the BOLAM and MOLOCH models, resulting in grid spacings of approximately 7 km and 2.5 km over the Mediterranean and Italian regions, respectively (Fig. 2). For a deeper dive into the specific experimental design used to create the BOLAM/MOLOCH hindcast and the characteristics of the models themselves, the reader can refer to a previous study[22)].

For the Italian domain, often characterized by complex orography that requires a more realistic representation of thermo-hygrometric conditions, the higher resolution of the MOLOCH data was crucial. The accuracy of the MOLOCH daily minimum and maximum values (Fig. 3) was shown against E-OBS observations[23)] by the Taylor diagram[24)]. Taylor diagram condenses the correspondence between modeled and observed behavior into three key statistics: correlation coefficient, root-mean-square error (RMSE), and standard deviation. Skill scores were averaged over the period 2009–2017 and mean values were reported (Table 1). Further details regarding the verification procedure can be found in Capecchi *et al*[22)]. This information demonstrated that the MOLOCH hindcast provide more accurate data than ERA5-Land, which was known to be the cutting-edge reanalysis for surface variables. As regards the quality of wind data, the MOLOCH hindcast has been validated against observations[25)] and using the original ERA5 data as benchmark. Results demonstrated that wind speed correlations were higher for MOLOCH hindcast than ERA5 values. In conclusion, the following meteorological variables (air temperature, humidity, wind speed, and solar radiation) were provided by the MOLOCH hindcast and used as input data for the calculation of the WBGT.

Wet Bulb Globe Temperature (WBGT) and workability loss calculation

According to established recommendations for calculating workplace WBGT from meteorological data[26)], hourly WBGT[15)] values were calculated using data from the MOLOCH hindcast, covering the summer months (June–

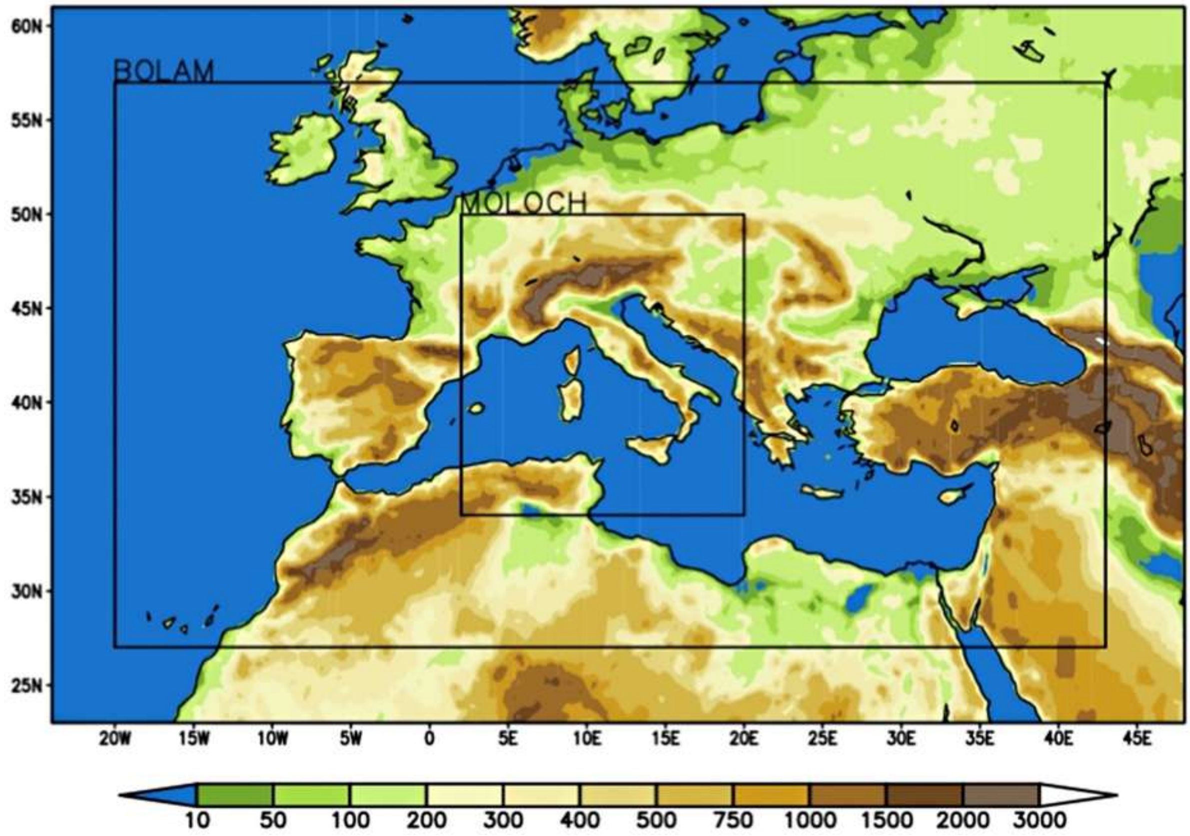

Fig. 2. Extent of the BOLAM and MOLOCH domains of integration with superimposed topography (m).
The BOLAM domain, outer black box, approximately corresponds to the Mediterranean Sea; the MOLOCH domain, inner black box, covers Italy and surrounding areas.

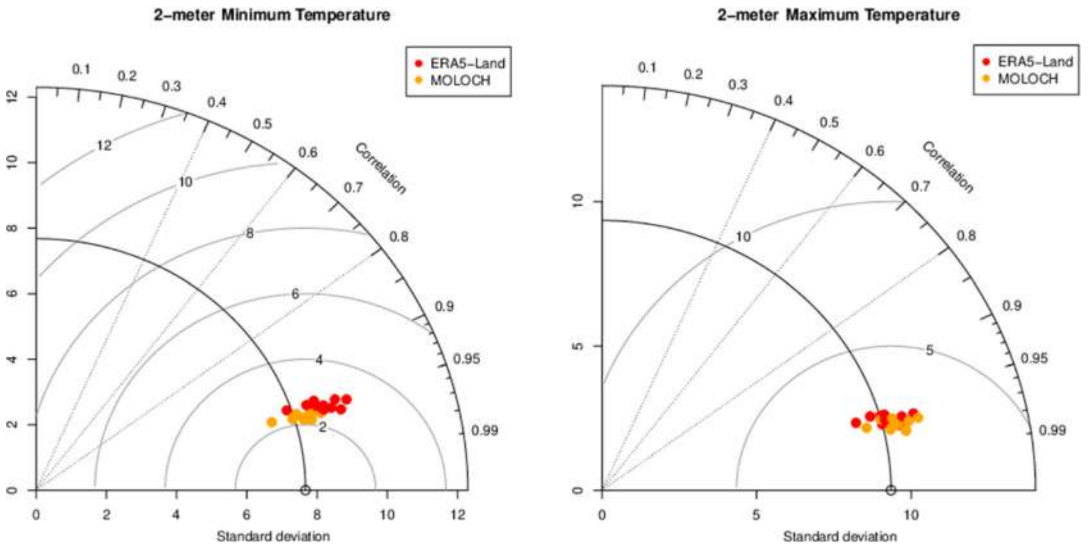

Fig. 3. Taylor diagram of MOLOCH (orange) and ERA5-Land (red) data, verified against E-OBS observations taken as ground truth.

Each point represents the skill scores for one single year over the period 2009-2017. Daily 2-m above ground minimum and maximum air temperatures are shown on the left and right panel, respectively.

Table 1. Average skill scores for the MOLOCH and ERA5-Land data

	Average skill scores			
	Daily minimum temperature		Daily maximum temperature	
Parameter	ERA5-Land	MOLOCH	ERA5-Land	MOLOCH
Correlation coefficient	0.95	0.96	0.96	0.97
RMSE (°C)	2.6	2.4	2.8	2.7
MAE (°C)	1.9	1.8	2.1	2.1

Mean values were obtained across the period 2009–2017. RMSE: root-mean square error; MAE: mean absolute error.

August) over a 9 yr (2009–2017) study period. In this way, both hourly $WBGT_{sun}$ (in conditions of direct short-wave radiation) and $WBGT_{shade}$ (no direct short-wave radiation) were calculated using the algorithms proposed in the R package "HeatStress"[27]. In particular, the "HeatStress" package applies the algorithm developed by Bernard and Pourmoghani[28] and Liljegren *et al.*[29] for computing $WBGT_{sun}$ and $WBGT_{shade}$, respectively. Hourly solar radiation values were obtained by the MOLOCH hindcast as direct input. This approach enabled the reconstruction of a time-varying solar radiation profile throughout the day, allowing for a dynamic estimation of globe temperature and, consequently, $WBGT_{sun}$.

These values were averaged on a ten-day basis (decade) over the entire 9 yr study period providing information at municipal level with a 2.5 km spatial resolution.

The "Workability" (ie, the ability to work) formula[11] was used to estimate the workability loss as done in a recent study[4] (WL, Eq. 1), a measure (%) that can be translated into productivity loss.

$$\mathrm{WL} = max\left\{100;\ min\left[0;\ \left(100 - \frac{WBGT_{lim,rest} - WBGT_{sun\ (or\ shade)}}{WBGT_{lim,rest} - WBGT_{lim}} \chi 100\right)\right]\right\} \text{ Eq. 1}$$

where $WBGT_{lim}$ is the WBGT limit reference value to which the $WBGT_{sun\ (or\ shade)}$ values are compared. The $WBGT_{lim}$ decreases when increasing the metabolic heat production (M, in Watts) and was calculated by using the equation (Eq. 2) proposed by the National Institute for occupational Safety and health (NIOSH) for unacclimatized workers[16].

$$WBGT_{lim} = 59.9 - 14.1\ log_{10} M \text{ Eq. 2}$$

Average metabolic rates referred to moderate (300 W) and high (415 W) workloads were used in accordance with the international standard ISO 7243[15].

$WBGT_{lim,rest}$ is the reference value referred to rest metabolic rate (115 W).

Average heat-related WL values were assessed at the municipal level referred to unacclimatized workers performing different metabolic rate tasks for various 8-h working time slots (5am–1pm; 6am–2pm; 7am–3pm; 8am–4pm; 9am–5pm). Average WL values were calculated for inland and coastal municipalities and were stratified at a geographical level, grouping the WL averages by municipalities in the north, center, south and Italian islands. Significant WL differences among the average values for each 8-h daily working period were investigated through the non-parametric Kruskal–Wallis and Mann–Whitney tests.

Geospatial and statistical analyses were performed by using R statistical software (version 4.4.1), the IBM SPSS Statistics (version 29.0.1.0), and QGIS (version 3.38.3).

Data collection in the Google Earth Engine (GEE) App

The WL dataset (vector data) of the Italian municipalities was collected through the GEE App, based on the JavaScript code development. The code was performed to optimize the collection and the visualization of the WL maps, developed at municipal levels, describing different working scenarios: sun and shade conditions, and moderate and high workload levels.

The input GEE data was the WL (vector polygonal) dataset of the Italian municipalities which were previously selected by morphology data (elevation less than 300 m a.s.l.). The WL dataset was expressed in percentage terms (percentage of WL), with values between 0 and 100%, available for different 8-h daily working time slots in summer months (June–August). The vector dataset was structured by different information (textual and number columns), as follows:

- Municipality ID and name (text).
- Geographical classes (number): 1 (northern), 2 (central), 3 (southern), and 4 (island) municipalities.
- Elevation means values (number, m a.s.l.) and the related elevation classes (binary): 1 (plain) and 0 (no plain) municipalities.
- Coastline distance classes (binary): 1 (coastal) and 0 (inland) municipalities.
- Workability loss percentage values collected by 45 data columns and calculated for the selected 8-h daily working time slots in summer months: from 0% to 100% values.

This dataset structure allowed the app development within the GEE platform.

Results

Heat-related workability loss (WL) by rescheduling working hours

During summer, WL was highest for workers performing high metabolic rate tasks in the sun (Fig. 4, black bars), followed by metabolic tasks (Fig. 4, gray bars), and lowest in the shade (Fig. 4, light gray and white bars). Compared to the high metabolic rate tasks in the sun, WL significantly ($p<0.01$) decreased by nearly 60% for moderate metabolic rate in the sun, 65% for high metabolic rate in the shade, and over 90% for moderate tasks in the shade. The highest WL values occurred in the 9am–5pm working time slot, peaking at about 30% for high metabolic rate tasks in the sun (Fig. 4).

Starting the work shift earlier than 9am reduced WL: by 4% starting 1-h earlier, 15% for 2-h earlier, 29% for 3-h earlier, and up to 46% for 4-h earlier (start at 5am).

Higher mean WL values were observed in inland municipalities (Tables 2–4) compared to coastal ones (Tables 5–7). However, an exception was noted during the warmest ten-day periods, specifically the third decade of July and all decades of August, when the highest WL values occurred in the coastal municipalities of southern Italy.

In June, the highest average WL (about 25%) occurred in the last ten days in inland municipalities of Northern and Southern Italy and major islands during the 9am–5pm and 8am–4pm shifts (Table 2), while early June values were mostly below 5%.

In July, WL exceeded 40% in the third decade, peaking in coastal southern Italy (Table 6), followed closely by inland municipalities in southern Italy and islands (Table 3).

In August, the highest WL were close to or above 50% during the 9am–5pm and 8am–4pm work shifts in coastal southern Italy (Table 7). High WL values, also exceeding 40–45%, were also observed in inland municipalities (Table 4) and in island coastal areas (Table 7).

Changes in work time slots generally led to significant ($p<0.01$) WL variations (Tables 2–7), except in the first ten days of June (Tables 2 and 5). The greatest WL variations from changing work time slots were observed in northern Italy's inland municipalities (Fig. 5).

Starting work earlier than 9am reduced average WL of approximately 7% starting 1-h earlier (8am start), 19% for 2-h earlier, 35% for 3-h earlier, and 53% for 4-h earlier.

Statistically significant decreases in WL ($p<0.01$ in Tables 5–7) were also observed in coastal municipalities in Northern Italy due to earlier work shift hours. Specifically, a 5am start lowered WL by ~45% (Fig. 5). In municipali-

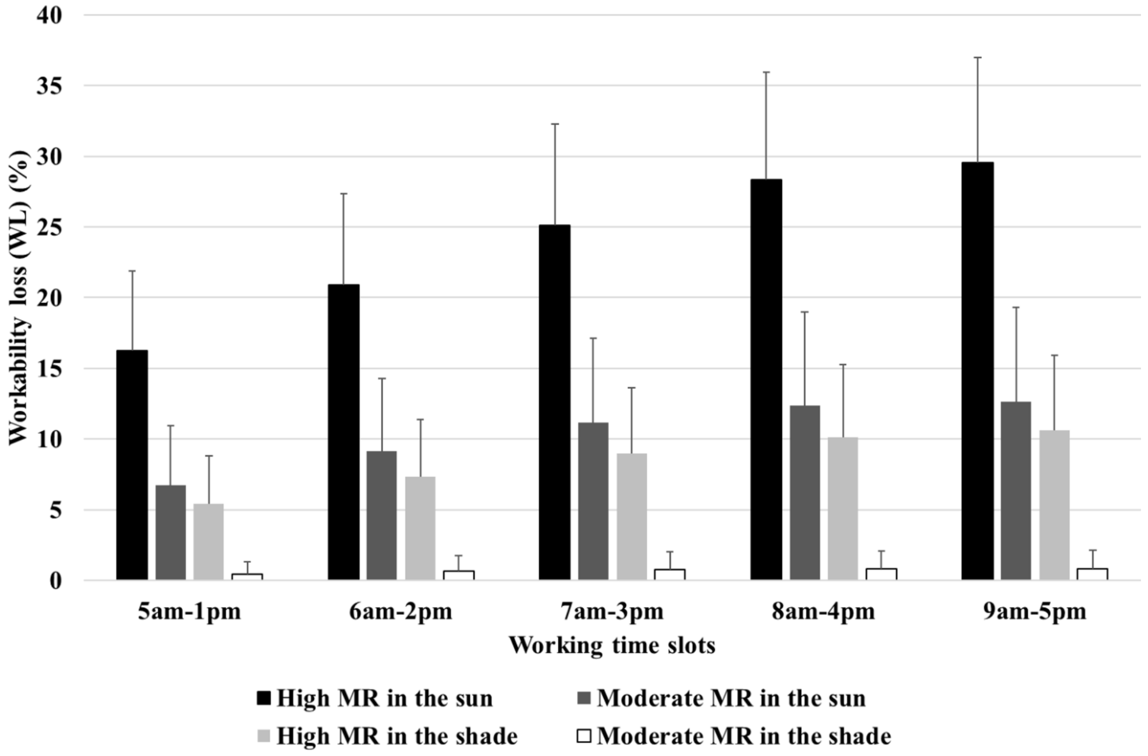

Fig. 4. Heat-related workability loss (WL) during summer (from June to August) for unacclimated workers performing high and moderate metabolic rate (MR) tasks in the sun and shade in different working time slots.

Table 2. Mean heat-related workability loss (%) ± standard deviation in inland municipalities for unacclimated workers performing high metabolic rate tasks in the sun during June

Month, decade	Working time slots	North	Center	South	Island
June, 1st dec.	5am–1pm	2.9 ± 2.2 (a)	1.9 ± 2.0 (a)	3.8 ± 2.9 (a)	1.2 ± 1.3 (a)
	7am–3pm	5.5 ± 3.8 (b)	2.7 ± 2.9 (a)	4.8 ± 3.9 (b)	1.7 ± 1.8 (a)
	9am–5pm	6.1 ± 4.3 (c)	2.7 ± 3.0 (a)	4.8 ± 3.9 (b)	1.7 ± 1.8 (a)
	Sig.	$p<0.01$	$p=0.13$	$p<0.01$	$p=0.15$
June, 2nd dec.	5am–1pm	6.8 ± 3.3 (a)	8.6 ± 3.9 (a)	14.3 ± 4.8 (a)	8.6 ± 3.6 (a)
	7am–3pm	12.4 ± 5.3 (b)	12.9 ± 5.6 (b)	20.1 ± 6.6 (b)	13.1 ± 4.9 (b)
	9am–5pm	15.0 ± 6.8 (c)	13.9 ± 6.3 (b)	20.7 ± 6.8 (b)	13.9 ± 5.3 (b)
	Sig.	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$
June, 3rd dec.	5am–1pm	11.7 ± 3.6 (a)	12.9 ± 4.2 (a)	15.9 ± 5.1 (a)	14.7 ± 3.3 (a)
	7am–3pm	20.4 ± 5.6 (b)	19.6 ± 6.0 (b)	22.5 ± 6.8 (b)	22.1 ± 4.6 (b)
	9am–5pm	26.5 ± 7.4 (c)	22.2 ± 7.1 (c)	23.7 ± 7.0 (c)	25.0 ± 5.3 (c)
	Sig.	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$

Different letters indicate statistically significant differences ($p<0.01$) between working time slots.

Table 3. Mean heat-related workability loss (%) ± standard deviation in inland municipalities for unacclimated workers performing high metabolic rate tasks in the sun during July

Month, decade	Working time slots	North	Center	South	Island
July, 1st dec.	5am–1pm	19.0 ± 4.9 (a)	23.6 ± 4.4 (a)	27.2 ± 5.7 (a)	23.1 ± 3.6 (a)
	7am–3pm	31.0 ± 6.8 (b)	34.1 ± 5.9 (b)	38.0 ± 7.3 (b)	34.1 ± 4.7 (b)
	9am–5pm	39.3 ± 8.1 (c)	38.0 ± 6.3 (c)	40.0 ± 6.9 (c)	38.8 ± 4.7 (c)
	Sig.	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$
July, 2nd dec.	5am–1pm	17.3 ± 4.6 (a)	21.1 ± 4.2 (a)	25.4 ± 5.8 (a)	22.2 ± 3.9 (a)
	7am–3pm	28.6 ± 6.5 (b)	31.1 ± 5.7 (b)	35.6 ± 7.4 (b)	33.0 ± 5.1 (b)
	9am–5pm	36.6 ± 7.9 (c)	35.1 ± 6.2 (c)	37.8 ± 7.1 (c)	37.9 ± 5.2 (c)
	Sig.	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$
July, 3rd dec.	5am–1pm	19.0 ± 4.4 (a)	21.7 ± 4.2 (a)	27.2 ± 6.3 (a)	23.3 ± 4.3 (a)
	7am–3pm	30.8 ± 6.4 (b)	32.0 ± 5.7 (b)	38.1 ± 8.0 (b)	34.8 ± 5.5 (b)
	9am–5pm	38.8 ± 7.6 (c)	36.5 ± 6.3 (c)	40.5 ± 7.5 (c)	39.9 ± 5.6 (c)
	Sig.	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$

Different letters indicate statistically significant differences ($p<0.01$) between working time slots.

Table 4. Mean heat-related workability loss (%) ± standard deviation in inland municipalities for unacclimated workers performing high metabolic rate tasks in the sun during August

Month, decade	Working time slots	North	Center	South	Island
August, 1st dec.	5am–1pm	22.0 ± 5.3 (a)	27.0 ± 4.6 (a)	33.3 ± 6.7 (a)	29.1 ± 4.1 (a)
	7am–3pm	35.2 ± 7.1 (b)	39.5 ± 6.2 (b)	46.4 ± 8.3 (b)	42.1 ± 5.1 (b)
	9am–5pm	44.0 ± 8.0 (c)	44.9 ± 6.6 (c)	49.0 ± 7.6 (c)	47.5 ± 5.2 (c)
	Sig.	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$
August, 2nd dec.	5am–1pm	15.1 ± 4.7 (a)	19.5 ± 4.4 (a)	25.2 ± 5.9 (a)	22.7 ± 4.1 (a)
	7am–3pm	25.4 ± 6.6 (b)	28.9 ± 5.9 (b)	35.5 ± 7.5 (b)	33.2 ± 5.2 (b)
	9am–5pm	32.2 ± 7.9 (c)	32.4 ± 6.5 (c)	37.4 ± 7.5 (c)	37.4 ± 5.4 (c)
	Sig.	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$
August, 3rd dec.	5am–1pm	12.0 ± 3.9 (a)	19.8 ± 4.9 (a)	26.9 ± 6.3 (a)	23.1 ± 4.8 (a)
	7am–3pm	21.1 ± 5.7 (b)	29.3 ± 6.8 (b)	37.9 ± 8.2 (b)	33.5 ± 6.0 (b)
	9am–5pm	26.7 ± 7.0 (c)	32.1 ± 7.4 (c)	39.8 ± 8.3 (c)	36.9 ± 6.1 (c)
	Sig.	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$

Different letters indicate statistically significant differences ($p<0.01$) between working time slots.

Table 5. Mean heat-related workability loss (%) ± standard deviation in coastland municipalities for unacclimated workers performing high metabolic rate tasks in the sun during June

Month, decade	Working time slots	North	Center	South	Island
June, 1st dec.	5am–1pm	1.1 ± 1.5 (a)	0.4 ± 0.7 (a)	2.1 ± 2.2 (a)	0.3 ± 0.8 (a)
	7am–3pm	1.7 ± 2.4 (a)	0.5 ± 0.9 (a)	2.8 ± 3.0 (b)	0.5 ± 1.1 (a)
	9am–5pm	1.7 ± 2.4 (a)	0.5 ± 0.9 (a)	2.8 ± 3.0 (b)	0.5 ± 1.1 (a)
	Sig.	$p=0.59$	$p=0.90$	$p=0.02$	$p=0.97$
June, 2nd dec.	5am–1pm	3.3 ± 3.4 (a)	6.1 ± 2.6 (a)	12.9 ± 4.3 (a)	5.5 ± 4.7 (a)
	7am–3pm	5.4 ± 5.2 (b)	9.2 ± 3.6 (b)	18.3 ± 5.7 (b)	8.4 ± 6.8 (b)
	9am–5pm	6.0 ± 5.8 (b)	9.7 ± 3.9 (b)	19.2 ± 5.7 (b)	9.2 ± 7.4 (b)
	Sig.	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$
June, 3rd dec.	5am–1pm	7.0 ± 3.0 (a)	10.5 ± 2.8 (a)	14.8 ± 4.4 (a)	10.7 ± 5.0 (a)
	7am–3pm	11.5 ± 4.3 (b)	15.8 ± 4.0 (b)	21.3 ± 5.7 (b)	16.4 ± 7.0 (b)
	9am–5pm	13.9 ± 4.9 (c)	17.7 ± 4.6 (c)	22.8 ± 5.7 (c)	18.9 ± 7.8 (c)
	Sig.	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$

Different letters indicate statistically significant differences ($p<0.01$) between working time slots.

Table 6. Mean heat-related workability loss (%) ± standard deviation in coastland municipalities for unacclimated workers performing high metabolic rate tasks in the sun during July

Month, decade	Working time slots	North	Center	South	Island
July, 1st dec.	5am–1pm	16.3 ± 4.6 (a)	21.3 ± 2.9 (a)	26.4 ± 4.4 (a)	20.8 ± 5.6 (a)
	7am–3pm	24.5 ± 6.1 (b)	30.7 ± 3.8 (b)	37.0 ± 5.6 (b)	30.4 ± 7.4 (b)
	9am–5pm	28.9 ± 6.2 (c)	34.4 ± 3.9 (c)	39.3 ± 5.0 (c)	34.7 ± 7.4 (c)
	Sig.	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$
July, 2nd dec.	5am–1pm	14.4 ± 4.3 (a)	19.3 ± 3.0 (a)	25.2 ± 4.3 (a)	20.7 ± 5.8 (a)
	7am–3pm	22.2 ± 6.0 (b)	28.3 ± 4.0 (b)	35.4 ± 5.4 (b)	30.4 ± 7.7 (b)
	9am–5pm	26.7 ± 6.5 (c)	32.1 ± 4.1 (c)	38.0 ± 4.9 (c)	34.9 ± 7.8 (c)
	Sig.	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$
July, 3rd dec.	5am–1pm	16.0 ± 4.1 (a)	20.9 ± 3.2 (a)	28.1 ± 5.2 (a)	22.5 ± 6.1 (a)
	7am–3pm	24.7 ± 5.5 (b)	30.6 ± 4.2 (b)	39.5 ± 6.5 (b)	32.9 ± 8.0 (b)
	9am–5pm	29.8 ± 5.8 (c)	34.9 ± 4.2 (c)	42.3 ± 6.0 (c)	37.7 ± 8.0 (c)
	Sig.	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$

Different letters indicate statistically significant differences ($p<0.01$) between working time slots.

Table 7. Mean heat-related workability loss (%) ± standard deviation in coastland municipalities for unacclimated workers performing high metabolic rate tasks in the sun during August

Month, decade	Working time slots	North	Center	South	Island
August, 1st dec.	5am–1pm	20.8 ± 4.5 (a)	26.2 ± 3.8 (a)	34.0 ± 5.1 (a)	28.6 ± 5.9 (a)
	7am–3pm	31.5 ± 5.9 (b)	37.8 ± 4.8 (b)	47.1 ± 6.3 (b)	41.0 ± 7.3 (b)
	9am–5pm	37.2 ± 6.0 (c)	42.6 ± 4.7 (c)	50.0 ± 5.7 (c)	46.1 ± 6.9 (c)
	Sig.	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$
August, 2nd dec.	5am–1pm	13.5 ± 4.3 (a)	18.6 ± 3.2 (a)	26.2 ± 4.9 (a)	22.1 ± 5.9 (a)
	7am–3pm	20.9 ± 5.7 (b)	27.4 ± 4.3 (b)	37.0 ± 6.3 (b)	32.4 ± 7.6 (b)
	9am–5pm	24.8 ± 6.1 (c)	30.9 ± 4.5 (c)	39.6 ± 6.0 (c)	37.0 ± 7.4 (c)
	Sig.	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$
August, 3rd dec.	5am–1pm	11.9 ± 3.3 (a)	18.9 ± 4.1 (a)	27.8 ± 5.2 (a)	23.2 ± 6.8 (a)
	7am–3pm	18.8 ± 4.3 (b)	27.8 ± 5.6 (b)	39.2 ± 6.7 (b)	33.6 ± 8.7 (b)
	9am–5pm	22.3 ± 4.7 (c)	30.9 ± 6.1 (c)	41.7 ± 6.5 (c)	37.9 ± 8.4 (c)
	Sig.	$p<0.01$	$p<0.01$	$p<0.01$	$p<0.01$

Different letters indicate statistically significant differences ($p<0.01$) between working time slots.

ties experiencing the highest levels of WL, such as those along the southern coast and inland areas of Italy, shifting from 9am to 6am reduced WL by ~17%, while a 5am start cut it by over 30%.

Similar trends, albeit with lower WL values, were also observed for workers in the shade or doing moderate tasks (Fig. 4).

Example maps illustrating WL variations at municipal level are available in Figs. 6 and 7.

The Worklimate 2.0 geospatial tool for the potential heat-related workability loss estimation

The GEE "Worklimate 2.0 App" developed in this study is available at the following link: https://ee-worklimate.projects.earthengine.app/view/workabilityloss. It features four interactive panels displaying workability loss maps for sun and shade conditions, considering moderate and high metabolic rates. Figure 8 illustrates an example of output, showing data for workers performing different tasks in both sun and shade.

Workability loss data are displayed on a color scale (Fig. 8) from gray (0−5%) to dark red (60−70%, the maximum observed value) for each geometry of flat municipalities (average altitude less than 300 m a.s.l.). This allows comparisons across work scenarios and summer periods. The "Worklimate 2.0 App" enables users filter data by month, decade, and 8-h shifts, focusing on 14 Italian metropolitan cities (Fig. 8): Bari, Bologna, Cagliari, Catania, Florence, Genoa, Messina, Milan, Naples, Palermo, Reggio di Calabria, Rome, Turin, and Venice.

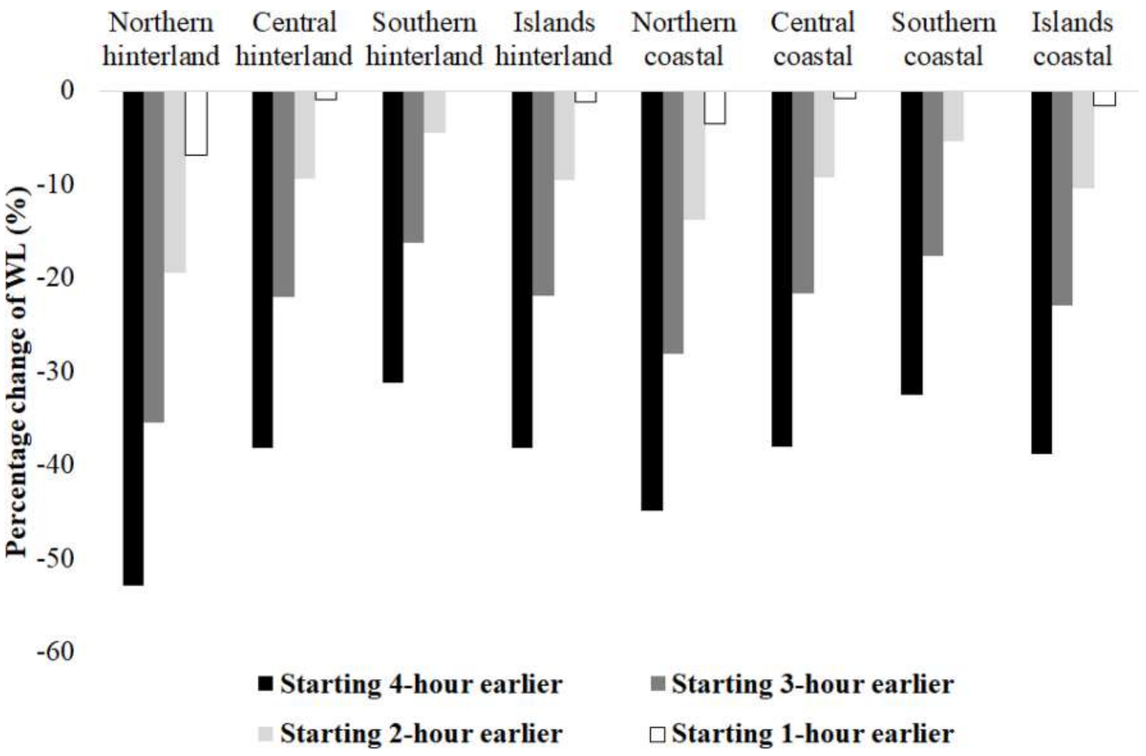

Fig. 5. Percentage change of workability loss (WL) starting the work shift earlier than 9am.
Starting 1-h earlier: work shift 8am–4pm; Starting 2-h earlier: work shift 7am–3pm; Starting 3-h earlier: work shift 6am–2pm; Starting 4-h earlier: work shift 5am–1pm.

Discussion

This study highlights rescheduling work to cooler hours as an effective strategy to reduce workplace heat exposure[14] in Italy, alongside working in shaded areas. The effectiveness of these heat adaptation measures in Italy varies significantly by geography, latitude, proximity to the sea, as well as the summer.

Aligning with previous studies[19, 30], this study confirms that early morning shifts help avoid peak heat-stress periods. Workers naturally reduce intensity and take breaks to cope with heat, leading to presenteeism and lower productivity[7, 10]. The benefits of shifting working hours from the traditional 9am–5pm schedule were quantified at national level, focusing on unacclimatized workers in high metabolic rate tasks, who experience the most heat-related labor loss[8, 10, 14]. Shifting work schedules earlier led to significant WL reductions over the summer: by 4% for a 1-h shift respecting the traditional 9am-5pm schedule, and with effects nearly halved (by 46%) for a 4-h shift (starting work at 5am). These results are significant, as heat-related labour productivity loss is major global economic impact of climate change[5, 31]. However, even a 5am start does not fully eliminate WL. Combining early shifts with shaded areas reduces WL further, though not entirely, to around 5% for workers performing high metabolic rate tasks. These findings emphasize the need for additional measures, like heat acclimatization and personal cooling strategies[5, 14]. Our study revealed that shifting work schedules in early June has limited impact, but it becomes crucial later in summer. In Northern Italy, a 5am start can cut WL by over 50%, while in Southern Italy and the islands, where WL exceeds 50% in early August, this strategy remains essential. Overall, earlier shifts, especially at 5am, significantly lower WL to more sustainable levels.

An important strength of our approach lies in the use of hourly solar radiation data in the calculation of WBGT_{sun}. Unlike simplified methods that rely on a fixed midday solar radiation value, our implementation leverages the HeatStress package's ability to incorporate hourly inputs from the MOLOCH hindcast. This enabled a more accurate representation of the diurnal cycle of solar heat exposure, which is particularly important for evaluating heat stress during early morning and late afternoon work shifts. As highlighted in recent studies[32, 33], the use of hourly solar radiation data enhances the precision of globe temperature

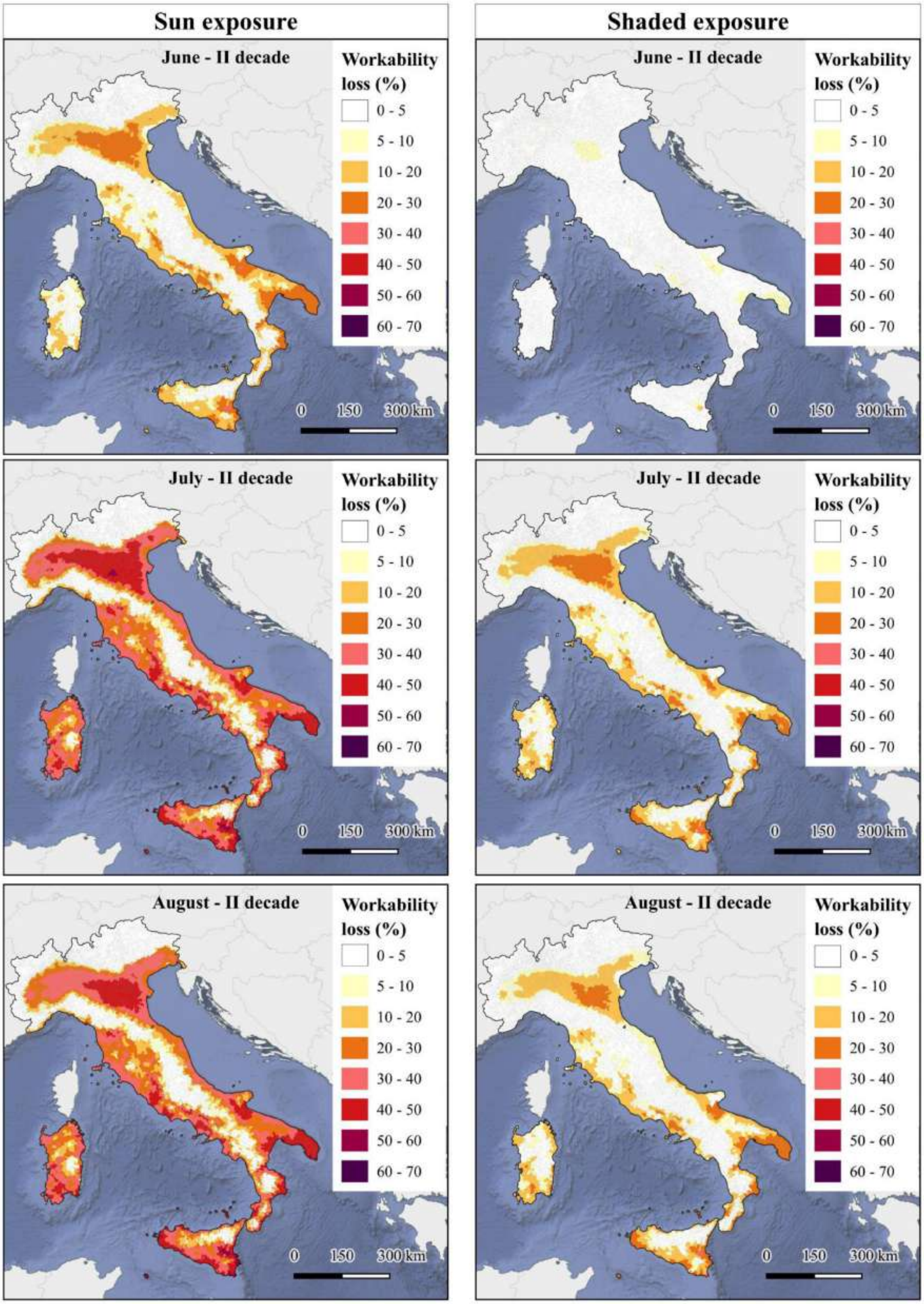

Fig. 6. Workability loss (WL) maps of the Italian municipalities showing the average WL of workers performing high metabolic rate tasks in the sun and the shade.

The maps refer to the second decade of each summer month for the traditional working time slot 9am–5pm.

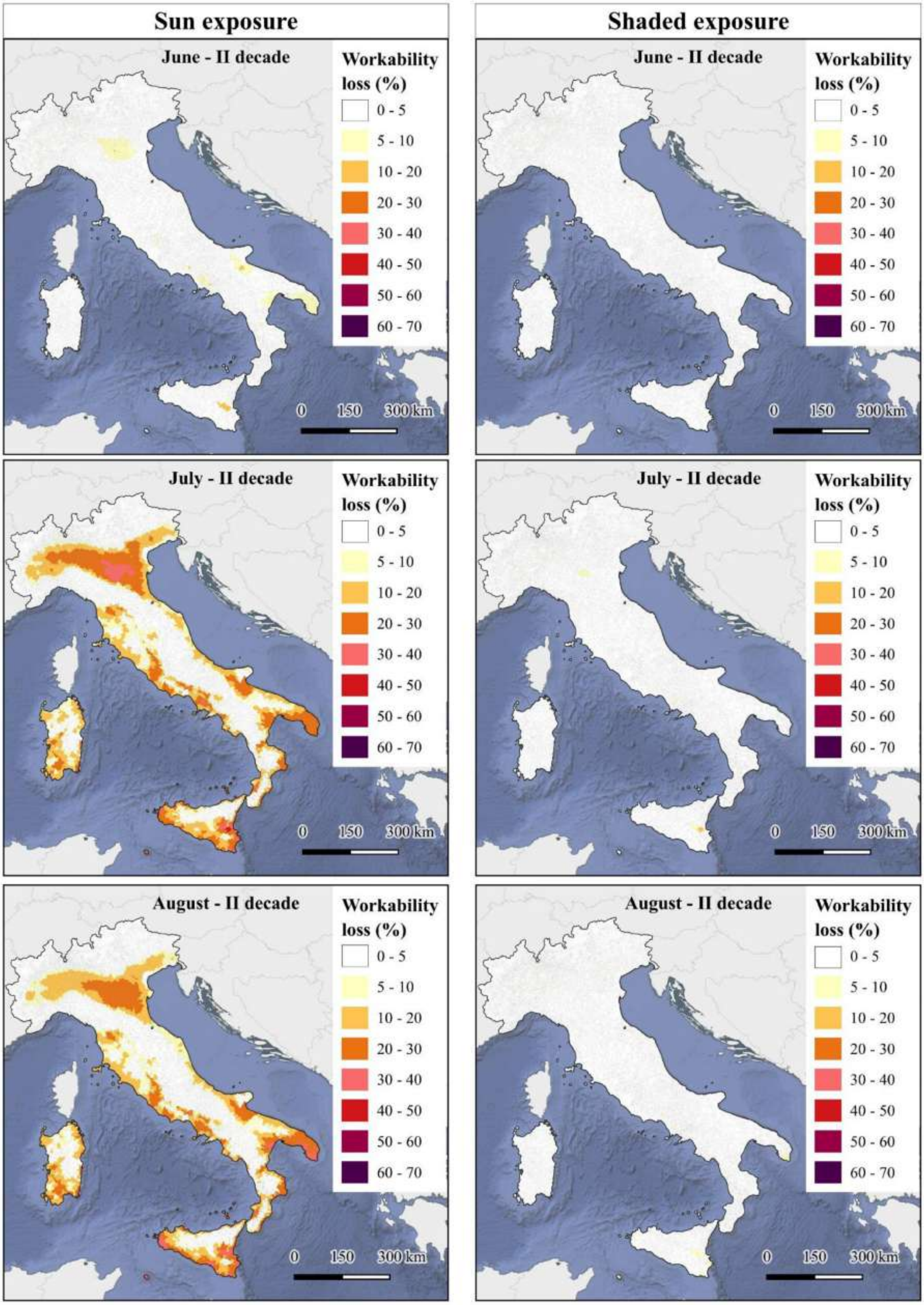

Fig. 7. Workability loss (WL) maps of the Italian municipalities showing the average WL of workers performing moderate metabolic rate tasks in the sun and the shade.

The maps refer to the second decade of each summer month for the traditional working time slot 9am-5pm.

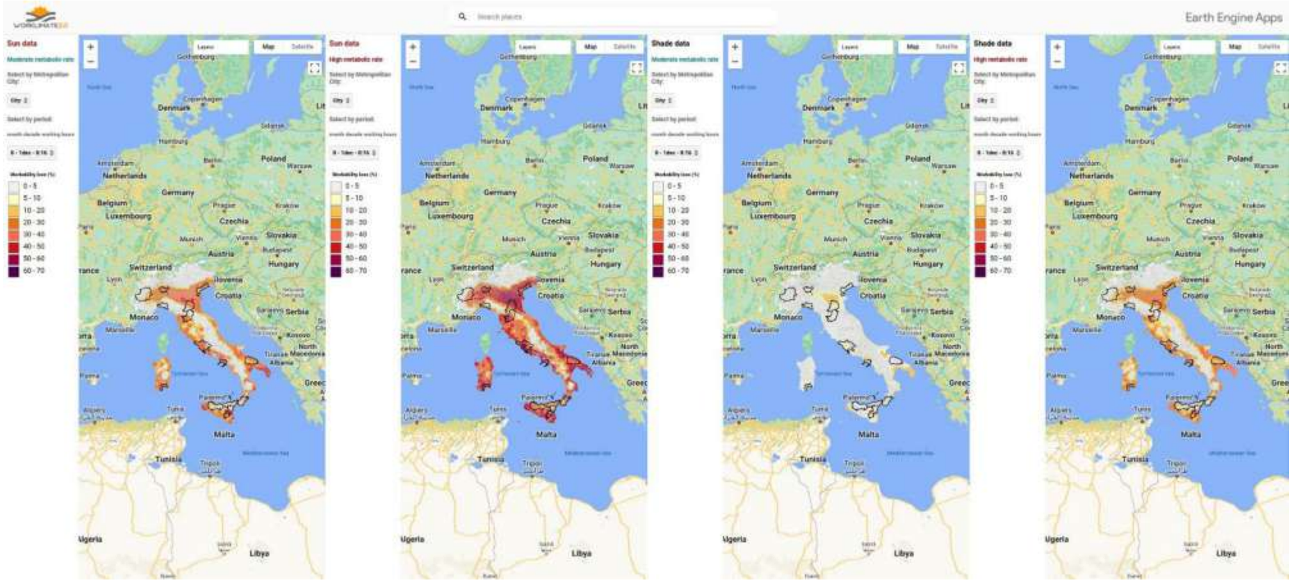

Fig. 8. The Google Earth Engine "Worklimate 2.0 App" preview.

estimation and supports more reliable assessments of occupational heat stress.

This study's work scenario aligns with heat-related ordinances issued in several Italian regions since 2021[34)]. These prevention policies protected workers by restricting work during critical heat hours (12:30 p.m. to 4 p.m.) based on national Worklimate forecast platform (https://www.worklimate.it/en/maps-choice/sun-intense-physical-activity/). Two of the five studied shifts (8am–4pm and 9am–5pm) fully overlap with these restricted hours, reinforcing the benefits of adjusting work schedules to reduce heat exposure.

In 2024, in a significant policy shift in Italy, 15 Italian regions mandated work hour modifications (regional ordinances), impacting nearly 2 million agricultural, construction, and floriculture workers, similar to mandatory midday breaks in the United Arab Emirates[35)].

Despite progress, the lack of quantitative WL data has led to arbitrary schedule changes that don't fully address job-specific heat risks. This study highlights the importance of targeted adaptation measures to reduce occupational heat exposure, injuries, and productivity losses. Effective policies should consider broader co-benefits of reducing workplace heat stress.

The Worklimate 2.0 project has also developed a high-resolution (2.5 km) geographic tool presented in this study, the GEE "Worklimate 2.0 App" (https://ee-worklimate.projects.earthengine.app/view/workabilityloss), which quantifies expected WL at municipal level across different work shifts, summer periods, and scenarios. This tool, implemented on an open planetary-scale platform (GEE), enables visualization of WL across Italian municipalities, considering adaptive strategies like rescheduling work hours and favoring shaded conditions, key for managing rising temperatures. This is the first study at Italian level and, to our knowledge, internationally, to propose a climate service like the Worklimate 2.0 App for mapping heat-related WL and supporting workplace management under heat conditions.

As global warming intensifies, many workers worldwide are already adjusting their schedules to reduce midday heat exposure[30)]. The Worklimate 2.0 App provides useful information for stakeholders to manage worker health and productivity while minimizing heat-related economic losses. Additionally, the use of the GEE platform allows for quick updates and potential global expansion of the tool.

In conclusion, integrating adaptation strategies into geospatial climate tools and national heat safety policies could reduce projected global costs from heat-related work loss[36)], safeguarding worker health and enhancing productivity in the face of climate challenges.

The quantification of benefits from rescheduling working hours to reduce productivity losses in this study has some limitations. Potential drawbacks include issues like sleep deprivation, which could increase the risk of injuries[37)]. Additionally, local noise ordinances[38)] and daylight limitations[17)] may restrict rescheduling in certain sectors.

This study focused on physical work intensity and workplace exposure conditions in analyzing workability. Future research should consider factors such as clothing, personal protective equipment, and the level of heat adaptation, as these also influence workability[5, 7)].

Data Availability

All outputs of the study (input, output geospatial datasets and codes) are available on the Zenodo platform (https://zenodo.org/records/14013352).

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Conflict of Interest

None.

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BRIEF COMMUNICATION

Exploring the effectiveness of a heat-related occupational prevention policy: A case study from Italy

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BACKGROUND: In summer 2024, fifteen Italian regions issued urgent ordinances banning outdoor work from 12:30 to 4:00 p.m. on "HIGH" heat risk days forecasted by the academic Worklimate platform.
OBJECTIVE: This study explores the policy's effectiveness in reducing workplace injuries.
METHODS: ERA5-Land hourly data were used to assess regional summer temperature variations in Italy. Injury data from the National Insurance Institute focused on construction and agriculture, while workforce statistics enabled injury rate comparisons between regions with and without ordinances. Results were stratified by sector and Worklimate heat risk levels.
RESULTS: Regions with ordinances saw a statistically significant 21.9% reduction (95% CI: −18.5−−24.7) in construction injury rates, and over 40% on "HIGH" risk days. Agriculture-related injuries decreased by 24.7% (95% CI: −10.3−−32.2), though not statistically significant.
IMPACT STATEMENT:

- This study provides the first European evidence that temporary work bans during periods of extreme heat can effectively reduce occupational injuries. By comparing Italian regions that implemented urgent ordinances prohibiting outdoor work on "HIGH" heat-risk days with those that did not, the analysis demonstrates that restricting outdoor activity during peak heat hours led to a significant reduction in construction-related injuries and a marked decline in agricultural accidents. These findings underscore the effectiveness of heat-prevention policies in safeguarding outdoor workers amid rising temperatures, offering a robust, evidence-based framework for future public health and occupational safety strategies.

KEYWORDS: Occupational injuries; Ordinance; High risk days; Worklimate; Construction; Agriculture

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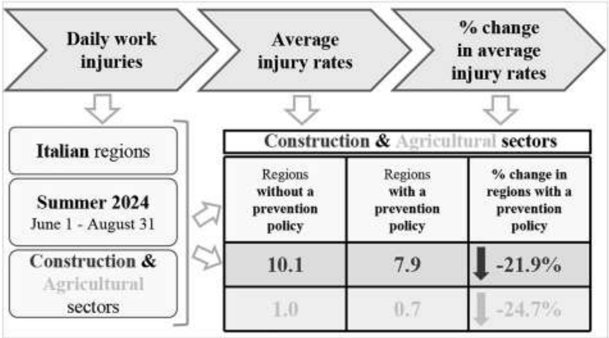
Graphical Abstract



INTRODUCTION

Every year, at least 2.41 billion workers globally are exposed to excessive heat [1]. Workers in Europe experienced the largest increase in heat exposure (about 17%) worldwide over the 20 years from 2000 to 2020 [2]. The Mediterranean basin is warming at a rate of 20% faster than the global average [3] and this trend is increasingly challenging to manage, particularly in Italy, where it has significant public health impacts. A recent nationwide study in

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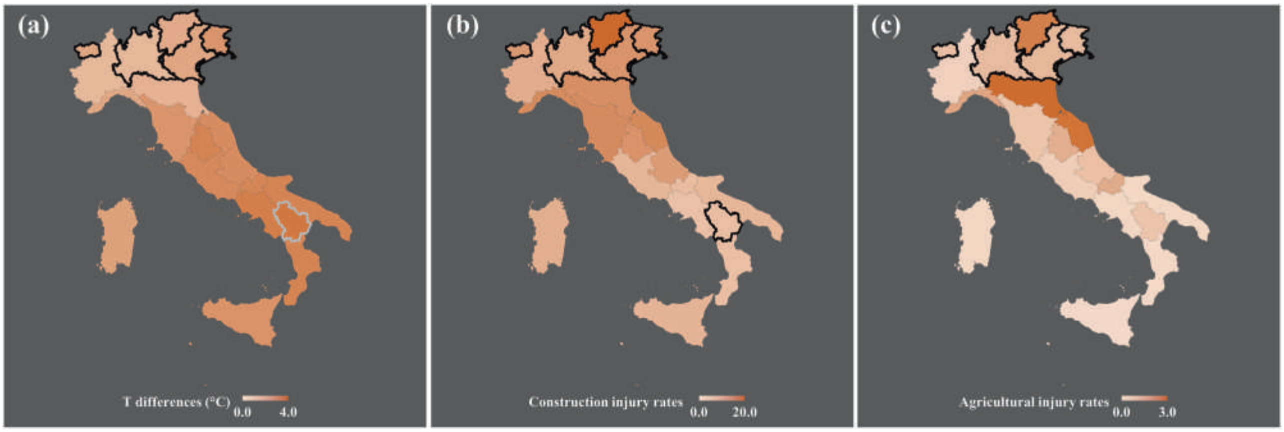

Fig. 1 Overview of summer 2024 conditions and sector-specific injury rates in Italy. a Average diurnal air temperature (T) differences compared to the 1991–2020 mean, along with **b** average injury rates in the construction and **c** agricultural sectors, during summer (June–August) 2024 in Italy. Regions where the prevention policy was not implemented are outlined in black. The grey outline in figure **a** indicates the region that implemented a prevention policy for the agriculture but not for the construction sector.

Italy, which analyzed over 2 million occupational injuries between 2014 and 2019 [4], estimated more than 4000 heat-related injuries per year. This number is expected to rise in the coming decades, as temperature extremes in the Mediterranean region are projected to increase at a rate exceeding the global average throughout the 21st century, as outlined in the IPCC report [5]. Without effective adaptation strategies, this will likely exacerbate heat-related risks during an already hot season.

At the national level, Italy has been addressing the impact of heat on workers' health and productivity, along with developing practical solutions and operational tools for managing heat risk in the workplace, through the national research project WORKLIMATE [6] launched under the INAIL (Italian National Institute for Insurance against Accidents at Work) Collaborative Research Calls and coordinated by Italy's main research institution, the National Research Council (CNR) and INAIL. A key outcome of this project was the development of an operational outdoor heat risk forecast platform [7], based on the Wet Bulb Globe Temperature (WBGT), a standard thermal stress indicator in the occupational sector [8]. This platform allows for customized forecasts based on specific work exposure scenarios [9].

Based on the Worklimate forecasting platform, since 2021, urgent regional ordinances on hygiene and public health have been issued during the summer season (June–August) in some Italian regions as a prevention measure with force of law against the effects of heat on workers. These ordinances were all based on the same criterion: the work ban between 12:30 p.m. and 4:00 p.m. on days when the Worklimate heat risk forecast at 12:00 p.m. indicated a "HIGH" risk level for "non-acclimatized healthy workers, exposed to the sun and engaged in intense physical activity". Between 2021 and 2023, these ordinances applied only to workers in the agricultural sector and were enforced in 3 or 4 of the 20 Italian regions [10]. Progressively, in the summer of 2024, the ordinances were expanded to 15 out of 20 regions across Italy, covering southern and central Italy, as well as parts of northern Italy. Overall, these protective public health measures covered 41.6 million residents and involved approximately 1.7 million exposed workers. These ordinances were issued between mid-June and early August (depending on the region) and remained in effect until August 31st. They applied to workers in agriculture, horticulture, construction, and related fields.

This study hypothesizes that this heat-related occupational prevention policy may have contributed to reducing heat-related risks, particularly by lowering injury rates. The aim is to conduct an exploratory analysis of the effectiveness of these regional ordinances during the summer of 2024, specifically by evaluating their impact on workplace injuries.

MATERIALS AND METHODS

All data presented in this section refer specifically to the summer period from June 1 to August 31, as the regional ordinances issued in 2024, where enacted, were only in effect during this timeframe.

The summer of 2024 was characterized on a regional basis from a climatological perspective using the ERA5-Land Hourly dataset from the Copernicus platform [11], produced by replaying the land component of the ECMWF ERA5 climate reanalysis [12]. The differences in summer regional mean air temperature (T) between the study period (summer 2024) and the reference period (summers 1991–2020) were calculated based on the daytime time slot (from 8 a.m to 8 p.m). The average T variations between regions without and with a prevention policy were also analyzed.

Data on daily work injuries that occurred throughout Italy at the regional and provincial levels in the construction and agriculture sectors during the summer of 2024 (from June 1 to August 31) have been collected from the open data portal of INAIL [13]. The information available from this open data portal concerns the date and place of occurrence (municipality) of the work injury, the worker's gender, age, and place of birth, the circumstances of occurrence (e.g. during work or while commuting), with or without vehicle involvement, and the employment sector, from which we selected injuries that occurred in the agriculture and construction sectors. Since the data refers to a single summer, no further filters were applied to avoid significantly reducing the sample size for analysis. Unfortunately, the available information did not permit filtering injuries by severity or specific causes, such as those related to heat.

Data on the workforce at regional and provincial levels averaged over 2024 have been obtained from the open database of the Italian National Institute of Statistics (ISTAT) [14]. These datasets were used to calculate the average injury rates (per 100,000 workers) involved in construction and agriculture sectors:

$$\text{Average Injury Rate} = \frac{N.daily\ injuries}{Workforce} \times 100,000$$

Changes in injury rates were evaluated by comparing regions that issued the ordinance (including all regions in central and southern Italy, along with the two major islands, as well as three northern regions: Emilia-Romagna, Liguria, and Piedmont) with those that did not (five northern regions: Aosta Valley, Lombardy, Veneto, Friuli Venezia Giulia, and Trentino-Alto Adige). Notably,

Table 1. Overall average injury rates and 95% confidence intervals (in parenthesis) in regions without and with a prevention policy (regional ordinance).

Occupational sectors	Average injury rates in regions without a prevention policy	Average injury rates in regions with a prevention policy	% change
Construction	10.1 (9.2–11.0)	7.9 (7.5–8.3)	−21.9% **(−18.5−−24.7)
Agriculture	1.0 (0.7–1.3)	0.7 (0.6–0.9)	−24.7% (−10.3−−32.2)

A statistically significant variation is indicated with ** ($p < 0.01$).

Table 2. Average injury rates and 95% confidence intervals (in parenthesis) in regional capitals on days without and with "HIGH" heat risk and average injury rates on days without and with work ban.

Regional capitals	Average injury rates		% change
Without a prevention policy	On days without "HIGH" heat risk 9.2 (8.0–10.5)	On days with "HIGH" heat risk 11.4 (9.7–13.1)	+24.0% * (22.4–25.2)
With a prevention policy	On days without work ban 9.6 (8.9–10.4)	On days with work ban 6.5 (5.7–7.3)	−32.1% ** (−35.3−−29.4)
% change	+4.2% (11.4−−1.2)	−42.9% ** (−41.1−−44.3)	

Statistically significant variations are indicated with * ($p < 0.05$) and ** ($p < 0.01$).

Basilicata, a southern region, issued an ordinance targeting only the agriculture sector, excluding construction. Statistically significant differences ($p < 0.05$ and $p < 0.01$) were evaluated through the t-test.

A further and more detailed analysis included the extraction at the regional capital level of all the heat risk levels forecasted during the summer 2024 by the Worklimate platform. This analysis was conducted exploratorily only in the regional capitals where daily heat risk level forecasts for the examined period were available, extracted from the Worklimate platform database. The approach used to forecast the heat risk levels is based on the calculation of the WBGT from the MOLOCH meteorological forecast model [15], which has a spatial resolution of approximately 2 km. The predicted heat risk condition is categorized into four levels, none (green), low (yellow), moderate (orange), and high (red), according to the percentage ratio between the forecasted WBGT and the recommended alert limit [16] (a customized WBGT threshold). The heat risk refers to an unacclimatized, healthy, standard worker (175 cm tall, 75 kg in weight) performing intense physical activity while being directly exposed to solar radiation. The customized heat risk forecast implemented in the Worklimate platform follows the approach developed within the previous European HEAT-SHIELD project [17] and has been recently described in detail elsewhere [9, 10].

Changes in regional capital injury rates and 95% confidence intervals (CI) were calculated by comparing regions where ordinances were issued (specifically, those with a work ban between 12:30 p.m. and 4:00 p.m. on days with a "HIGH" heat risk) to regions without such restrictions (days without a work ban: including days without a "HIGH" heat risk level or those occurring earlier in the summer before the ordinance was implemented).

Changes in regional capital injury rates and 95% CI were also calculated in regions without the prevention policy, comparing days with and without "HIGH" heat risk.

RESULTS

During summer of 2024 (June 1 to August 31), all Italian regions experienced positive diurnal average T differences compared to the 1991–2020 reference period (Fig. 1). These differences were especially pronounced in regions with a prevention policy (i.e., where an ordinance was issued) showing an average absolute T difference of 2.3 °C: T increased by 9.3% in 2024 compared to the reference period. The average temperature variation observed in regions without a prevention policy was more limited, though still noticeable. In this case, the absolute T difference was 1.5 °C and T increased by 7.9% in 2024 compared to the reference period.

During the summer of 2024, a total of 11,197 injuries were reported in the construction sector and 451 in the agricultural sector in Italy. The regional average injury rates for both sectors are presented in Fig. 1.

Average injury rates in both the construction and agricultural sectors were lower in regions with a prevention policy (i.e., where an ordinance was issued) compared to other regions (Table 1). This reduction was statistically significant ($p < 0.01$) for the construction sector.

For injuries in the construction sector, which showed a statistically significant difference between regions without and with a prevention policy (Table 1), a more detailed analysis was conducted at the level of regional capitals.

In regional capitals without a prevention policy, the injury rate on days with a 'HIGH' heat risk (characterized by an average air temperature of 34.0 °C ± 1.9 °C and a relative humidity of 37% ± 8%) was significantly higher ($p < 0.05$) compared to other days (average air temperature of 27.9 °C ± 4.2 °C and a relative humidity of 40% ± 13%) (Table 2). Conversely, in regional capitals where a prevention policy was in place, the opposite trend was observed: the injury rate on days with a work ban (characterized by an average air temperature of 34.9 °C ± 2.5 °C and a relative humidity of 36% ± 13%) from 12:30 p.m. to 4:00 p.m. (which correspond to days with a 'HIGH' heat risk when the ordinance was in force) was significantly lower ($p < 0.01$) than on days without a ban (average air temperature 30.2 °C ± 4.1 °C and a relative humidity of 41% ± 14%) (Table 2).

Regional capitals with a prevention policy showed a statistically significant reduction in injury rates ($p < 0.01$) on days with a work ban (− 42.9%) compared to regions without a prevention policy on days with a 'HIGH' heat risk level. However, no statistically significant difference was observed between regional capitals without a prevention policy (considering days without a 'HIGH' heat risk) and regional capitals with a prevention policy (considering days without a work ban).

DISCUSSION

This exploratory study provides valuable evidence on the potential effectiveness of a prevention policy issued for the first time on a broad scale across several Italian regions during the summer of

2024. The observed reduction in injury rates (particularly a 21.9% decrease in the construction sector) in regions where the ordinance was enforced, compared to those where it was not, highlights the policy's potential to mitigate heat-related injuries.

This is the first study at both the Italian and European levels to quantify the effects of an urgent preventive policy aimed at protecting occupational safety and health in high-risk work sectors during periods of extreme heat. Although EU Directive 89/391/EEC [18] requires the protection of workers from all risks, including emerging ones, there is currently no binding legislation at the European level that specifically addresses heat stress in the workplace. A recent report by the International Labour Organization [2] notes that several EU Member States have independently developed plans to safeguard workers from excessive heat exposure. However, these strategies vary widely and lack a standardized policy framework. To date, no studies at the European level have demonstrated or quantified the effectiveness of such preventive measures, an essential step in understanding their real-world impact and informing future policy development or adjustments.

To the best of our knowledge, the only study [19] to date that has evaluated the effectiveness of a national labor protection policy in preventing occupational injuries related to extreme heat was conducted in the megacity of Guangzhou, southern China. Su et al. [19] reported a 13% reduction in the risk of occupational injuries following the implementation of the policy. Our study observed a more substantial reduction in injury rates (slightly over 20%) in the Italian regions that implemented the ordinance, compared to those that did not adopt the prevention policy. The differences in injury rate reduction observed between the Chinese megacity and the Italian context are likely attributable to differences in the implementation of the restrictive measures outlined in their respective prevention policies. Specifically, the Chinese policy provided for the activation of preventive measures when the exceedance of certain daily maximum temperature thresholds was forecasted. In such cases, work activities were prohibited from 12:00 p.m. to 4:00 p.m. when temperatures exceeded 37 °C, and all outdoor work activities were completely halted when temperatures rose above 39 °C. On the other hand, the Italian policy prohibited work between 12:30 p.m. and 4:00 p.m. when high heat risk conditions were forecasted. These were defined by the exceedance of a WBGT threshold calculated for an unacclimatized worker to heat, exposed to solar radiation, and engaged in intense physical activity. Exceeding this WBGT threshold and reaching a high heat risk level also depends on forecasted values of relative humidity, solar radiation, and wind intensity. In several situations, high heat risk levels may occur even when air temperatures are not extreme for most population, i.e., close to or below 30 °C, thus representing a more restrictive and precautionary intervention criterion for worker health compared to the Chinese policy. Consequently, this more stringent approach, together with local contextual factors, likely contributes to explaining the greater reduction in injury rates observed in Italy.

The injury rate reduction in Italy was even more pronounced (just over 40% in the construction sector) when comparing injury rates in regional capitals specifically on days classified as "HIGH" heat risk, the most critical days of the summer season. This finding is particularly noteworthy considering that, in 2024, the regions where the ordinance was enforced experienced significantly higher temperatures and levels of thermal stress compared to those where it was not. Despite facing more intense heat conditions, the implementation of the preventive measure still led to a significant reduction in injury rates.

The reason why the variation in injury rates was statistically significant only in the construction sector may lie in the distinct dynamics that characterize the agricultural sector. It is well established that official data on occupational injuries in agriculture are often imprecise and significantly underestimate the true burden, due to inadequate and heterogeneous reporting and notification systems [20]. This underreporting reduces the number of recorded cases, making statistical analyses less robust. In Italy, part of the underestimation in the INAIL database is due to the exclusion of irregular or informal workers, who are not registered and therefore not represented in official statistics. Additionally, the significant regional variability in agricultural activities and processes further complicates accurate data collection [21, 22], making it difficult to generalize findings both within and across sectors and potentially introducing uncontrolled heterogeneity into the analysis. In addition, the absence of personal-level exposure or injury data (e.g., by worker, occupation, or shift) limits the ability to control for confounding variables or to conduct more detailed stratified analyses. It is indeed important to note that in many Italian regions, it is common practice in the agricultural sector to shift working hours forward by approximately two hours compared to the standard schedule and concluding activities by 1:00 p.m. This adaptation helps to avoid work during the hottest and most hazardous hours of the day, thus reducing both health risks and productivity losses [23]. In contrast, the construction sector presents a different scenario: for various reasons (including noise restrictions) work activities often cannot be anticipated to the very early morning hours, and therefore frequently continue during the most critical central and afternoon hours of the day, when heat exposure is highest.

It is important to highlight that the findings of this exploratory investigation, which quantify the effectiveness of a prevention policy, may not be directly applicable to other countries or work sectors, due to contextual differences in climate conditions, labor regulations, and occupational health infrastructure. Although work bans ("stop work") during specific times of the day represent a key protective measure, their implementation may not be feasible in all settings due to operational or economic constraints. Therefore, greater emphasis should be placed on strengthening and expanding existing preventive policies through the integration of complementary strategies that enhance the scalability and feasibility of their implementation. These include training and awareness programs for both workers (particularly targeting non-acclimatized or inexperienced individuals, such as young or newly hired workers) and employers, considering behavioral and cultural factors that influence compliance (with particular attention to migrant workers, for whom language barriers represent the main obstacle), and adapting interventions to the specific needs of high-risk sectors, including informal, seasonal and temporary labor groups and employees of small businesses with limited resources for prevention. Active engagement of key stakeholders (e.g., labor inspectors, local health authorities, occupational physicians, prevention officers, and Workers' Safety Representatives) is essential to support enforcement and foster effective feedback mechanisms.

Nonetheless, it is advisable to encourage replication of this study in other European and international contexts where similar measures aimed at protecting workers from extreme heat exposure have been implemented. Once such comparative data becomes available, it will be possible to identify the most effective prevention policy for safeguarding workers' health against the impacts of heat.

STUDY LIMITATIONS AND FUTURE PERSPECTIVES

This study has several limitations, and future research involving the collection of longer time series data should enhance the statistical robustness of the analyses and potentially confirm the findings of this exploratory investigation into the policy's effectiveness. This study assumes that the work ban ordinance (from 12:30 p.m. to 4:00 p.m.) was uniformly enforced and consistently followed across all regions. However, there remains uncertainty regarding the actual implementation of the policy and the degree of compliance. The availability of multi-year data in the future will enable more detailed analyses, depending on data availability, for example, baseline injury rates, labor conditions, urbanization levels, and workforce characteristics. Future analyses could also be stratified by injury type and the time of day when injuries occurred. The complete assessment of the individual causality between the risk of injuries and the effectiveness of the working limitation policies is not possible in this context. Nevertheless, our epidemiological findings suggest an association that provides a framework useful at aggregate level as policy impact evaluation.

This exploratory analysis focused on the most populous regional capitals. To strengthen the robustness of these initial findings, future research should expand to include a broader range of locations and extend the analysis to other warm periods throughout the year, using longer time series.

As more longitudinal data on regional ordinances become available, it will be important to assess whether the relationship between heat exposure and occupational injuries, already demonstrated in recent and detailed national-level studies [4, 22, 24], undergoes any changes following the implementation of these preventive measures. Notably, the only study currently available on this topic [19] found that the association between extreme heat and occupational injuries was no longer statistically significant after the policy came into effect. It will also be essential to evaluate the effectiveness of these interventions through detailed cost-effectiveness analyses or through interactions with the competent authorities (Local Health Unit and Labor Inspectorate) involved in monitoring compliance with the ordinances. Such analyses should consider the broader economic implications of the policy, including changes in insurance payouts, costs associated with the reorganization of work schedules, and potential compensation for work carried out during inconvenient hours or for delays in project completion resulting from adjustments made to comply with the ordinance.

DATA AVAILABILITY

The data used in this study are largely derived from open databases, such as the ERA5-Land Hourly dataset (https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_LAND_HOURLY#description); daily work injury records from the open data portal of the Italian National Institute for Insurance against Accidents at Work (INAIL, https://dati.inail.it/portale/it/dataset/infortuni-sul-lavoro.html); workforce data at regional and provincial levels obtained from the open database of the Italian National Institute of Statistics (ISTAT, http://dati.istat.it/Index.aspx?DataSetCode=DCCV_FORZLV1#). Additional data concerning the daily heat risk levels forecasted during summer 2024 by the Worklimate platform are available from the corresponding author upon reasonable request.

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AUTHOR CONTRIBUTIONS

MM drafted the manuscript. MM, MB and AM conceived and designed the study. MM, AC and GG conducted the formal analysis. AC, GG, MB and AM contributed to the research content, provided writing support and interpretation of results, and reviewed the manuscript. All authors approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

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COMPETING INTERESTS

The authors declare no competing interests.

ETHICAL APPROVAL

The activities planned within the Worklimate 2.0 project have received ethical clearance from the Ethics and Integrity Commission of the National Research Council (CNR) (Prot N. 0050824, 15 February 2024).

ADDITIONAL INFORMATION

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Impacts of heat waves on agricultural workers: An analysis of adaptation measures

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Abstract. This study evaluates the effectiveness of different farm-level adaptation measures aimed at mitigating the adverse impacts of heat waves on labour productivity. Despite the increasing frequency of heat waves, existing literature on occupational heat stress primarily relies on modelled estimates. To address this gap, exploratory interviews and structured questionnaires were employed to identify key challenges posed by heat waves, as well as the perceived benefits and limitations of different adaptation strategies. Data were collected from nine farms located in Emilia-Romagna (Northeast Italy), all of which were characterized by a long-standing commitment to improving working conditions. The Analytic Hierarchy Process was used to evaluate the perceived effectiveness of adaptation measures according to three criteria: acceptability, flexibility, and timeliness. Findings indicate that, in the absence of adaptation strategies, productivity losses may reach up to 30%. Among the measures assessed, shifting work hours was identified as the most effective strategy. The study underscores the need for structured thermal risk assessment protocols and provides recommendations to inform sustainable and worker-centered adaptation policies in the agricultural sector.

Keywords: heat waves, adaptation measures, agricultural workers, productivity loss, Analytic Hierarchy Process (AHP).

1. INTRODUCTION

Worldwide, climate change scenarios point to an intensification of extreme heat events across all regions with growing implications for outdoor workers (IPCC AR6 WGI, 2021). According to the World Meteorological Organisation (WMO), a heat wave is defined as a period of at least six consecutive days during which the maximum daily temperature exceeds the 90th percentile based on the climatological reference period (1981-2010 or if available 1991-2020). Studies, such as de Sario et al. (2023), have shown that heat waves have significant economic impacts on society, including increasing healthcare costs (Martínez-Solanas et al., 2018), and costs for the social security system, that must compensate workers for heat-related injuries (Ma et al.,

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2019). In addition to these social costs, several studies have reported economic costs linked to a reduced worker productivity resulting from high temperature exposure in working environments (Morabito et al., 2021; Kjellstrom et al., 2009). In sectors such as agriculture, where most activities, are carried out outdoors, heat waves significantly increase the risk of work-related injuries and work productivity reductions (Di Blasi et al., 2023).

Thus, in recent years, the necessity to introduce acceptable preventive measures able to reduce the risk of outdoor work-related injuries and excessive heat exposure has become pressing. For instance, in recent years, countries such as Italy have introduced regional regulations to improve the working conditions during heat waves. Specifically, these regulations limit the working time between 12:30 and 16:00 for specific sectors such as agriculture and construction during the summer months and in case of heat waves. In 2021, these measures were implemented in three southern Italian regions (Puglia, Calabria and Basilicata). In 2024, similar regulations were adopted by 15 of the 21 Italian regions.

Economic effects linked to heat waves can be classified as direct and indirect impacts. Workers' productivity loss (PL) involves a direct output loss for farms. This can entail relevant indirect effects because of the interdependencies along the value chain, and at a macroeconomic level on household consumption, national output, etc. (Zhao et al., 2021). These aspects related to climate changes are often neglected, but the magnitude of their potential impact on workers' health and productivity underlines the need for case studies providing information on PL in different contexts and activities, and for different economic sectors (Kjellstrom et al., 2009). Indeed, current knowledge is scarce about the economy-wide effects of heat waves on the productivity of diversified economic sectors that range from outdoor to indoor activities and feature a heterogeneous structure and production orientation, such as agriculture (Day et al., 2019).

One approach to quantifying heat-related productivity loss is the use of the Wet Bulb Globe Temperature (WBGT) index and ISO 7243 standards. Kjellstrom et al. (2018) developed risk functions based on these metrics to estimate reductions in work capacity under different levels of heat stress. These functions assume that workers self-regulate their workload to avoid severe health consequences, such as heat stroke. Accordingly, these models can estimate productivity loss (PL) as a function of heat exposure and work intensity.

Individuals and firms can reduce the heat-stress implementing specific adaptation strategies able to cope with heat conditions (Kjellstrom, Holmer et al., 2009). A range of adaptation options are available and these offer different solutions that can fit to different working conditions and contexts cost-effectively. In general, behavioural adaptations such as the anticipation of working hours to avoid heat peaks, and passive adaptation options such as frequent drink breaks, together with technical equipment are indicated as valuable options for outdoor workers (Day et al., 2019). However, the identification of the adaptation measures strictly depends on local contexts and the type of activities. This warns against a generic identification of adaptation solutions and highlights a particular need for economic sectors such as agriculture, for an evaluation carried out at the farm level and able to consider the complexity of adaptation decision-making (Day et al., 2019).

The effectiveness of the available adaptation measures in reducing the impact of heat waves has a specific relevance to evaluate their soundness as tools to be included in regulations targeting the adaptation of working environments to climate risks. For instance, building on the work of Kjellstrom et al. (2018), Morabito et al. (2021) applied different heat risk functions to estimate the effectiveness of simple adaptation measures. In this study, WBGT and typical working hours data were combined to compare PL and economic costs related to farming activities in an Italian region with and without the adoption of adaptation measures. Using the modelled functions, Morabito and colleagues estimated a significant effect of the adaptation measures, and thus highlighted a potential positive impact for firms and workers engaged in intensive activities during heat waves, such as agricultural workers.

While model-based approaches provide valuable insights, evaluating the perceived effectiveness of adaptation measures and understanding workers' and managers' perceptions of climate risks are equally important. Risk perception is a critical factor influencing adaptive behavior (Madhuri and Sharma, 2020), and a range of psychological, economic, and contextual factors may shape the willingness to adopt preventive strategies (D'Alberto et al., 2024). Despite a robust body of literature focused on modeled projections of productivity loss under heat stress (e.g., Orlov et al., 2019; Kjellstrom et al., 2009; Morabito et al., 2021), empirical data on the perception of heat waves from both the individuals directly affected and those responsible for managing and organizing outdoor working activities during these events are currently limited.

Moreover, research on the operational feasibility and perceived efficacy of various adaptation strategies is still limited. In particular, studies investigating the views of land managers on the implementation and effectiveness of such measures are, to our knowledge, lacking. Yet, understanding these perspectives is important, as land managers are ultimately responsible for adopting and enforcing adaptation strategies at the farm level. The lack of empirical data on the perceived utility and impact of adaptation measures impedes the development of evidence-based policies that ensure worker safety and productivity during heat events. Without such insights, efforts to identify and promote tailored, context-specific adaptation measures risk being ineffective or unsustainable (Final Scientific Report of the WORKLIMATE Project, https://www.worklimate.it/).

This study aims to address this research gap by investigating how farm managers in Emilia-Romagna perceive and evaluate various adaptation measures designed to mitigate the impacts of heat waves on outdoor agricultural workers. The work contribution to the existing literature is twofold: (1) it provides an in-depth analysis of the challenges posed by heat waves within a specific agricultural context; and (2) it evaluates the perceived effectiveness of adaptation strategies based on empirical data collected from nine farms in the region. Specifically, the research explores land managers' assessments of the impacts of heat waves on different types of workers, their evaluation of the advantages and disadvantages of various adaptation strategies, and their perceptions of these strategies' effectiveness in reducing productivity losses.

2. METHODOLOGY

2.1. Analytical approach

In this analysis, the analytic hierarchy process (AHP) method was employed (Saaty, 2013). AHP was developed to support decision-making by structuring complex problem into a hierarchical framework. AHP organises decision problems into a hierarchy of factors that can be easily interpreted by an expert, thereby facilitating complex judgments and enabling a structured evaluation of multiple alternatives across different criteria. Originally developed by mathematician Thomas Saaty in the 1970s (Saaty, 1977), AHP is a widely used multi-criteria decision analysis (MCDA) technique. At the core of AHP lies the pairwise comparison approach, which evaluates decision elements in pairs, allowing for a more nuanced assessment of their relative importance. The hierarchy itself takes the form of a tree structure with successive levels representing broader decision criteria, specific subcriteria, and eventually alternatives. These elements are compared pairwise at each level of the hierarchy, from the lowest level (typically comprising the alternatives or specific actions under evaluation) up to the highest-level criterion (Saaty, 1987). In this study, the objective was to identify the most effective adaptation measures to mitigate the impacts of heat waves. The AHP process involves assigning numerical values to each pairwise comparisons using a 1-to-9 scale, where 1 indicates equal importance and/or relevance of the two elements on the control element and 9 represents extreme importance of one element over another (Saaty, 2008) (Tab. 1). These comparisons are recorded in pairwise comparison matrices that reflect the relationships between criteria and adaptation measures. After completing the pairwise comparisons, the relative weights (or priority) for each criterion are calculated using specific procedures, particularly the eigenvalue method. This priority is defined as a vector representing the influence (or weight) of each single element within that level of the hierarchy (Duke & Aull-Hyde, 2002). The process entails calculating the normalized values for each matrix to derive weights that reflect the relative importance of each criterion, by means of the eigenvector method and a process of averaging over the normalised columns of the matrix (Meade & Sarkis, 1999; Saaty, 2008). For further details on the calculation of the priority by means of different matrix multiplication methods see in particular Villanueva et al. (2015). Subsequent consistency checks are then carried out to ensure the reliability of comparisons. The Consistency Ratio (CR) is utilised to assess consistency, by comparing the consistency index of the judgments to a random index. A CR value below 0.1 is generally considered acceptable, indicating a reasonable level of consistency in the decisions made during pairwise comparisons. Finally, the calculated weights are aggregated to determine the overall priorities of the adaptation measures (Liu et al., 2025).

However, one of the main limitations of this methodology is that the quality of results heavily depends on the expertise and understanding of the respondents. Biases may be introduced if participants are not sufficiently knowledgeable about the subject matter (Villanueva et al., 2015). Furthermore, AHP does not rely on assumptions regarding known probability distributions (Duke & Aull-Hyde, 2002). As a result, the method is not statistical in nature and typically involves a relatively small number of expert respondents, due to the in-depth knowledge required to complete the questionnaires accurately.

2.2. Identification of target participants

As illustrated in Figure 1, the survey was organized in three main phases. The first step involved identifying the target group of participants.

Table 1. Saaty's fundamental scale for pairwise comparison judgments.

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective.
2	Weak or slight	Experience and judgment slightly favor one activity over another.
3	Moderate importance	Experience and judgment slightly favor one activity over another.
4	Moderate plus	Experience and judgment strongly favor one activity over another.
5	Strong importance	Experience and judgment strongly favor one activity over another.
6	Strong plus	An activity is favored very strongly over another.
7	Very strong or demonstrated importance	An activity is favored very strongly over another.
8	Very, very strong	The evidence favoring one activity over another is of the highest possible order of affirmation.
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation.

Source: Saaty, 2013.

For our study, the target participants were farm managers of large, well-structured farms with a significant number of workers. Given the exploratory nature of the research, we considered appropriate to begin by involving farm managers operating within the same geographical area (Emilia Romagna). This choice allowed for greater homogeneity and consistency in the data collected, thereby minimising the influence of contextual and structural difference across regions. In light of the limited number of studies investigating the impact of heatwaves on farm management and the scarcity of empirical data on this issue, the survey specifically targeted farms with a demonstrated commitment to workers' welfare. Indeed, the selected farm managers had already been implementing strategies and measures to mitigate the effects of heat waves on their employees over several years. Such an analysis enabled an in-depth analysis of the current implementation status of various adaptation measures. The first part of the survey focused on the Cooperative Agricole Braccianti (CABs) in the province of Ravenna. Later, the survey was extended to include other large farms in the region with the help of trade associations.

Collectively, these cooperatives manage approximately 11,500 hectares of utilised agricultural area (UAA). Their production is primarily oriented towards fruit trees, vegetables and cereal crops, although some also operate in the livestock and nursery sectors. These cooperatives were of particular interest due to their organisational structure: workers are also cooperative members and are involved in the decision-making process. Being directly exposed to the working conditions, the worker-members have developed a deeper awareness of the impacts of heat waves, including suggestions and proposals to more effective prevention and protection measures.

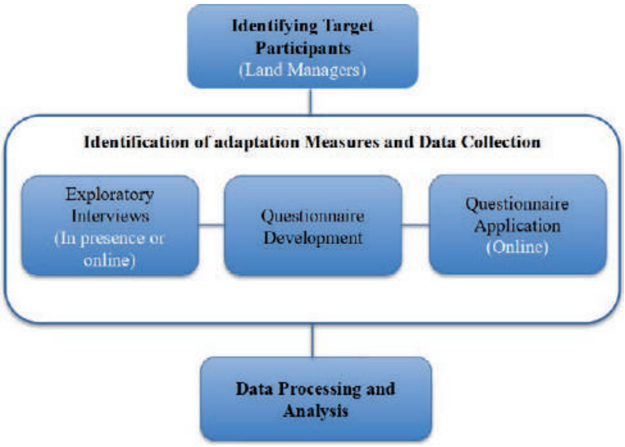

Figure 1. A flow diagram of the research process.

2.3. Identification of adaptation measures and data collection

We conducted a literature review to identify the adaptation measures able to reduce the impacts of heat waves on agricultural workers. Four adaptation measures were identified through a literature review (Day et al., 2019; Habibi et al., 2023; Kjellstrom et al., 2009; Marinaccio et al., 2022; Morabito et al., 2021; Spector et al., 2019; Zhao et al., 2021):

- shifting/anticipating work hours;
- setting up shaded areas;
- increasing the frequency of work breaks with facilitation of the availability of water;

- special equipment (ventilated jackets, clothing in technical, breathable fabric).

These measures represent different management options for the organisation of outdoor labour that can improve workers' resilience to heat stress and aim to maintain a safe work environment. Therefore, the adoption of the measures also allows to enhance significantly worker performance, productivity, and company profits (Habibi et al., 2023).

The second phase involved the data collection (Figure 1). We started with exploratory interviews with the CAB farm managers, aimed at collecting preliminary information on the phenomenon of heat waves and identifying pros and cons related to the potential implementation of adaptation measures at farm level and productivity-related issues or operational problems observed during the last heat wave events. Five exploratory interviews were conducted with the managers of the seven CABs in the province of Ravenna. Each interview lasted on average 40 minutes and was conducted either online or in person. The interview was divided into two main sections: The first section focused on framing the problem and identifying the work problems already encountered during the last heatwaves (summer 2022-2023). The second section assessed the advantages and disadvantages and the respondents' perceptions of the four selected adaptation measures. Then, based on the information gathered in the exploratory interviews, a questionnaire was designed to collect quantitative data on the adaptation measures and assess their effectiveness in reducing the impact of heatwaves on agricultural workers.

The questionnaire included 34 questions, and it was implemented on the Qualtrics^{XM} (2024) platform (Provo, Utah, USA, https://www.qualtrics.com).

The questionnaire was structured in three main sections: the first section included general information about the respondents and the farms, such as their role, main crops, farm size, the main symptoms observed in workers during the heat waves of the summers of 2022-2023, the activities most affected by the heat waves, and the adaptation measures adopted in these circumstances.

The second part of the questionnaire dealt with the assessment of the effectiveness of adaptation measures. In order to assess the effectiveness of the identified heat wave protection measures, we included four questions to collect data using the AHP method (Fig. 2). Three of these questions focused on specific criteria for assessing the effectiveness of each adaptation measure, namely:

1. Worker acceptability, i.e. the expected willingness of outdoor agricultural workers to adopt the measures.
2. Timeliness of implementation, i.e. the time needed to implement the measure after a heat wave forecast.
3. Flexibility of application, i.e. the possibility to adopt the measure in different types of farms.

In addition, a further question concerned the comparison between the selected criteria. These criteria were derived from those identified by Day et al. (2019) and subsequently adapted based on the information gathered during the exploratory interviews.

This set of questions included four matrices comparing adaptation measures according to each of the criteria listed above using the AHP 1-9 scale.

As an example, we report two of the submitted questions for the two assessment levels:

- (Q11) - *With respect to the criterion acceptability by workers, which of the following pairs of factors do you think is the preferred adaptation measure by workers? (Shifting of working hours VS Setting up shaded areas; Shifting of working hours VS Increased frequency of breaks… etc.) For each pair, express your preference on a scale of 1 to 9, where 1 indicates that the measures are equally preferred and 9 indicates that one measure is extremely more accepted than the other.*
- (Q13) - *Which criterion, among the following pairs of criteria, do you think is most important for an effective reduction of workers' productivity loss?* (*Acceptability by the workers VS Timeliness of implementation; Acceptability by the worker VS Flexibility of application…etc) For each pair, express your preference on a scale of 1 to 9, where 1 indicates that the criteria are of equal importance and 9 indicates that one criterion is extremely more important than the other for reducing productivity loss.*

The final part of the survey focused on estimating the productivity loss of agricultural workers. In the land manager survey, respondents were asked to report any adaptation measures implemented to cope with heat wave events. Respondents were then asked to estimate productivity loss in the following ranges in the absence of adaptation measures: 0-10%, 10-20%, 20-30%, and more than 30%. Specifically, the questionnaire asked respondents to provide an estimate of the percentage of daily productivity loss estimated for general workers and specialised workers during heat waves and in the absence of adaptation measures.

The questionnaire was distributed in June and July, and it was initially distributed to the CABs and to the main regional farmers' associations, who then distributed it to the agricultural land managers in Emilia-Romagna. The distribution of the questionnaires to Emilia-Romagna was motivated by the need to obtain data that were as homogeneous as possible. This strategy helped to reduce the variability linked to geographical and struc-

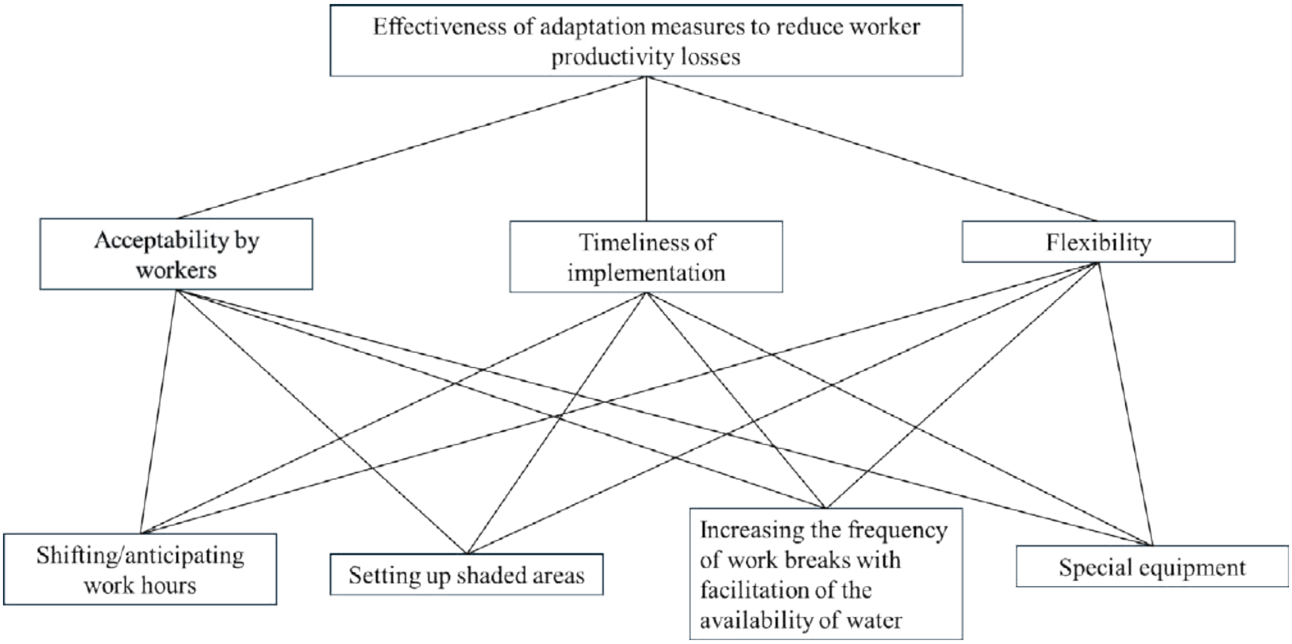

Figure 2. Hierarchical decision-making structure for selecting the most effective heat wave adaptation measures.

tural factors, ensuring greater consistency in the results and facilitating comparisons between the different farm realities analysed.

2.4. Data processing and analysis

The survey collected a total of 15 responses from land managers in Emilia-Romagna. Only 9 questionnaires were completed in all parts and included in the analysis. For the AHP questions, we normalised the comparison matrix data and determined the priorities for each level of the hierarchy. Elaborations were performed with R 4.4.1 (2024) (RStudio: Integrated Development for R. RStudio, PBC, Boston, MA, http://www.rstudio.com/). The priority calculation was used to compare the relative contribution of the elements at each level of the hierarchy with an element in the adjacent higher level. We conducted a synthesis of the priorities to calculate a composite weight for each alternative, based on the preferences guided by the comparison matrix. After calculating the composite weight, the relative priority of each adaptation measure was obtained, and a final ranking was developed to identify the best adaptation alternative through the calculation of the average of all the overall priorities that were calculated for each questionnaire (Veisi et al., 2022).

Finally, the consistency ratio (CR) was calculated to verify the consistency of the judgments expressed by the respondents. The CR is suggested as a valid indicator of the cognitive stress of respondents, i.e. a high CR indicates a high complexity level of the questions and thus higher efforts required in the judgement process.

3. RESULTS

3.1. Results of the exploratory interviews

We conducted five interviews with CAB farm managers to get an initial overview of the impacts of the heatwaves, the benefits and challenges of the adaptation measures selected.

It emerged that all farms observed issues related to heat waves during the summers of 2022-2023, particularly in orchards during the harvesting of peaches and apricots: "*The issue of heat waves is primarily felt in the orchard*". One farm also encountered difficulties in nurseries and in organic fields: "*Heat waves are also felt in open fields across the 1,200 hectares of organic farmland, which requires frequent tilling to eliminate weeds*". Additionally, all managers reported that in the orchards, due to heat waves combined with high levels of humidity, the presence of nets and rows of trees themselves limit air circulation, workers experience signs of fatigue, tiredness, and breathing problems. The farm managers also stated that the productivity of workers decreased during heat waves: *"During the hot-*

test hours, fewer kilograms are harvested and in general during heat waves, yields decrease because workers are slower", "From eleven o'clock onwards, employee performance drops by about 30 per cent".

The interviewed farm managers stated that, to avoid extreme heat during the central hours of the day, they adjust the work schedule. In fact, field workers (who are mostly women) finish their workday by noon and, depending on daylight, they start working about an hour earlier, around 5 a.m. The shifting/anticipating of working hours was implemented by 5 out of 5 farms. For greater clarity, we provide the interviewee's response as follows: "*During the summer, it became necessary to start the workday an hour to an hour and a half earlier (depending on daylight) or to leave an hour earlier (by 12 p.m.)*". The anticipation of the working time also contributed to mitigate operational problems related to harvesting and storing the product. Indeed, excessive heat also affects the quality of the harvest, especially if it remains under the sun and is not delivered immediately to storage or processing centres.

Regarding the adaptation measures already implemented by the interviewed farms, in addition to adjusting work hours, five out of five farms also indicated the use of shaded areas represented by break rooms, warehouses, or shelters near the orchards. Other shaded areas included seminatural elements like hedges and groves established for instance with the support of agro-environmental measures in the past. The interviewees reported that most employees rely on own water supply. In the five farms however, the interviewees reported that supervisors are always supplied with drinking water as well as with a first aid kit. The availability of water supplies at the farm centre was also indicated by the five interviewed farm managers. Regarding the use of special equipment, the purchase of technical clothing to promote better breathability was reported in one interview: "*In the summer of 2023, the farm purchased technical fabric shirts that allow workers to work more comfortably. The request originated from the workers*".

3.2. Results of the questionnaires

The main characteristics of the sample are presented in Table 2. The results of the questionnaire indicate that heat waves have a notable impact on farm workers' health. Respondents reported significant physical symptoms among workers, including intense fatigue, excessive sweating, drops in blood pressure, muscle cramps, and dehydration. These symptoms typically occur during labor-intensive tasks such as fruit and vegetable harvesting, field operations, and manual activities like weed removal.

Table 2. Characteristics of respondents.*

	Frequency	%
Respondent type		
Entrepreneur	2	22.22%
Director/Manager	5	55.56%
Technician/Foreman	2	22.22%
Farming system		
Cereal farming	7	77.78%
Horticultural	4	44.44%
Viticultural	5	55.56%
Fruit farming	4	44.44%
Zootechnical	3	33.33%
Other	2	22.22%
Symptoms observed during heat waves		
Tiredness	9	100.00%
Pressure drops	1	11.11%
Muscle cramps	1	11.11%
Intense sweating	8	88.89%
Activities affected by heat waves		
Fruit and vegetable harvesting	6	66.67%
Field operations	4	44.44%
Other (manual weeding)	3	33.33%
Measures against heat waves		
Shifting/anticipating work hours	8	88.89%
Setting up shaded areas	6	66.67%
Increasing the frequency of work breaks with facilitation of the availability of water	9	100.00%
Special equipment	2	22.22%
Other (e.g. umbrellas)	1	11.11%

* Each participant had the opportunity to select more than one answer, so the total number of answers may exceed the number of participants.

To mitigate the effects of heat waves, most farms have already implemented various adaptation measures. All respondents reported increasing the frequency of breaks and improving access to drinking water. Additionally, more than half of the farms have either shifted the start time of work to earlier hours, shortened the duration of work shifts, or established shaded rest areas near the fields. Fewer than a quarter of respondents reported the use of specialized equipment during heat waves. Among the additional adaptation measures mentioned, several farms have introduced portable shading structures, such as umbrellas, to protect workers during fruit harvesting.

The average of the assigned priorities allowed for the development of a ranking of the most effective adap-

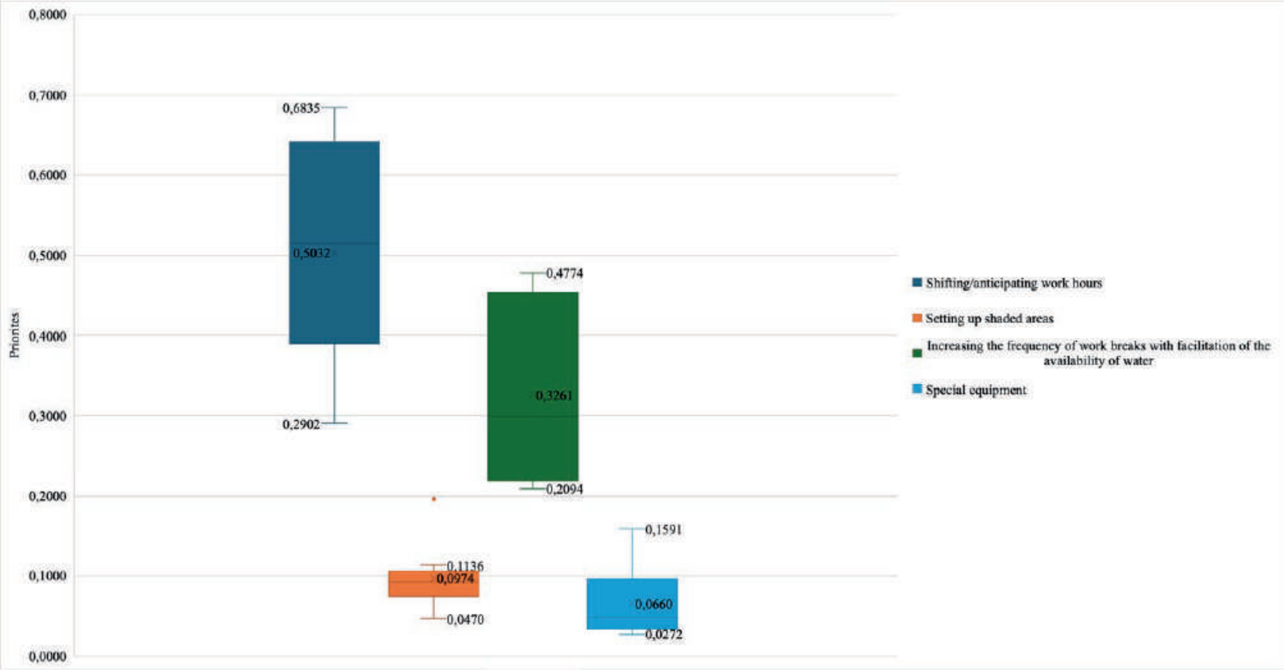

Figure 3. Priorities of adaptation measures as resulted in the AHP analysis.

tation measures based on the selected criteria: worker acceptability, timeliness of implementation, and flexibility of application. As shown in Fig. 3, the adaptation measure with the highest ranking is the shifting or anticipation of working hours, with an average priority value of 0.5032. The second-highest ranked measure is increasing the frequency of work breaks and ensuring access to potable water, with a value of 0.3261. Considerably lower priority values were assigned to the creation of shaded areas (0.0974) and the use of special equipment (0.0660). The consistency ratio for the group of respondents was 0.20. This value is above the commonly accepted threshold (0.1), and indicates that the evaluation process posed a considerable cognitive challenge for respondents, likely due to the complexity of comparing multiple criteria and adaptation options.

The third part of the survey asked participants to provide an estimation of the average percentage of daily productivity loss observed among both common and specialized workers in case of heat waves. The results showed that the most relevant productivity losses occurred among common workers, with reduction rates ranging from 20% to 30% or more (44 % of respondents). As for specialized workers, such as tractor drivers, most respondents (44%) reported productivity losses between 0% and 10%.

4. DISCUSSION

The study, for the first time, explores the perception of land managers regarding heat wave adaptation measures that farms could easily implement to reduce the impact on productivity losses.

Overall, we found that common workers, especially those involved in fruit harvesting, can have productivity losses of over 30% in the absence of adaptation measures; this is confirmed by evidence in the literature, where productivity losses of this magnitude are reported (Morabito et al., 2021). Beside this and according to the perception of land managers, the most effective adaptation measure to reduce productivity losses is shifting/anticipating working hours. This evidence is based on the criteria of worker acceptability, timeliness of implementation, and flexibility, and it is also reported in some of the regulations focusing the reduction of heat wave impacts on workers (Emilia-Romagna region).

Common workers is the category that is most at risk during heat waves because of their exposure to outdoor activities performed in periods that can be affected by heat waves such as fruit picking. Thus, this worker category is exposed to heat and a higher risk of physical stress and reduced productivity. Specialised workers, such as tractor drivers, work in more favourable conditions (e.g. air-conditioned cabins) that mitigate the negative effects of high temperatures and preserve work capacity.

In this context, a more specific focus on the potential heat-related threats that can affect tractor drivers is necessary as the frequency of getting-on and -off tractors to e.g. operate changes/adjustments on equipment could generate abrupt changes of temperature and impact the workers' health.

We also found that the interviewed land managers believe that the shifting/anticipating of the working hours is the most effective measure to reduce productivity losses, probably because it is easy to use low cost and immediately implementable. The effectiveness of this measure is also supported by Morabito et al., (2021), that showed how the adoption of such a measure reduces workers' productivity losses by up to 33% and lowers the economic costs associated with such losses. Moreover, earlier working hours would have positive effects on the quality of the harvest, as it would not be exposed to the heat and delivered earlier to the harvest centres

Nonetheless, as also highlighted by Day et al. (2019), changing working hours could impact total working hours, associated income and economic and social costs that should not be underestimated. Indeed, anticipating the working schedule involves a range of benefits, but it is important to consider that this change could cause disadvantages and reorganization of workers' routines, especially for those who have long commutations to reach the working place. In addition, the measure would have a significant impact on the various costs that the farm has to bear, including organisational, operational and logistic costs. In fact, 25% of the respondents reported the need to add about one extra working day per week, to compensate for the reduction in working hours. This also involves the need of additional workers or of additional trips to storage points during the week. Another challenge for the adoption of this measure is the limited availability of light in the early morning hours, which is essential for fruit picking.

It is therefore essential to make workers aware of the importance of this measure and to ensure the smooth running of activities. This is possible thanks to the presence of adequate infrastructure, implemented by companies to enable optimal harvesting even in low light conditions. For example, the installation of appropriate lighting systems can support early operations at dawn, ensuring effective implementation of activities.

Our results show that other simple adaptation measures such as increasing the frequency of breaks and providing shaded areas are also effective in protecting workers from heat and reducing production losses according to the land managers. Shade areas are understood to be groves and hedges or mobile shade structures such as canopy shelters. Despite the benefits of these measures, they represent an economic cost that could be significantly higher than the anticipation of the working time because workers are paid even during breaks and because setting up shade zones requires some investments for farms.

Lastly, the least effective measure for managers is special equipment (ventilated jackets and clothing in technical, breathable fabric) because, beside its cost, it is expected to be hardly acceptable by workers. Measures such as the use of special equipment may be rejected if they are considered inconvenient or unnecessarily complex. For this reason, whatever the measure, it is essential to involve workers in the decision-making process and to gather their feedback in order to identify the most practical and valued solutions.

The limitations of this study lie in its focus on data from a limited geographic area within Italy. However, the selection of large farm cooperatives with strong attention towards working conditions and safety allowed to collect the perception of adaptation measures and their effectiveness in farms with relevant awareness of the problem. This sampling approach may have introduced a bias linked to the farms' greater capacity to implement adaptation strategies. Consequently, the findings reflect a localized perspective that may not be representative of the views of entrepreneurs at the national level or in other parts of the world. Significant differences could emerge if the research were conducted nationwide or expanded to include a broader range of Italian regions and farm types. Additionally, the CR of 0.2 points to some cognitive stress. This could be due to the small sample size or respondents' lack of experience with such specific questions on heat waves and adaptation measures. This might have caused difficulties in fully understanding and evaluating the question, affecting the consistency of their responses.

5. CONCLUSIONS

This study presents an overview of how land managers perceive the impacts of heat waves on agricultural workers and assesses the perceived effectiveness of various adaptation measures. The research is based on empirical data collected from nine farms in Emilia-Romagna, each demonstrating a long-standing commitment to improving working conditions and mitigating heat-related risks in agricultural operations.

Although the sample size limits the statistical generalizability, our results offer valuable insights to inform future policy interventions. One key recommendation emerging from the study is the potential introduction of targeted incentives to support the adoption of adaptation practices that entail additional costs for farms. Such incentives could be designed to provide economic support for more resource-intensive but highly effective measures, such as installing shading infrastructure or rescheduling work to nocturnal hours.

Another crucial aspect relates to institutional collaboration in developing early warning systems and heat alert tools. These tools could serve both farms and regulatory bodies as a reliable reference for determining the timing and geographic location for the applicability of mandatory or recommended heat adaptation actions.

The findings confirm that heat waves have a significant impact on business operations and reduce labor productivity, particularly in open-field tasks such as fruit harvesting. The selected adaptation strategies, many of which are low-cost and easy to implement, provide effective ways to reduce productivity losses and enhance worker protection. Among the most effective measures identified are adjusting work schedules to earlier hours and increasing the frequency of breaks with access to potable water. These actions were recognized as widely applicable, simple to implement, and well-accepted by both managers and workers.

Beyond improving worker safety and reducing the risk of heat-related accidents, certain adaptation measures can generate operational benefits. For instance, shifting working hours not only reduces exposure to peak temperatures but may also improve the quality of harvest, particularly in sectors such as fruit cultivation.

A crucial aspect is the ease of implementation and high acceptance of many adaptation strategies. This enhances their feasibility and potential for widespread adoption. Because these measures typically do not require complex organizational changes or significant financial resources, they represent a practical starting point for improving heat adaptation of the agricultural sector.

In conclusion, the study underscores the dual benefits of adaptation strategies: they contribute both to worker well-being and to the operational efficiency of farms. By reducing the incidence of heat-related accidents and minimizing inefficiencies due to loss of labour productivity, targeted adaptation measures can serve as a foundation for sustainable and inclusive agricultural policy under conditions of increasing climate stress.

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Climate change and occupational health and safety. Risk of injuries, productivity loss and the co-benefits perspective

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Abstract

Background: Climate change is a fundamental threat to human health and outdoor workers are one of the most vulnerable population subgroups. Increasing heat stress and heatwaves are directly associated with the health and safety of workers for a large spectrum of occupations. Heat stress negatively affects labour supply, productivity, and workability.

Objectives: The aims of this study are to estimate the risk of work-related injuries for extreme temperature outdoor exposure in Italy, to evaluate the loss in productivity and the associated insurance costs for supporting the co-benefits analysis of the adaptation measures.

Methods: The relationship between air temperature and occupational injuries (in the period 2014-19) was evaluated using a time-series approach, by means of a specific over-dispersed Poisson generalized linear regression model, applied to compensation data. To assess the effect of temperature on workability, the wet bulb global temperature (WBGT) was estimated by different levels of humidity and vapor pressure. The costs of injuries have been estimated according to the potential consequences in terms of paid insurance premium and including all management and human resources costs.

Results: We estimated 25,632 (95%CI 22,353-28,862) occupational injuries in Italy attributed to heat (between 75° and 99° percentiles) in the period 2014-2019, which corresponds to an average of 4272 cases for year. A decrease in productivity of about 6.5% was estimated for workers engaged in physical activities requiring high metabolic rates for every unit degree increase in temperature between 19.6 C° and 31.8 C°. The overall compensation costs associated to extreme heat exposure have been estimated to more than 292 million euros between 2014 and 2019, almost equal to 49 million euros per year.

Discussion: Prevention measures and adaptation strategies for contrasting the occupational exposure to extreme temperatures can help contain both the risk of injury and, productivity loss, in a co-benefits perspective.

Keywords: Adaptation actions; Climate change; Co-benefits; Extreme outdoor temperature; Global warming; Occupational injuries; Productivity loss.

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[Tools of action for reducing the effects of climate change on occupational health and safety]

[Article in Italian]

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Mitigating heat effects in the workplace with a ventilation jacket: Simulations of the whole-body and local human thermophysiological response with a sweating thermal manikin in a warm-dry environment

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Abstract

Climate change is increasingly affecting human well-being and will inevitably impact on occupational sectors in terms of costs, productivity, workers' health and injuries. Among the cooling garment developed to reduce heat strain, the ventilation jacket could be considered for possible use in workplaces, as it is wearable without limiting the user's mobility and autonomy. In this study, simulations with a sweating manikin are carried out to investigate the effects of a short-sleeved ventilation jacket on human thermophysiological responses in a warm-dry scenario. Simulations were performed in a climatic chamber (air temperature = 30.1 °C; air velocity = 0.29 m/s; relative humidity = 30.0 %), considering two constant levels of metabolic rate M (M_1 = 2.4 MET; M_2 = 3.2 MET), a sequence of these two (Work), and three levels of fan velocities ($I_f = 0$; $I_f=2$; $I_f=4$). The results revealed a more evident impact on the mean skin temperature (T_{sk}) compared to the rectal temperature (T_{re}), with significant decreases (compared to fan-off) at all M levels, for T_{sk} from the beginning and for T_{re} from the 61st minute. Skin temperatures of the torso zones decreased significantly (compared to fan-off) at all M levels, and a greater drop was registered for the Back. The fans at the highest level ($I_f=4$) were significantly effective in improving whole-body and local thermal sensations when compared to fan-off, at all M levels. At the intermediate level ($I_f=2$), the statistical significance varied with thermal zone, M and time interval considered. The results of the simulations also showed that the Lower Torso needs to be monitored at M_2 level, as the drop in skin temperature could lead to local overcooling and thermal discomfort. Simulations showed the potential effectiveness of the ventilation jacket, but human trials are needed to verify its cooling power in real working conditions.

Keywords: Cooling garments; Heat stress; Occupational heat strain; Sweating manikin; Thermophysiological response; Ventilation jacket.

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Occupational heat stress, heat-related effects and the related social and economic loss: a scoping literature review

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Introduction: While there is consistent evidence on the effects of heat on workers' health and safety, the evidence on the resulting social and economic impacts is still limited. A scoping literature review was carried out to update the knowledge about social and economic impacts related to workplace heat exposure.

Methods: The literature search was conducted in two bibliographic databases (Web of Science and PubMed), to select publications from 2010 to April 2022.

Results: A total of 89 studies were included in the qualitative synthesis (32 field studies, 8 studies estimating healthcare-related costs, and 49 economic studies). Overall, consistent evidence of the socioeconomic impacts of heat exposure in the workplace emerges. Actual productivity losses at the global level are nearly 10% and are expected to increase up to 30–40% under the worst climate change scenario by the end of the century. Vulnerable regions are mainly low-latitude and low- and middle-income countries with a greater proportion of outdoor workers but include also areas from developed countries such as southern Europe. The most affected sectors are agriculture and construction. There is limited evidence regarding the role of cooling measures and changes in the work/rest schedule in mitigating heat-related productivity loss.

Conclusion: The available evidence highlights the need for strengthening prevention efforts to enhance workers' awareness and resilience toward occupational heat exposure, particularly in low- and middle-income countries but also in some areas of developed countries where an increase in frequency and intensity of heat waves is expected under future climate change scenarios.

KEYWORDS

productivity loss, workers, climate change, occupational heat exposure, economic costs, scoping review

1. Introduction

There is a consistent body of evidence that high outdoor and indoor temperatures have adverse health effects in exposed workers (1–4). Workers are normally healthier than the general population, but they, especially those severely exposed and engaged in heavy workloads, may be equally affected by heat stress when the thermoregulatory capacity of the body is disrupted, and physiological pathways resulting in heat-related illness, acute outcomes (e.g., myocardial infarction), or exacerbations of pre-existing diseases (e.g., cardiovascular and respiratory outcomes) are activated (2). Individuals working in the heat are also prone to physical strength losses and cognitive function impairments, leading to work-related injuries (3), missed workdays, and productivity reductions (4) and, in the long term, may develop chronic kidney impairment (5, 6). Health and productivity outcomes related to heat strain have a huge impact in terms of social and economic costs on the different actors involved (7): the workers themselves due to the temporary or permanent health and quality of life impairments and missed wages, the farm or factory due to necessity of maintaining production despite employees absences or output reductions, the healthcare system due to the healthcare expenditures due to workers seeking care, the social security or insurance system due to reimbursements to laborers for injuries, permanent disability, or occupational diseases, and the whole country or region in terms of reductions of the gross domestic product due to production losses in specific economic sectors. Moreover, climate change is expected to worsen heat exposure in some regions exceeding work-related productivity thresholds (8).

Heat exposure in the workplace is a growing hazard throughout the world, considering climate change scenarios showing a universal increase in heat extremes virtually in every region, but larger in Central and South America, the Mediterranean region, north Africa, the Arabian Peninsula, India, and Southeast Asia (9). Most of the affected regions are low-income economies mostly relying on manual labor and manufacturing work with agriculture and construction being the economic sectors at higher risk of heat exposure and at higher workload intensity than others. The quantification of economic impacts of heat exposure in the workplace is of worth for individual companies, labor policymakers, insurance companies, but also for occupational safety and healthcare systems and should be taken into account when analyzing markets and economies at both the local and global scale. The knowledge of economic losses related to heat may serve as a basis to plan prevention measures at company level with a view on cost–benefit analysis, to set up specific heat adaptation policies, or to strengthen social security systems by enclosing climate risk concerns, especially toward poorer population and countries (10).

Differently from the strong evidence available on the effects of heat on workers' health and safety, there is still limited but growing evidence on the resulting social (7, 11) and economic impacts (12). The lack of standardized methodologies for evaluation (epidemiological vs. econometric studies), as well as in the operational definitions of productivity loss (lost worktime, reported physical and cognitive performance reductions, and work output reductions in case of manual workers), heat-related productivity losses, and economic costs (i.e., lost salaries and wages due to fatigue/sickness, cost per compensable claim, and healthcare costs related to treatment and rehabilitation) make it difficult to have consistent findings and clear trends. Despite the close connection between indicators of social and economic heat-related impacts and the common underlying causal pathways, no previous literature review considered both social and economic losses related to heat at the same time.

As part of the Italian WORKLIMATE Project (https://www.worklimate.it) funded by the Italian Workers' Compensation Authority (INAIL), a literature review was carried out to update the evidence on both social and economic impacts related to workplace heat exposure. To address such a comprehensive research question, a scoping review was considered to be more suitable, as suggested also by other authors (13), to address the whole body of evidence deriving from different type of studies (i.e., epidemiological and economic modeling studies).

2. Methods

The scoping literature search was conducted in two bibliographic databases (Web of Science and PubMed), using both free terms and controlled vocabulary (Supplementary Table 1) to select studies published since 2010 to April 2022. Since previous reviews considered impacts of occupational heat stress on workers' productivity (7, 11, 14) and on economic losses (12) separately, and in consideration of the interconnections between work performance, workers' health and safety, and monetary costs, the outcomes of interest were both social impacts related to workers (i.e., work hours losses and work absences), and economic impacts for a specific group of workers or economic sector (i.e., monetary costs associated to production losses) or for social security systems (i.e., compensation for work-related injuries and diseases). Both indoor and outdoor occupational heat exposure and all potentially exposed economic sectors and tasks (e.g., manual workers) were considered. The first group of relevant studies were from epidemiological studies (both qualitative and quantitative) on workers estimating productivity losses in the field or estimating costs related to occupational heat-related illnesses and injuries. The second category of suitable studies was represented by recently conducted economic studies adopting several approaches such as structural economic models and econometric models, to estimate the impacts of climate change on labor productivity and related economic costs, using occupational health and safety recommendations in an entire economic sector and for regional or global economies. Experimental studies (e.g., on physiological responses), epidemiological studies on occupational heat-related illnesses not estimating economic implications, studies focusing only on the impact of heat exposure on workers' cognitive functions, and studies on other occupational exposures (e.g., cold, air pollution) were excluded. Only original studies were retrieved, while literature reviews (7, 11, 12, 14–16) were excluded but used to screen for additional relevant studies, as well as the 6th assessment report of the Intergovernmental Panel on Climate Change (https://www.ipcc.ch/report/ar6/wg2/) (8). The selection of studies and data extraction were conducted according to PRISMA guidelines (17). The outcomes considered were as follows:

- Lost productivity estimated or perceived by the worker associated with the heat exposure.
- Economic costs associated with heat-related injuries or hospitalizations in workers.
- Projections of productivity losses due to heat and related economic costs for current climate or under climate change scenarios.

Given the heterogeneity of study designs, methods for estimating costs or productivity, outcomes considered, and occupational sectors investigated, a narrative synthesis was undertaken by grouping studies by design (epidemiological vs. economic studies).

3. Results

A total of 8,151 potentially relevant records were identified after duplicates were removed, of which 104 were identified from previous reviews on the topic (7, 11, 12, 14–16) or other sources (Supplementary Figure 1). Out of these, 137 were assessed as full texts because potentially relevant, and, finally, 89 studies were included in the qualitative synthesis. The largest number of studies was carried out in Asia (49 studies) and the lowest in Central and South America (24 studies) (all totals include the 21 global economic modeling studies) (Figure 1). Field studies accounted for a larger proportion of studies in Asia, Oceania, and Europe, healthcare-related studies were more prevalent in North America and Oceania, and regional modeling studies were mostly conducted in North America, Europe, and Asia.

Table 1 describes the results of the epidemiological studies ($n = 40$), including 32 field studies and 8 studies estimating healthcare-related costs.

3.1. Field studies

Most field studies (20 out of 32) were conducted in low- or middle-income countries (18, 20–22, 24, 27, 29–31, 33, 37, 38, 40–42, 45–47, 49), with only 11 studies from Europe, the USA, and Australia/New Zealand (19, 23, 25, 26, 28, 34, 35, 39, 43, 44, 48) and 1 multicenter study (36). Three studies were qualitative, based on interviews or focus groups (28, 33, 43), while the other studies were quantitative with 27 cross-sectional and 2 longitudinal studies (26, 42) and provided an estimation of the association between heat and labor productivity measured in the field or perceived by workers. The study size overall ranging from 16 (30) to 4,095 workers (21) in different occupational sectors (9 on agriculture, 4 on construction, 1 on mining, and 18 from several sectors) also includes indoor workers (13 studies). Two main approaches were followed by studies in estimating heat impacts on productivity. The first approach provides an estimation of productivity and then evaluates the losses due to heat by comparing productivity data collected at different WBGT levels. In these studies, productivity was estimated in different ways: by worktime (direct, indirect, and non-productive) (22, 30), cognitive and physical performance (e.g., time to complete task/work extra hour absenteeism/taken sick leave) self-reported from questionnaires or interviews (26, 30, 32, 38), clinical examinations (e.g., walking speed) (42), daily output reported or measured by field instruments (e.g., tally counters) (21, 25), and premature worker attrition (21). In the second approach, productivity was not measured by itself, but in terms of productivity losses due to heat in different ways: published physiological models (31), self-reported by workers (29, 49), and prediction models of economic losses due to heat based on number of laborers and the given laborers salary when exceeding WBGT thresholds (44). All studies used individual productivity measures except Amini et al. (18), which evaluated productivity at area level.

Despite the great heterogeneity in the work sectors and study size, nearly all field studies consistently showed a reduction in productivity due to occupational heat exposure. The only exception was one study on office workers not providing evidence of influence of thermal stress on work performance, possibly due to the fact that the thermal stress variable evaluated included both heat and cold temperature; therefore, their single contributions on work performance could not be disentangled (26). The estimated productivity losses ranged between 0.3% and 10% reduction for an increase of 1°C in WBGT (30, 40–42, 47). Considering the whole summer season, the prevalence of workers reporting heat-related productivity loss varied among studies from 11% (46) to 81% (35). Some studies also found an association of heat with an increase in indirect non-productive time at work (30), an increase in idle time at work (30), or in personal household time needed to rest to adapt to heat stress (22). Four studies (36, 44, 48, 49) also provided an estimate of the related economic costs by applying the productivity losses to the gross wages or income of workers with an estimated cost of 6–8 euros per hour worked in Italy (36), 1100 Canadian dollars annually per worker in Ontario (44), 655 USD annually per worker in Australia (48), and 257 euros annually per worker in Malaysia (49). In one study (45), 25% of the workers self-referred a loss in their wages due to fatigue or sickness related to heat. The study by Langkulsen et al. (27) showed a reduction in productivity only in two of the occupational sectors considered (pottery and construction) but not in the others. Only Li et al. (30) and Yi and Chan (47) adjusted for individual worker characteristics such as age and BMI. Given the cross-sectional approach adopted in most studies, the results do not allow causal inference on the association between occupational heat exposure and work productivity.

In some field studies, specific worker subgroups appeared to be more susceptible to the productivity losses due to occupational heat exposure: men (38, 40, 45, 48), females (31), younger, less educated or less experienced workers (37), workers exposed to direct sun (36), workers performing heavy tasks (45, 48), those using personal protective equipment (PPE), such as face masks (23, 29, 35), those affected by comorbidities such as kidney failure or other conditions (21, 22), migrant workers (32, 34), and workers not following safety protocols such as hydrating or taking breaks in cooling places (20, 24, 37).

3.2. Studies evaluating healthcare-related costs

In contrast to the field-based studies, the eight studies estimating healthcare-related costs due to occupational heat exposure used data from administrative databases; therefore, they were mostly conducted in western countries such as Europe, Australia, the US, and Canada (50–52, 54, 56–58), with only one study from China (53). Six studies considered all occupational sectors, while three studies only considered specific sectors, such as agriculture and construction. Five studies were descriptive analyses of occupational injuries or diseases identified as heat-related and consequent compensation costs in specific occupational sectors

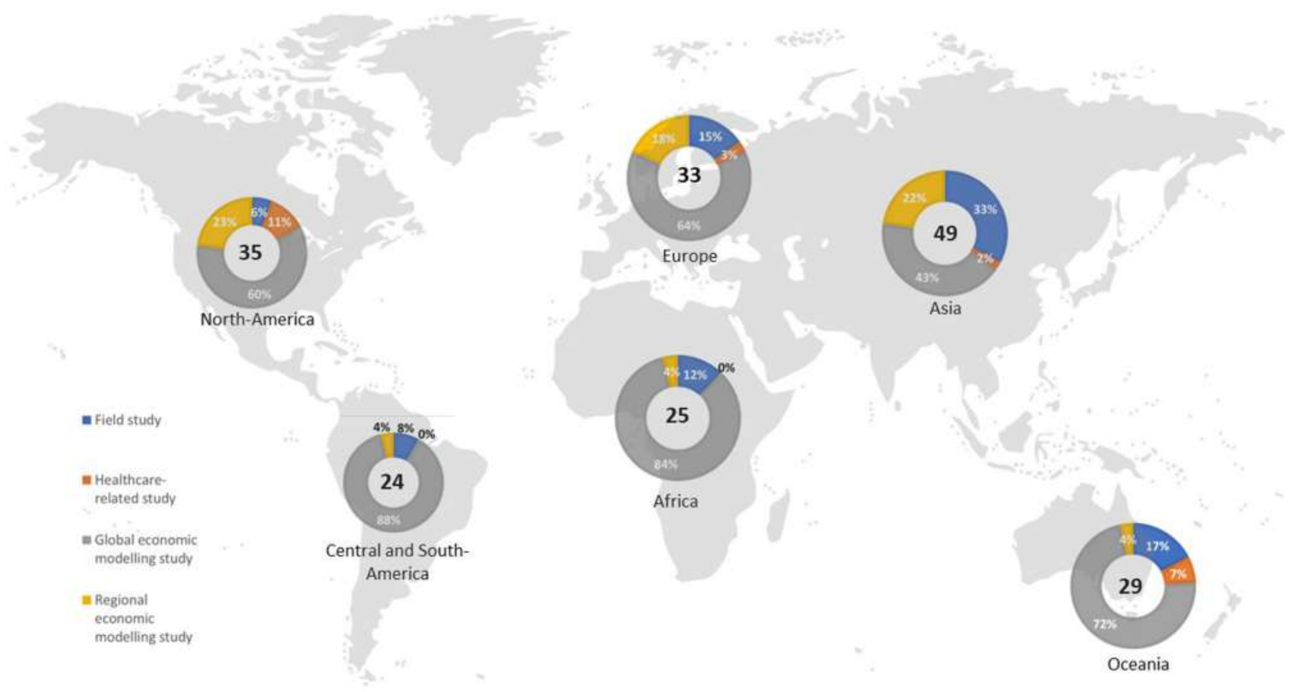

FIGURE 1
Geographical distribution of included studies based on the study design by continents.

(50–52, 56, 57), while the other three were etiological studies estimating the occupational injuries attributable to heat exposure through time-series or case-crossover analysis and then quantifying the related costs (53, 54, 58).

The national Spanish study from Martinez-Solanas et al. (54) was the only one to estimate heat-related injuries corresponding costs including not only the direct costs attributable to social or private insurance refund to the workers (for long-term losses) or to the healthcare system but also the indirect costs associated with maintaining production, and costs of pain and suffering. The total economic impact of heat-related injuries in the study period was 320 million euros, with the costs associated with pain and suffering higher than other types of costs. The study conducted by Ma et al. (53) in China evaluated the attributable fraction of insurance pay-out related to occupational heat exposure (temperatures above the limit of the Wet Bulb Globe Temperature (WBGT) in accordance with international standards) of 4.1% (95% CI 0.2%–7.7%). In an Australian study, an increase of 1°C in maximum temperature above 33.8°C was associated with an increase of 41.6% in healthcare costs and 74.8% in working days lost due to heat-related injuries (58).

Two descriptive studies conducted in Washington State, US (50, 52), reported an increase in both the median cost per heat-related injury over time (from 537 USD in 1995–2005 to 909 USD in 2006–2017) and the number of working days lost due to injury (from 46 to 93 days per claim on average). The studies also reported an increase in temperatures over time associated with the injuries. In the same study area, Spector et al. (57) estimated a median cost per claim of 654 USD specifically for the agricultural and forestry sectors similar to the previous study conducted in the area (50). These studies suggest a higher median costs related with non-compensable claims for heat-related than for total injuries suggesting a possible under-reporting of work-related accidents in this sector (50, 52, 57). Another South Australian study on construction industry (56) calculated average cost during heat waves higher than in control periods (26,381 vs. 12,747 Australian dollars), with higher costs in the urban area than in the suburbs and for specific agents of injury (i.e., work platform, electricity, and equipment). Finally, a Canadian study in Ontario (51) estimated the rate of injuries related to loss of productive worktime (injury loss time), which is equal to 1.7 cases per million full-time equivalent months in the period 2004–2010.

Studies estimating healthcare-related costs identified some worker subgroups are related to higher costs or worktime losses such as manual workers (51), Black or Latinos workers (52), new workers (56, 58), workers aged 15–24 years (51), men (53), and workers of small- (56) or medium-sized companies (53, 58).

3.3. Results from economic studies

Table 2 describes the results of the 49 economic studies at the global (59–70, 72, 74–80) and regional level (73, 81–107). Most studies focused on impacts of current and projected heat on workers' productivity, with the exception of some studies estimating production output reductions due to heat (59, 72, 83) or studies evaluating heat-related impact on both workers and farm production output (66, 70, 100, 101). Climate change scenarios were considered in most studies, with only few studies providing estimated economic impacts for current climate only (66, 73, 77,

TABLE 1 Results of epidemiological studies estimating productivity, social, or economic losses related to occupational heat exposure.

Reference	Study type	Country	Heat exposure	Study population	Study period and duration	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Field studies								
Amini et al. (18)	Field study	Southwest Iran	Predicted mean vote (PMV) index	Agriculture workers	2016	Manpower productivity index at area level	Productivity loss due to heat calculated based on equation in Mohamed (2005) at area level	A strong and significant ($P < 0.05$) relationship between temperature index in the cold regions was found. In the hot regions, all three main environmental variables have a strong and significant correlation ($P < 0.05$) with the P index.
Bonafede et al. (19)	Field study	Italy	Perceived stress from heat and heat waves	345 workers in several occupational sectors indoor (with and without air conditioning) and outdoor	June–October 2022	na	Perceived labor productivity loss due to heat	73% of workers perceived heat completely or very much as an important contributor to productivity loss (mean score of 3.93 on a scale of 1 to 5).
Budhathoki and Zander (20)	Field study	Nepal	Perceived stress from heat and heat waves	350 farmers	2012–2017	na	Perceived labor productivity loss due to heat	Farmers' perceived heat stress levels, and the number of associated illnesses or symptoms, significantly increase labor productivity loss during heat waves ($p < 0.05$). Residency in urban areas, access to weather information, past implementation of prevention measure increases labor productivity losses perception due to heat.
Dally et al. (21)	Field study	Guatemala	Wet-bulb Globe Temperature (WBGT)	4, 095 male sugarcane cutters	November 2015 to May 2016 harvest season.	Daily output (average daily tons)	Change in productivity due to heat (lag 0–5) estimated by distributed lag non-linear models	The cumulative effect on tons of sugarcane cut for workers with impaired kidney function who experienced exposure to a WBGT of 34°C is estimated to be a loss of 1.16 (95% confidence interval (CI): −2.87, 0.54) tons over the next five days compared to if they were exposed to a WBGT of 29°C. The estimated cumulative effect on tons of sugarcane cut by workers with functioning kidneys was 0.59 tons (95% CI: −2.05, 0.87) less.

(Continued)

TABLE 1 (Continued)

Reference	Study type	Country	Heat exposure	Study population	Study period and duration	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Das (22)	Field study	India (two cities)	Heat wave days	150 low-income urban informal workers (mostly outdoor)	April–May 2013	Worktime (in hours)	Change in time allocation and worktime loss during heat wave compared to normal days (adjusting for workplace, family size and income, and worker's health)	The results show that workers work 1.19 h less and spend 0.46 h less at home, and they rest 1.65 h longer on average on a heat wave day than on a normal summer day. Worktime loss is more for people doing manual work and having health problems
Davey et al. (23)	Field study	UK	Perceived heat stress and heat-related illness	Healthcare workers	May and August 2020	na	Perceived cognitive and physical performance reductions due to heat stress and PPE	Heat stress impaired both cognitive and physical performance of workers. Respondents reported that PPE impaired their physical performance at work (76%) and made their job more difficult (92%).
Cortez (24)	Field study	Nicaragua	Wet-bulb Globe Temperature (WBGT)	22 sugarcane workers	2006/2007 harvesting season (15 days)	Work output (in daily tons)	Change in production output related to water intake (no analysis of production output and temperature)	Output production increased significantly among those best hydrated, from 5.5 to 8 tons of cut sugarcane per worker per day.
Gun and Budd (25)	Field study	Australia	Wet-bulb Globe Temperature (WBGT)	43 male sheep shearers	January–March of two consecutive years (54 days)	Work output: hourly number of sheep shorn and wool bales pressed recorded in a tally book	Change in productivity due to heat estimated by linear regression analysis between productivity and thermal stress variables	Shearers under thermal discomfort tended to be less productive ($r = -0.32$, $b = -3.0$, $p = 0.04$). No influence by age, dehydration, alcohol consumption, and obesity on productivity loss.
Lamb and Kwok (26)	Field study (longitudinal within-subjects design)	New Zealand	Indoor Environmental Quality (thermal stress including both cold and heat stress)	114 office workers	8 months	Several measures of productivity: 11-point scale of work performance relative to average perceived performance; 11-point scale of level of distraction from work; Reaction time and accuracy measured by Stroop test; 9-point scale of tiredness; 11-point scale of motivation.	Work performance reduction related to thermal discomfort (both heat and cold) evaluated descriptively. Change in productivity related to a combined exposure index (noise, temperature, light) also evaluated.	Thermal comfort did not significantly affect work performance.

(Continued)

TABLE 1 (Continued)

Reference	Study type	Country	Heat exposure	Study population	Study period and duration	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Langkulsen et al. (27)	Field study	Thailand	Wet-bulb Globe Temperature (WBGT)	21 workers in pottery industry, power plant, knife industry, construction site, and agricultural site	October 5 to October 16, 2009	Work output	Productivity loss measured as percent change of the daily work output due to heat relative to the daily work output	In knife and agriculture workers no losses of productivity. In power plant workers not applicable. In pottery and construction workers losses of productivity from 10 to 60%.
Lao et al. (28)	Field study (qualitative study)	South Australia	na	32 male outdoor workers	July 2014	na	Heat impact on productivity evaluated in a narrative way by workers in focus group	Narratives revealed that working on hot days could affect health and wellbeing, and work productivity
Lee et al. (29)	Field study	India and Singapore	Perceived heat stress	165 hospital workers using PPE during COVID-19 epidemic	May-June 2020	na	Perceived productivity loss due to heat stress and PPE self-assessed from questionnaire	Workers reported a reduced productivity due to heat and when wearing PPE
Li et al. (30)	Field study	China	Wet-bulb Globe Temperature (WBGT)	16 rebar workers	summer 2014	Worktime: time for labor productivity of direct worktime, indirect worktime, and idle time measured by observers	WBGT-productivity relationship evaluated in regression models (adjusted for age, BMI, work experience)	High-temperature environments decrease labor productivity, with the percentage of direct worktime decreasing by 0.57% and the percentage of idle time increasing by 0.74% when the WBGT increased by 1 °C.
Lundgren et al. (31)	Field study	Chennai, India	Wet-bulb Globe Temperature (WBGT)	77 workers in industrial, service, and agricultural sectors (most workers with moderate to heavy work)	January–February and April–May	na	Productivity loss estimation based on Predicted Heat Strain (PHS) model from core temperature and maximum water loss as a function of ISO standard guidelines.	Heat strain was related to productivity loss in the PHS model in all workplaces, apart from the laundry facility, especially during the hot season
Lundgren-Kownacki et al. (32)	Field study	India	Perceived heat stress	87 migrant brick kiln workers in summer and 61 in winter	June–July 2013, March–April 2014 (hot season); February 2013, January–February 2015 (cool season)	na	Perceived productivity loss due to heat: absenteeism/taken sick leave due to heat; Less productivity/more time to complete task/work extra hours; Irritation/interpersonal issues; Wages lost	16% of workers in summer reported absenteeism/sick leave due to heat stress, 48% reported less productivity
Mathee et al. (33) - HOTHAPS study	Field study (qualitative study)	South Africa	Perceived heat stress	151 workers involved in sun-exposed occupations	March 2009	na	Perceived productivity loss due to heat. No analysis was carried out, only narrative description of interviews.	Where daily maximum temperatures may reach 40°C, workers reported a wide range of heat-related effects, leading to difficulty in maintaining work levels and output during very hot weather

(Continued)

TABLE 1 (Continued)

Reference	Study type	Country	Heat exposure	Study population	Study period and duration	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Messeri et al. (34) (EU HEAT-SHIELD project)	Field study	Italy	Perceived heat stress	104 native and migrant workers in agriculture and construction	Summer months of 2017	na	Perceived productivity loss due to heat (the worker noticed to be less productive during a heat wave or need more energy for the same work)	Migrant workers declared that work required greater effort than do native Italian workers (Chi squared $p = 0.001$) but reported less impact from heat on productivity (Chi squared $p = 0.014$) and on thermal discomfort.
Messeri et al. (35) (WORKLIMATE project)	Field study	Italy (mostly areas from Center-South of Italy)	Perceived heat stress	191 hospital workers using PPE during COVID-19 epidemic	June–October 2020	na	Perceived productivity loss due to heat and PPE	A great number of HCW (81%) self-reported a productivity loss related to heat stress exposure. The productivity loss was significantly correlated ($p < 0.001$) to the perception of thermal sensation due to the use of PPE.
Morabito et al. (36) (HEAT-SHIELD)	Field study	Florence and Guangzhou	Wet-bulb Globe Temperature (WBGT)	18 outdoor workers in agriculture	Summer 2017–2018	na	Productivity loss (% of reduced work capacity) in outdoor workers for moderate (300 W) work activities in sun and shady areas assessed by risk functions based on ISO standard and on epidemiological data (37). Economic costs (euros) estimated from workers' salaries multiplied for productivity losses.	The hourly economic cost in Italian farm related to the productivity loss in the sun during the typical working time ranged between €5.7 and €8.0, higher than productivity loss in the shade. The productivity loss values estimated in the sun in Guangzhou were 7.3, 8.2, and 8.3 times higher than the values estimated in Florence and even greater considering shade conditions.
Nunfam et al. (37)	Field study	Ghana	Perceived heat stress	320 miners	October 2017–January 2018	na	Causal analysis evaluating the relationship between heat exposure and productivity outcomes by structural equation models. Evaluation of moderation effect by adaptation strategies and demographic and work variables.	Heat exposure had a significant direct effect on the productivity outcomes of mining worker. This effect was moderated by barriers to adaptation strategies, mediated through adaptation strategies (not significantly), and controlled by some demographic and work-related variables.
Pradhan et al. (38) (HOTHAPS study)	Field study	Nepal	Wet-bulb Globe Temperature (WBGT) and Humidex	120 workers indoor and outdoor	2010	Worktime: Average work hours by season (work efficiency)	Descriptive comparison of worktime across months.	Duration of work is longer in summer due to longer days and more frequent rests or longer mid-day off.
Quiller et al. (39)	Field study	Washington, US	Wet-bulb Globe Temperature (WBGT)	46 tree harvesters	2015 August and September	Work output: Total weight of fruit bins collected per time worked (kg/hours)	WBGT-productivity relationship estimated by linear mixed effects models (adjusted models for work experience, gender, price paid per bin, BMI, and shift duration)	There was a trend of decreasing productivity with increasing WBGT, but this was not statistically significant (significant only in unadjusted model).

(Continued)

TABLE 1 (Continued)

Reference	Study type	Country	Heat exposure	Study population	Study period and duration	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Sadiq et al. (40)	Field study	Nigeria	Wet-bulb Globe Temperature (WBGT)	396 maize farmers	July to September, 2016	Work output: number of ridges cultivated during the working hours	WBGT-productivity relationship estimated by multiple linear regression adjusting for body mass index (BMI), age, and gender.	Productivity was significantly higher between the hours of 6–9 am ($p < 0.001$) and 12–3 pm ($p < 0.001$), compared to the hours of 9 am—12pm ($p < 0.001$)- For temperature increases, productivity decreases (beta coefficient = −0.6, *p*-value <0.001).
Sahu et al. (41)	Field study	India	Wet-bulb Globe Temperature (WBGT)	124 rice harvesters	April-June 2011	Work output measured in terms of volume or quantity of items collected (rice bundle)	Productivity loss estimated for WBGT exceeding the standard (26–32°C) corresponding to 30–38°C of air temperature.	High heat exposure in agriculture caused heat strain and reduced work productivity (−5% per 1°C). This reduction will be exacerbated by climate change and may undermine the local economy
Sett and Sahu (42)	Field study (longitudinal study)	West Bengal, India	Wet-bulb Globe Temperature (WBGT)	120 female brickfield	October 2008 to May 2009 (first session), from October 2009 to May 2010 (second session), and then from October 2010 to May 2011 (third session)	Work output (number of bricks molded or carried per person per week) recorded on a weekly basis from the record register book	Productivity loss estimated for WBGT exceeding the standard (26–32°C) corresponding to 30–38°C of air temperature. Comparison of wages by season. Comparison of walking speed by season.	Productivity loss for every degree rise in temperature was about 2%. Wages of the female workers vary from 800 INR/week in the extreme summer months to 1,500 INR/week in the winter months. Reduced walking speed in summer compared to winter.
Singh et al. (43)	Field study (qualitative study)	Australia	n.a.	47 workers outdoor in several industries (encl. Farming, construction)	Summer 2010	na	Perceived productivity loss due to heat. No analysis was carried out, only narrative description of interviews	All interviewees reported that excessive heat exposure presents a significant challenge for their industry or activity. People working in physically demanding jobs in temperatures>35°C frequently develop symptoms, and working beyond heat tolerance is common. To avoid potentially dangerous health impacts, they must either slow down or change their work habits. Such health-preserving actions result in lost work capacity.
Vanos et al. (44)	Field study	Ontario, Canada	Wet-bulb Globe Temperature (WBGT)	Outdoor laborers at an industrial worksite	2012–2018 (May–October)	na	Worktime loss due to heat estimated by risk functions for different WBGT levels. Loss of money (Canadian dollars) due to heat per 15-min work interval estimated by laborer type (*via* hourly wages).	On average, 22 h per worker were lost each summer (ca 1% of annual work hours) as a result of taking breaks or stopping due to heat. This amount of time corresponded to an average individual loss of 1100 Canadian dollars to workers or the company.

(Continued)

TABLE 1 (Continued)

Reference	Study type	Country	Heat exposure	Study population	Study period and duration	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Venugopal et al. (45)	Field study	South India	Wet-bulb Globe Temperature (WBGT)	84 steel workers	April 2014	na	Perceived productivity loss due to heat stress defined as: loss in production, not achieving work targets, loss of workdays/work hours due to fatigue/exhaustion, sickness/hospitalization, and/or wages lost due to heat or heat-related illnesses	Workers exposed directly to heat sources reported higher productivity losses than other workers. Heat exposure was related to greater absenteeism (+1% increase), less productivity (−10.6%), larger work extra hours (26.9%), and increase in irritation/interpersonal issues (+7.7%)
Venugopal et al. (46)	Field study	India	Wet-bulb Globe Temperature (WBGT)	Several occupation types (indoor and outdoor, heavy, moderate, and light)	Cooler (2012) and hotter (2013) seasons	na	Perceived productivity loss due to heat stress defined as: loss in production, or not achieving set work targets, or loss workdays/work hours due to fatigue/exhaustion, or sickness/hospitalization, and/or wages lost due to heat or heat-related illnesses.	Of the 442 workers, approximately 62% reported reduced productivity by not achieving targets, 30% reported absenteeism as a reason for productivity loss and 25% of workers reported lost wages due to fatigue/sickness due to workplace heat stress. Males and workers with heavy workload (especially outdoor workers) were significantly affected by heat-related productivity losses.
Yi and Chan (47)	Field study	Hong Kong	Wet-bulb Globe Temperature (WBGT)	14 male construction workers	August and September 2016	Productivity measures as direct worktime (Make use of wrenches to connect, cut, band, and modify reinforcing steel bars, Place reinforcing steel bars, Modify reinforcing steel bars, Carry reinforcing steel bars, Use meter sticks for measurements, Bending)	WBGT-productivity relationship estimated by linear regression models (adjusted for age, work duration, cigarette intake, alcohol drinking consumption, weight, and work intensity)	Heat stress reduces construction labor productivity, with the percentage of direct worktime decreasing by 0.33% when the WBGT increased by 1 °C.

(Continued)

TABLE 1 (Continued)

Reference	Study type	Country	Heat exposure	Study population	Study period and duration	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Zander et al. (48)	Field study	Australia	Self-reported heat stress	1726 workers in several occupation types (both outdoor and indoor)	2013/2014	Productivity measured as absenteeism, or presenteeism (less productive days) from the work productivity and activity impairment (WPAI) questionnaire	Self-reported estimates of absenteeism and reductions in work performance (presenteeism) caused by heat. Total production loss (TPL) was calculated as sum of PLA is the annual production loss from absenteeism and PLP the annual production loss from presenteeism. PLA was calculated for each individual as NA x DI where NA=number of days absent per year due to heat stress and DI=daily income. PLP was calculated for each individual as HL x NP x HI, where HL=hr lost per less productive day, NP=number of days per year of lower productivity, and HI=hourly income. HL was calculated as p x H where p=the percentage by which productivity was reduced on less productive days and H=number of hours per day spent working for payment. Annual total productivity loss is adjusted for compensation and in US$.	The individual annual economic losses due to heat were US$655 per person, which translates to an economic burden totaling US$6.2 billion in Australia. Percent reduction in productivity 30% in both males and females. Annual total productivity loss higher for workers with medium-high proportion of time outdoor and higher physical exertion, higher for machinery operators/drivers. Across the whole sample, of whom 70% were less productive and 7% absent on at least one day per year owing to heat, the total economic loss was US$711 per person per year, which was reduced to US$655 if compensatory behavior is accounted for (i.e., compensate for productive time lost by working longer hours). This was, on average, 1.2% of respondents' gross annual income.
Zander and Mathew (49)	Field study	Urban Malaysia	Self-reported heat stress	514 workers several occupation types (both outdoor and indoor)	2017–2018	Productivity measured as absenteeism, or presenteeism (less productive days) from questionnaire	Self-reported estimates of work absenteeism and reductions in work performance caused by heat. Individual economic losses estimated from productivity loss per daily average income per number of affected days.	The median number of days in a year on which people felt their productivity had been compromised because of heat stress was 29. On those days, half of the respondents felt their work capacity had been at least halved. The estimated median annual loss from reduced productivity was 257 €, nearly 10% of respondents' median annual income. Annual losses greater in medium-heavy physical exertion categories and heavy mental exertion categories.

(Continued)

TABLE 1 (Continued)

Reference	Study type	Country	Heat exposure	Study population	Study period and duration	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Studies evaluating healthcare-related costs								
Bonauto et al. (50)	Descriptive study of compensation claim data related to heat	US Washington State	n.a.	All work sectors (480 compensation claims for heat-related illness in the study period)	1995–2005	Both compensable and non-compensable claims were included. Non-compensable claims (medical-only). Compensable claims involve 4+ lost workdays, a permanent partial disability award, were kept on-salary by the employer or resulted in a fatality. Workers' compensation claim costs represent those paid to date for closed claims. For open claims on the date of extraction, the claim costs represent those paid to date and an estimate by the L&I workers' compensation case reserve unit of future expected claim costs. Indirect costs to employers and workers and the administrative costs of managing the claim are not included in the claim costs.	Descriptive analysis of heat-related illness compensation claims and risk factors (outdoor/indoor, comorbidity, hours of the day, acclimatization) and related costs.	Median cost for all compensable and not compensable claims for heat-related illness was 537 USD (mean 1,864 USD), higher than for total claims (not only for heat-related injuries). Also median cost for non-compensable claim was higher for heat-related illness than for total claims (513 vs. 251 USD). Median cost per compensable claim for heat-related illness was 1,916 USD, lower than for total claims (4,771 USD). For time loss claims, the median number of working days lost was 6 (46 days on average).

(Continued)

TABLE 1 (Continued)

Reference	Study type	Country	Heat exposure	Study population	Study period and duration	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Studies evaluating healthcare-related costs								
Fortune et al. (51)	Descriptive study of heat-related injuries	Ontario, Canada	na	All work sectors (612 compensation claims for heat-related illness in the study period)	2004–2010	na	Lost time claims related to excess heat exposure. Incidence rates calculated using denominator estimates from national labor market surveys and estimates were adjusted for workers' compensation insurance coverage. Proportional morbidity ratios were estimated for industry, occupation and tenure of employment.	Incidence of heat illness and lost time claims related to excess heat exposure highest in the June to August period. A total of 40% of all heat illnesses were clustered in epidemics over contiguous days. The rates of lost time claims were highest among workers aged 15–24, males, and among manufacturing (25%), Government Service (15%), construction (10%), and self-insured public sector employers (10%) sectors.
Hesketh et al. (52)	Descriptive study of heat-related injuries	US Washington State	Maximum daily and 3-day temperature (°F) > 89°F (threshold to protect workers)	645 heat-related injuries occurred in all work sectors	2006–2017	Worktime loss due to heat-related injuries. Claim costs (in USD) for compensable and non-compensable (medical aid only) claims, excluding indirect costs to employers and workers and the administrative costs of managing the claim.	Descriptive analysis of time losses and costs per injury	For time loss claims, median time loss of 13 work days related to heat injury (mean of 93 days). Higher median costs for heat-related injuries than for total injuries for both all claims (909 USD and 800 USD, respectively) and non-compensable claims (876.9 vs. 560 USD). For compensable claims higher costs for total than for heat-related injuries.
Ma et al. (53)	Time-series study of the relationship between temperature and occupational injuries	China	Wet-bulb Globe Temperature (WBGT)	all work sectors	2011–2012	The daily insurance payouts calculated by aggregating amounts of individual payouts and also showed as USD	Time-series study (Distributed Lag non-linear models) to examine the association between heat stress (WBGT values) and work-related injuries and insurance payouts. To calculate the measures of injury claims and the cost of compensation attributable to high WBGT values, the daily maximum WBGT and the corresponding relative risks were combined to assess the attributable numbers of each day.	4.1% of insurance payouts was attributable to heat stress (all days in the study period with WBGT>25°C), corresponding to 11.58 million Chinese Yuan. Stronger risk of heat-related injuries in workers aged 35–44 and <35, workers employed in small enterprises, and workers with intermediate education level, and in workers severely injured. Significantly higher costs in males (but significant impact also in females), medium-sized enterprises, workers with intermediate education level.

(Continued)

TABLE 1 (Continued)

Reference	Study type	Country	Heat exposure	Study population	Study period and duration	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Studies evaluating healthcare-related costs								
Martínez-Solanas et al. (54)	Time-series study of the relationship between temperature and occupational injuries	Spain	Extreme cold and heat defined as temperatures below the 2.5th and above the 97.5th percentiles, and moderate heat and cold between minimum mortality temperature and the extreme threshold, respectively	Occupational injuries in specific economic sectors (no information about indoor and outdoor)	1994–2013 (both heat and cold)	Occupational injuries that caused at least one day of leave were considered. Costs (euros) estimated based on a previous study on the costs of occupational injuries in the Catalonia region (55) estimating (a) costs associated with maintaining production (including overtime payments and costs of replacement and training), (b) long-term lost incomes (total income lost when a worker suffers an injury and cannot come back to work), (c) health costs associated with costs of treatment and rehabilitation, and (d) costs of pain and suffering (level of disability).	Time-series study (Distributed Lag non-linear models) between daily maximum temperature and the daily count of occupational injuries. Analyses of economic losses due to working at extreme temperatures (total economic costs due to non-optimal temperature per year) by multiplying cost of each lost workday due to injury for the number of working days lost due to non-optimal temperatures by considering the empirical distribution of the number of days of sick leave for each category of leave duration and the attributable number for both cold and heat.	0.67 million (95%CI: 0.60–0.73) person-days of work lost every year due to temperature. 319.39 million euros annually related to heat (297.82 for moderate heat, 21.57 for extreme heat). Annual costs related to moderate and extreme heat from pain and suffering: 182.97 million euros, maintaining production: 59.21 million euros, long-term lost incomes: 49.16 million euros, and health costs: 28.06 million euros.

(Continued)

TABLE 1 (Continued)

Reference	Study type	Country	Heat exposure	Study population	Study period and duration	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Studies evaluating healthcare-related costs								
Rameezdeen and Elmualim (56)	Descriptive study of heat-related injuries	Adelaide, Australia	Heat wave: five or more consecutive days of maximum temperature in excess of 35°C or three or more consecutive days of temperature in excess of 40°C	Construction sector (29,438 compensation claims during the study period)	heat waves 2000–2010	Compensation claims and costs (Australian dollars)	Descriptive analysis of occurrence and severity of construction accidents by worker's characteristics. Compensation claims recorded during the heat wave periods were compared with those during similar "control periods".	The average cost per compensation claim was 26,381 Australian dollars during heat waves compared to 12,747 Australian dollars during control periods. Worker characteristics (older workers 55+ years old, new workers, male workers), type of work (civil subsector, slight over-representation of bricklayer, carpenter, electrician, mechanic, and plant operator), work environment, and agency of accident increase the risk of injuries (both total and severe) during heat waves. Small companies had a proportionately higher share of severe injuries during heat waves and higher costs. Higher cost of severe injury for specific agencies of accident (structure, electricity, environment, small tool, and vehicle).

(Continued)

TABLE 1 (Continued)

Reference	Study type	Country	Heat exposure	Study population	Study period and duration	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Spector et al. (57)	Descriptive study of heat-related illness	Washington, US	Maximum and minimum temperature and temperature range, heat index	Agriculture and forestry sector (84 heat-related claims in the study period)	1995–2009	Cost per compensation claim (USD). Time-loss days per claim measured as lost worktime due to work-related injury or illness after a 3-day waiting period (days)	Descriptive analysis of determinants of heat-related compensation claims	Comorbidity and drug use increase risk of heat-related claim. The mean Tmax for outdoor agriculture and forestry heat-related injuries claims was 95°C (99°C for Heat Index). 76% of agriculture and forestry heat-related injuries in males. The mean cost per heat-related claim was 3502 USD and 3071 USD for total and non-compensable (medical-only) claims, respectively. Mean number of time-loss days was 25 (0–96) days. Costs were several times lower than average cost of all claims (not only heat-related ones and in all sectors). Severe heat-related claims (requiring hospitalization or death) mean cost was 24,533 USD.
Studies evaluating healthcare-related costs								
Xiang et al. (58)	Time-series study on heat-related workers compensation claim data for injuries	South Australia	Maximum temperature	All work sectors (438 heat-related occupational injuries in the study period)	2000–2014	Work days lost due to injury Medical costs of heat-related injuries (Australian dollars)	The quantitative association between heat and work days lost (count data) assessed using negative binomial regressions to account for over-dispersion	A 1°C increase in Tmax above about 33.8°C was associated with a 41.6% increase in medical costs and a 74.8% increase in days lost due to OHI, respectively. Average expenditure per claim is larger in males, in 25–44 age group, in new workers, in medium size employer, in advanced clerical and service workers, in mining sector, in workers not having had injuries before. There were no significant differences in medical costs and work days lost between heatwave and non-heatwave periods.

PPE, personal protective equipment; BMI, body mass index; USD, US Dollars.

TABLE 2 Results of economic modeling studies estimating productivity, social, or economic losses related to occupational heat exposure present and future at the regional and global level.

References	Country	Heat exposure	Work sectors	Study period	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Global studies							
Burke et al. (59)	Global and regional level (rich and poor countries)	Annual mean temperature	Several occupational types	2050–2100 compared to 1960–2010 (two socioeconomic scenario consistent with RCP8.5)	Productivity of industries not of individuals (change in GDP per capita)	Econometric study. Non-linear analysis between global and country economic production and temperature. Industry productivity is a function of capital and labor and respective productivities that are influenced by temperature. To form a measure of aggregate output, such as gross domestic product (GDP), industry-specific productivity is summed up across all industries and integrate production across all locations in a country and all moments in time within the period of observation.	Overall economic productivity is non-linear in temperature for all countries, with productivity peaking at an annual average temperature of 13.6°C and declining strongly at higher temperatures. Climate change reduces projected global GDP by 23% in 2100 (best estimate, SSP5) relative to a world without climate change. Reductions are similar in rich and poor countries, while are larger in countries becoming warmer.
Chavaillaz et al. (60)	Global and regional level (high- and low-income countries)	Wet-bulb Globe Temperature (WBGT) index of heat stress	vulnerable industries to heat exposure (agriculture, mining and quarrying, manufacturing, and construction workers)	Different emission scenarios (1% CO$_2$, RCP4.5, and RCP8.5) compared to the pre-industrial period (1861–1880)	Productivity calculated as working time (resting times)	Estimation of the effect of heat exposure on working time loss per year (due to increasing resting times) based on WBGT safety threshold for different job intensities. From statistics of the International Labor Organization, the change in annual labor productivity (expressed as a relative annual loss of total GDP) for each country and each vulnerable economic sector was calculated based on mean hourly output of the sector, and the GDP of the country. Socioeconomic conditions assumed to be invariant over the study period.	The relationship between productivity loss and CO$_2$ emissions is robustly linear at global scale. For each trillion tons of carbon emitted, the annual productivity loss will globally increase by 1.84% (±0.94, 1σ-intervals due to climate and inter-model variability), 2.96% (±1.97) and 3.61% (±1.77) of total GDP in the 1% CO$_2$, RCP4.5 and RCP8.5 scenarios, respectively. Some high middle-income countries are subject to the highest impacts; for example, Gabon, India, Thailand, and Malaysia all experience productivity losses from 3 to 5% of total GDP per year for every TtC emitted. Non-CO$_2$ gases contribution seemed larger than that of CO$_2$ alone.
DARA (61)	Global and country level	Annual mean temperature	Several occupation types (both indoor and outdoor)	2030 scenario SRES A2 vs. 2010 (baseline)	Work capacity as the maximum percentage of an hour that a worker should be engaged working (%) (62)	Analysis of labor productivity losses from WBGT change exceedance of safety standards in acclimatized populations. The changing structure of the workforce over time, in particular, the industrial shift of developing countries away from outdoor agriculture was included. Assuming the different work intensities for each sector, regional labor productivity change estimated based on the weighted average of work activities across each sector. Labor patterns assumed to change over time, consistent with economic growth projected under the A2 emission scenarios.	These results projected a total global GDP loss of US$2.5 trillion (PPP $) per year for 2030 (1% loss of global GDP in 2030, 0.5% loss in 2010). As a percentage of the national GDP, losses varied markedly and were greatest in tropical low- or middle-income countries (e.g., 0.0% in the United Kingdom and Japan, 0.2% in the United States, 0.8% in China, 3.2% in India, 6.0% in Indonesia and Thailand, and 6.4% in Nigeria and Ghana)

(Continued)

TABLE 2 (Continued)

References	Country	Heat exposure	Work sectors	Study period	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Dasgupta et al. (63)	Global and regional level	Mean temperature and wet-bulb globe temperature (WBGT).	Low-exposure working conditions (labor outside in the shade or indoors—e.g., manufacturing) and high-exposure working conditions (outside with no shade—e.g., agriculture and construction)	1.5°C, 2.0°C, and 3.0°C of global warming compared with the historical baseline period (1986–2005)	Change in Effective Labor = (100% + Change in Labor Supply) * Change in Labor Productivity, where labor supply is measured by hours worked and labor productivity derived from published temperature-productivity functions	The effect of climate change on labor productivity was assessed using five different exposure-response functions established in the literature. Warming levels were assessed over the observational period until the reference period 1986–2005 (0.6°C) and modeled warming for the individual climate models relative to the reference period.	Current climate conditions already negatively affect labor effectiveness, particularly in tropical countries. Future climate change will reduce global total labor in the low-exposure sectors by 18% and 24.8% in high-exposure sectors under 3°C global warming scenario. Higher impacts for labor outdoors in full sunlight. Europe is expected to be the least affected region, while the highest impact will be in Sub-Saharan Africa.
De Lima et al. (64)	Global and regional level	WBGT	Agriculture	1.5°C, 2.0°C, and 3.0°C of global warming compared with the 1986–2005 baseline	Individual labor capacity estimated (1) by WGBT safety standard (NIOSH) for agricultural workers (400 W) and an associated function for labor capacity; and (2) by Dunne algorithm (65)	Labor capacity change estimated for baseline and climate change scenarios accounting for impacts in crop yields change. Global economic model to predict impacts on yield and labor changes.	In sub-Saharan Africa and Southeast Asia heat stress with 3°C global warming could reduce labor capacity in agriculture by 30%—50%, increasing food prices and requiring much higher levels of employment in the farm sector.
Dunne et al. (65)	Global level	Wet-bulb Globe Temperature (WBGT)	Outdoor workers	Reanalysis 1971–1980 and 2001–2010, projected 2091–2100 and 2191–2200 under high emissions (RCP 8.5) and mitigation (RCP 4.5) scenarios	Population-weighted individual labor capacity (%) during annual minimum and maximum heat stress months estimated from WBGT applied to US national and international standards for safe work intensities (90% means 10% losses in labor capacity)	Analysis focused on the loss of labor productivity as a function of WBGT levels during the hottest months in reference period and under scenarios.	Reductions in work capacity during the hottest months already occur at the global level (10% reduction). By 2050 under both scenarios, work capacity loss is 2-fold higher than in the historical period (20% reduction). By 2100, the reductions in the hottest month may reach 37% based on RCP8.5 and 20% based on RCP4.5. By 2200, very significant further changes in work capacity are projected for the hottest month based on RCP8.5 (61% reduction), and 12% of population is exposed to work capacity losses. To offset these reductions a substantial increase in unskilled farm workers will be required.

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TABLE 2 (Continued)

References	Country	Heat exposure	Work sectors	Study period	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Heal and Park (66) Gray literature	US and other countries at global level	annual mean temperature	all work sectors	1950–2005 no future climate change scenarios	Output shocks related to heat as % per capita GDP per 1°C (Per capita output is increasing in effective labor supply)	Analysis based on statistical model of work output (or GDP) and thermal stress (controlling for institutions, capital stock, and education). Linear regression between GDP is produced using a combination of capital and effective labor input. Effective labor input is defined as a composite of labor hours, labor effort, and labor performance as a function of the ambient temperature. We allow for the possibility that temperature may affect GDP with a time lag, by allowing for 1, 5, and 10 lags. For the US, household data on air conditioning and heating expenditures.	Very hot countries such as Thailand, India, and Nigeria suffer negative output shocks on the order of 3–4% per capita GDP per 1°C. Very cold countries such as the UK, Canada, Norway, and Sweden have significantly higher output in warmer years (and lower output in colder years). In the US, a household with an average age of 20 spends roughly 15% (28 USD) more per year on air conditioning and 12% (54 USD) less on heating than an otherwise equivalent household with an average age of 60 and expenditure on both air conditioning and heating are higher for households with someone at home who is working than for those with someone at home but not working.
Kjellstrom et al. (67)	Global and regional level (21 geographical regions)	Wet-bulb Globe Temperature (WBGT)	All work sectors (service, industry, and agriculture) both indoor and outdoor	2020, 2050, and 2080 compared to 1961–1990 under climate scenarios SRES A2 (worst) and B2 (best)	Change in labor productivity expressed as percent work days lost and incremental change relative to baseline.	Projections of future labor productivity losses (in terms of lost labor days) under climate scenarios compared to baseline climate applying dose–response function between WBGT and work capacity estimated in Kjellstrom et al. (67). Assuming the different work intensities for each sector, regional labor productivity change estimated based on the weighted average of work activities across each sector. Labor patterns assumed to change over time, consistent with economic growth projected under the A2 emission scenarios.	By the 2080s, the greatest absolute losses of population-based labor work capacity (in the range 11% to 27%) are seen under the A2 scenario in Southeast Asia, Andean and Central America, and the Caribbean. Under B2 scenario smaller impacts in all regions (the greatest loss being 16% in Central America), and labor productivity gains in some regions (up to 6%).
Kjellstrom et al. (68)	21 global regions (high and low- and middle-income countries)	Wet-bulb Globe Temperature (WBGT) index of heat stress (calculated using Hothaps functions)	All work sectors (outdoor and indoor)	2030 and 2050 vs. 1960–1989	Reduction of hourly active worktime expressed as loss of work capacity due to heat. Cost of labor productivity loss due to excessive heat, % of GDP	Lost work capacity calculated using exposure–response relationships from literature. The national loss estimates used the proportion of the work force in jobs with different physical demands and different heat exposure levels, based on a World Bank model. The losses, as percent of daylight work hours, were multiplied with the estimated GDP for 2011 and 2030. Workforce changes are taken into account.	For Southeast Asia work capacity losses increase from 17% to 29% (of daylight work hours) from 1975 to 2050 for outdoor workers doing heavy labor. The losses for indoor workers doing heavy labor increase from 3% to 8%, and for outdoor workers doing moderate labor the estimates go from 7% to 15%. Low- and middle-income countries have losses 6% of annual GDP, higher compared to high income countries. The estimated annual losses, expressed as $US PPP, are already in 2010 up to 55 billion (India) and in 2030 up to 450 billion (India and China).

(Continued)

TABLE 2 (Continued)

References	Country	Heat exposure	Work sectors	Study period	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Kjellstrom (16) (gray data embedded in the review)	global and country level	Wet-bulb Globe Temperature (WBGT) index of heat stress	all work sectors (service, industry, and agriculture) both indoor and outdoor for a mixed workforce (average metabolic rate = 300W; in shade or indoor non-cooled work)	2085 (2070–2099) under global warming scenarios 4°C (RCP8.5) (worst) and 1.5°C (RCP 2.6) (best) compared to 1995 (1980–2009)	Person-hours lost due to heat in each region (i.e., the work capacity loss multiplied by the working population in each grid cell and then summed up for all grid cells in a region). Lost work hours are expressed as the annual percent of daylight hours lost due to heat at 300W.	Projections of future labor productivity losses (in terms of lost labor days) compared to baseline climate, applying dose–response function between WBGT and work capacity estimated in literature for moderate labor	Productivity is already lost up to 10% of annual daylight hour in some regions. There is a 10-times or more increase of work hours lost from 2015 to 2085 for several countries under RCP8.5 scenario. The substantial reduction in work capacity (and related labor productivity) between 1995 and 2085. The areas with the greatest risk in 2085 remain the same (Amazon region, West Africa, Arab Gulf area, Pakistan, North India, Indonesia, and parts of China), but substantial reductions in work capacity are apparent in the southeast United States, parts of Europe (South), Africa, and the rest of India and China. By the end of the century impact will increase in the hottest areas even if temperatures are held at 1.5°C (RCP2.6), but the increase is much higher for the business-as-usual scenario of 4°C (RCP8.5), reaching more than 30–40%.
Kjellstrom et al. (69)	Seven countries (USA, China, India, Cambodia, Philippines, Ethiopia, Costa Rica)	Wet-bulb Globe Temperature (WBGT) index of heat stress	all work sectors (service, industry, and agriculture) assuming agriculture is the hardest work (400 W) and mostly occurs outdoors in the sun, industry at 300 W is in the shade or indoors and servicing the easiest at 200 W and in air conditioned spaces	2011–2040, 2041–2070, and 2071–2099 vs. 1981–2010 under climate change scenarios of 1.5°C (RCP2.6) and 2.7°C warming (RCP6.0)	Percent of potential work hours lost calculated from daylight person hours lost for each grid cell in a geographical area and total potential work hours in the population.	Productivity loss due to heat estimated based on dose–response function between WBGT and work capacity in each grid cell and each region. Projections of future labor productivity losses estimated for workers in moderate-intensity jobs (MR = 300W).	Under the more extreme climate change trend (RCP6.0; increase of 2.7 °C), as much as 12–16% of annual work hours will be lost in some areas. The impact is naturally mainly occurring in the southern hotter areas. Countries with large cool climate areas (such as USA) have limited work hour losses due to heat now (0.17%), but it may increase beyond 1.3% at the end of the century based on the current global climate policy pathway (RCP6.0). The most affected countries, such as Cambodia, may have losses exceeding 10%.

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TABLE 2 (Continued)

References	Country	Heat exposure	Work sectors	Study period	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Kjellstorm et al. (62) gray (ILO report)	global and regional level	Wet-bulb Globe Temperature (WBGT) index of heat stress	all work sectors (agriculture, construction, industry, services)	2030 compared to 1995 (1981–2010) under RCP6.0 (worst) vs. RCP2.6 (best)	Estimated annual labor productivity losses expressed as total working hours, or $US PPP (or % of GDP) or equivalent full-time jobs due to excessive heat	Productivity loss due to heat estimated based on dose–response function between WBGT and work capacity in each grid cell and each region for moderate and heavy labor. Projections of future labor productivity losses estimated for workers in moderate-intensity jobs (MR = 300W).	By 2030 the share of total working hours lost will rise to 2.2%, a productivity loss equivalent to 80 million full-time jobs at global level. The loss in monetary terms is then expected to total US$2, 400 billion (PPP). Lower-middle- and low-income countries would be the worst affected, losing 4% and 1.5% of their GDP in 2030, respectively. Losses are close to zero in Europe. Agricultural and construction workers will be the worst affected. The agricultural sector alone accounts for 83% and 60% of global working hours lost to heat stress in 1995 and 2030, respectively. Construction is expected to account for 19% of the total loss in 2030, up from 6% in 1995.
Knittel et al. (70)	All world regions (European and not European)	Wet Bulb Globe Temperature	heavy outdoor work (agriculture, construction) and medium intensity indoor work (manufacturing industry)	Shared Socioeconomic Pathways (SSP1, SSP2, and SSP3) and two Representative Concentration Pathways (RCP4.5 and RCP8.5) in 2036–2065 vs. 1981–2010	Productivity loss as relative change in work ability (%). Productivity costs as output losses due to excessive heat, % of GDP	Impact of heat on production estimated based on heat-production function by literature (71) based on labor input, change in work ability based on dose–response function between WBGT and work capacity from literature. The study evaluated these impacts on Germany economy using a global CGE models.	Impacts on productivity higher for outdoor than indoor work. By 2050, within Europe, reductions are most pronounced for Italy and other Mediterranean countries (Cyprus, Greece, Malta, Portugal, Spain), while other countries are only marginally affected. Other world regions are severely impacted such as Southeast Asian countries, India, and oil exporting countries. In the Amazon region, heavy outdoor work (400W) is projected to decline by more than 50% under RCP8.5.

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TABLE 2 (Continued)

References	Country	Heat exposure	Work sectors	Study period	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Kuhla et al. (72)	global and regional level	daily mean temperature	agriculture, fishing, mining and quarrying, hotels and restaurants, wholesale trade, and others	2020–2039 vs. 2000–2019 (RCP2.6 and RCP6.0 scenarios)	Direct output production losses by region (billion USD). Also indirect production and total losses (in terms of value of goods and services) are calculated.	Absolute and relative heat stress-induced direct output losses based on risk function between temperature and productivity from literature (perturbed productivity) (73). Absolute output losses are then determined by multiplying the perturbed productivity with the baseline production of that region	Globally, between 2000 and 2039 direct output losses increase by 47% if no further adaptation measures are taken. Regional increase in direct losses in the billions USD (e.g., in India, Saudi Arabia, or Mexico) or nearly double the direct output losses (e.g., in Northern America or Europe) within the next decades.
Matsumoto et al. (74)	global and regional level	Wet-bulb Globe Temperature (WBGT)	agriculture, manufacturing, and service	2100 business-as-usual scenario BaU, and two emission-reduction scenarios ("S45" and "S2") vs. 2007 (baseline)	labor productivity reductions (%) and associated GDP losses (%)	Coupled socioeconomic (CGE) and climate models. Changes in labor productivity affect the labor input necessary to produce goods/services in the production functions. Climate change impact on labor productivity based on dose–response function between WBGT and work capacity estimated in literature.	The impacts were the largest for the agricultural (36.8–100% labor productivity reduction by 2100), and the lowest for the service sectors (83.0–100% productivity reduction by 2100). Labor productivity reached its minimum levels during the warmest and wettest parts of the year in already hot and humid regions (similar trends were observed for both of the mitigation scenarios as well). Such declines in labor productivity reduced production and, consequently, affected the macroeconomy. The global-level negative impact on GDP grew with temperature increases, which was about 2% per 1°C

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TABLE 2 (Continued)

References	Country	Heat exposure	Work sectors	Study period	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Orlov et al. (75)	Global and regional level	Wet-bulb Globe Temperature (WBGT)	all work sectors agriculture and construction (high-intensity jobs, 400 W), manufacturing and services (moderate-intensity, 300 W and low-intensity work, 200 W)	2020, 2030, 2040, 2050, 2060, 2070, 2080, and 2090 compared to 1981–2005 under RCP8.5 (worst) and RCP2.6 (best) scenarios (and SSP1, SSP4, and SSP5 scenarios for CGE model)	Percentage reductions in global GDP from labor productivity loss, estimated by decreased work efficiency	Interdisciplinary approach that combines climate projections, epidemiological findings, and economic analyses. Work capacity loss (a physiological variable) estimated using the dose–response function between WBGT and work capacity estimated in literature (Hothaps and ISO). The spatiotemporal data of relative worker productivity losses are matched with the gridded data on the population count to obtain population-weighted impacts on worker productivity at a regional level. and the associated economic costs are assessed by using a dynamic multi-region, multi-sector computable general equilibrium model. Autonomous mechanization of outdoor work in agriculture and construction and presence of air conditioning for indoor work is implemented in the model.	Heat stress leads to substantial reductions in worker productivity. For RCP8.5, using the Hothaps function with constant work intensity results in an average reduction of 0.7% (1.8%) in global GDP by 2050 (2100) relative to the reference period. Impacts are higher for high-intensity work in low-latitude countries of Africa, South America, and Asia. Given the assumption of absence of air conditioning and constant work intensity, reductions in worker productivity in some regions under RCP8.5 could even exceed 40% by 2100 compared to the reference. Approximately 42% of the global mitigation cost could be offset by avoiding the adverse impacts of heat on worker productivity. Agriculture and construction are the most adversely affected by heat because these sectors require many work-intensive activities in the outdoor environment. While many low-latitude regions experience considerable reductions in worker productivity, less vulnerable regions such as Oceania, North America, Former Soviet Union, and Europe, receive a comparative advantage in production of agricultural goods, which explains those moderate increases in their production. Due to the penetration of air conditioning and a lower work intensity, manufacturing is less adversely affected by heat compared to agriculture and construction. The service sector exhibits a low risk of exposure to heat.

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TABLE 2 (Continued)

References	Country	Heat exposure	Work sectors	Study period	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Parsons et al. (76)	global and country level	WBGT	outdoor heavy labor work sectors (agriculture, forestry, fishing, and construction)	2001–2020 and future scenarios (1°C, 2°C, 3°C, and 4°C climate warming)	Heavy labor lost (hours) Productivity loss (Billions PPP USD)	Models combining climate projections and epidemiological findings on heat-productivity risk functions. The spatiotemporal data of work capacity loss based on WGBT using the dose–response function between WBGT and work capacity estimated in literature (at 400W intensity) in the 12-h work day and combining with the working population in each country to estimate the heavy labor work hours lost. Economic losses related to lost earnings were also calculated by estimated of hourly earnings and converting hours lost to job loss equivalent and expressed as reduction in GDP.	Strong relationship (non-linear) between global annual mean temperature and annual sums of hours lost both in the reference period and in future global warming scenarios. In the current climate, 25–30 h lost/person/year could be recovered if workers in many low-latitude regions could move heavy labor to a cooler hour from the hottest hour of the day. Current global estimates of productivity losses are 670 billions PPP USD in the 12-h work day every year. Under +2°C warmer world, productivity losses reach 1.6 trillion PPP USD.
Parsons et al. (77)	global and country level	WBGT	outdoor workers in heavy labor sectors (agriculture, forestry and fisheries; construction)	2001–2020 compared to 1981–2000 (baseline) (no climate change scenarios)	Heavy labor lost (hours) Productivity loss (Billions PPP USD)	The spatiotemporal data of work capacity loss based on WGBT using the dose–response function between WBGT and work capacity estimated in literature (at 400W intensity) in the 12-h work day and combining with the working population in each country to estimate the heavy labor work hours lost. Economic losses estimated by multiplying the full-time equivalent (FTE) work hour loss by the average value added per worker in each sector. To calculate FTE work hour losses, we divide the hours lost per year by the total possible work hours in a year by sector and region, expressed as GDP per capita (PPP) in USD.	Over the study period, global-mean, near surface air temperatures have increased by ca 0.4°C resulting in increases in per capita labor losses of up to 150 h person−1 yr−1 (12.5 days person−1 yr−1) in some low-latitude regions. Global labor losses higher estimates are 2.1 trillion PPP USD. China and India again experiencing the largest losses, and Indonesia and the United States showing over 90 billion PPP USD losses per year. India experiences annual productivity losses equivalent to almost 7% of its 2017 GDP.
Romanello et al. (78) (the Lancet Countdown 2022)	global and regional level (low, medium, high, and very high human development index)	Wet Bulb Globe Temperature	agricultural, construction, manufacturing and service sectors	1990–2021 (annual estimates)	Potential hours of labor lost due to exposure to heat by labor sector (in millions)	Hours of work lost calculated by linking Wet Bulb Globe Temperature with the amount of energy typically expended by workers by sector and combining with the proportion of people working (over 15 years old) in each country.	470 billion h of potential work were lost due to extreme heat exposure in 2021, —an increase of 37% from the annual average in 1990–99, an average of 139 h lost per person, with 87% of all losses in countries with a low Human Development Index occurring in the agricultural sector. Two-thirds of all labor hours lost globally in 2021 were in the agricultural sector. Conservative estimates since shade work is considered.

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TABLE 2 (Continued)

References	Country	Heat exposure	Work sectors	Study period	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Roson and Sartori, (79)	global and regional level	Wet-bulb Globe Temperature (WBGT)	Agriculture (high intensity, 500W), manufacturing (medium intensity, 300 W), service (low intensity, 200 W)	Global warming scenarios of 1°C, 2°C, 3°C, 4°C, and 5°C increases in average temperature (study period not specified)	Relative percentage change in (annual) productivity with respect to the baseline, for all countries and sectors	The spatiotemporal data of work capacity loss estimated based on WBGT using the dose–response function between WBGT and work capacity found in the literature projection of loss in labor productivity from relationships between average temperature and labor productivity under scenarios of 1, 2, 3, 4 and 5 °C increases in average temperature (study period not specified).	The estimated percentage variation of labor productivity for 140 regions and for a +1°C increase in temperature is—0.27%. The mean productivity losses range from—2.52% to—17.48%. Agriculture is the sector most significantly affected by higher heat stress. Some effects are felt by about half of the countries already at +1°C.
Takakura et al. (80)	Global and regional level	Wet-bulb Globe Temperature (WBGT)	all work sectors (outdoor and indoor) industry and construction (high intensity, 400W), manufacturing (moderate intensity, 300W), and service (low intensity, 200W)	2100 under four representative concentration pathways (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) and three socioeconomic scenarios (SSP1, SSP2, SSP3) compared to baseline (2005)	Work–rest ratio changes (worktime reductions) Productivity losses (worktime lost) and direct costs of worktime loss both expresses as GDP percentage reduction under climate change scenarios compared to the reference period	Work capacity (work hours loss) estimated based on WBGT using the dose–response function between WBGT and work capacity found in the literature and on safety recommendation of work/rest ratio. Daily total worktime was calculated by the hourly work capacity and summed the hourly work capacity from 9:00 AM to 5:00 PM. In order to express the labor productivity loss due to reduced worktime in economic costs, the labor input was multiplied by the ratio of the worktime reduction, and their product was used as the effective labor input to the production function. The direct cost is calculated as the additional wages required to compensate the worktime loss associated with the additional labor requirements. Presence of air conditioning for indoor work is implemented in the model.	At the end of the 21st century, the aggregated worktime ratios decrease under both low and high emission scenarios. Under RCP8.5, the aggregated worktime ratios decrease to 0.23 in Southeast Asia, 0.36 in India, and 0.42 in Sub-Saharan Africa. Indoor work is also adversely affected under RCP8.5. For example, in India, the worktime ratio was 0.62 for indoor/moderate work and 0.76 for indoor/light work if air-conditioning devices are not available. Under the highest emission scenario, GDP losses in 2100 will range from 2.6% to 4.0% compared to the current climate conditions. Under RCP8.5, the GDP loss rates (median values) are 14.3%—17.3% in India and 4.6%—6.9% in Southeast Asia. In terms of direct costs, the construction sector is affected primarily by worktime loss in terms of direct costs. Based on the relationship between temperature increase and GDP loss, if the 1.5°C goal were achieved, the GDP loss rate would be reduced by approximately 0.3%, as compared to that of the 2.0°C goal.
Regional studies							
Altinsoy and Yildirim (81)	western Turkey	WBGT	agriculture and construction at different work intensities (light, medium, heavy, very heavy)	1971–2000 (baseline) 2011–2040, 2041–2070, 2071–2100 (scenario SRES A1B - one of the highest emissions scenario) Only Spring, Summer, Autumn seasons.	labor productivity losses in terms of percentage of potential work days in season	Spatiotemporal WGBT values used to calculate labor productivity losses as work hour loss estimated from recommended rest/work ratio (25%—50%—75%—100% corresponding to 15–30–45–60 min rest for 1 work hour) at different WBGT values and work intensities. Expected decline in labor productivity is multiplied with the agriculture contribution to the economy to yield the total decline in labor productivity in agriculture.	The most important productivity decreases are expected in the summer. The main impact on work productivity becomes evident after 2040. In Turkey decrease in labor productivity losses in agriculture vary from 1% (baseline), to 2% in 2011–2040, 5% in 2041–2070, and 8% in 2071–2100. In some areas, the largest decrease reaches 52%.

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TABLE 2 (Continued)

References	Country	Heat exposure	Work sectors	Study period	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Amnuaylojaroen et al. (82)	5 megacities in Thailand	Steadman Heat Index	not specified	1990–1999 (baseline), 2020, and 2029 RCP 8.5 (very high emissions)	Percent decrease in labor productivity (%)	Labor productivity losses (work hours) calculated from heat index with a formula based on experimental data	The maximum decrement in work performance there was in December between 4% and >10%, with Southern areas facing most decrement than the rest of the country.
Behrer and Park (83) Gray literature	US	Daily maximum temperature	Non agricoltural sectors	1986–2011 and climate change scenarios in 2040–2050 (under RCP 4.5)	Annual payroll per capita (close proxies to changes in total and marginal labor product)	Analysis of heat stress impact on production outputs (payroll per capita) based on inputs labor productivity, effective labor supply, and temperature stress (number of hot days per year with maximum temperatures above 95°F). Panel regression of payroll and maximum temperature by county and year. Presence of air conditioning for indoor work is implemented in the model.	An average US county experiences a—0.04% reduction in payroll per capita during a year with one additional day with maximum temperatures above 95°F (35°C). The impacts are roughly 9 times as large in exposed sectors (construction, transportation, utilities, manufacturing, and mining). For instance, lost payroll under a no adaptation scenario is at least 50% higher in 2040–2050 compared a scenario in which local economies adapt to their new (hotter) climates (corresponding to 18 billion USD losses).
Costa et al. (84) Gray literature	3 EU cities Antwerp (Belgium), Bilbao (Spain), and London (United Kingdom)	Wet-bulb Globe Temperature (WBGT)	all work sectors (indoor and outdoor) at different level of intensity	near future (2026–2045) and the far future (2081–2100) scenarios compared to a reference period (1986–2005) (under RCP8.5)	Annual labor productivity loss, estimated by lost hourly worktime, and expressed as % of Gross Value Added (GVA) at the sector level	Production was measured by Gross Value Added (GVA) at the sector level. Spatiotemporal WGBT values used to calculate productivity loss as hourly productivity loss across all working hours and working regimes estimated from recommended rest/work ratio (25%—50%—75%—100% corresponding to 15–30–45–60 min rest for 1 work hour) at different WBGT values (ISO and NIOSH standards) and work intensities. Analysis of sectoral production as a function of WBGT, sector-specific capital and labor. Economic costs estimated by an explicit production function from input capitals and labor for each sector that is aggregated into city-specific Gross Value Added (GVA) at city level. Adaptation measures (shifting work hours, increase in insulation and air conditioning for indoor work) were implemented in the model.	Productivity (annual GVA) loss of 0.4% in London, 2.1% in Antwerp, and 9.5% in Bilbao projected in 2081–2100. These correspond to total losses of around 1, 900 million Euros for London, 669 million Euros in Antwerp, and 2, 500 million Euros in Bilbao, in 2005 prices. Losses will tend to increase with time, in particular in warm years, although not always linearly. GVA was observed to monotonically decrease with increasing WBGT. Losses vary greatly across sectors and by city. The construction sector accounts for only 4% and 6% of losses in Antwerp and Bilbao, respectively, while it accounts for 18% in London. Air conditioning is the most effective in reducing labor productivity losses from heat stress.

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TABLE 2 (Continued)

References	Country	Heat exposure	Work sectors	Study period	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
deBoer et al. (85) Gray literature	Phoenix area (US)	number of days with maximum temperature over 110°F	all work sectors (both high- and low-risk sectors)	2020–2039 and 2040–2059 (RCP 4.5 low emission and RCP 8.5 high emission) vs. 1986–2005 baseline	Labor productivity losses in million USD and as % of county GRP (Gross Regional Product)	Regression models from literature estimating the relationship between temperature and allocation of time to labor as well as leisure activities (for high-risk labor, time allocated to labor drops by 59 minutes on days with daily maximum temperatures over 100°F). The relative productivity loss was calculated on projected days above the temperature threshold (100°F) relative to the counterfactual in which the number of days above the temperature threshold is equal to the baseline. This number was subtracted from the projected number of days above the temperature threshold (100°F) from projected climate data for a future year. Impacts were estimated both with constant employment and GRP.	Labor productivity losses are 927–1313 and 1512–2138 million USD for RCP4.5 and RCP8.5, respectively, in 2020–2059, corresponding to 0.3% and 0.6% labor productivity losses.
Deloitte (86) Gray literature	Australia	annual mean temperature	all work sectors	global average warming of above 3°C by 2070 under RCP 8.5 compared to 2020 (baseline)	Economic losses due to job losses caused by climate change, as % of GDP or USD	The climate change models for different emission scenarios are the basis for translating a given temperature increase into economic damage by sector, region, and over time. Damage functions include capital damages, sea level rise damages to and stock, heat stress damages on labor productivity, human health damages to labor productivity, agricultural damages from changes in crop yields, tourism damages to net inflow of foreign currency and damages to energy demand. From physical climate damages to the factors of production, then economic impacts are estimated.	The economic losses to Australia from unmitigated climate change are 3.4 trillion USD (2020) or 6% of GDP by 2070. On average over the 30 years to 2050, that is a loss of 135, 000 jobs per year and 1.8% of GDP. The worst impacted industries are service sectors (both government and business), trade and tourism, manufacturing, and mining. Agriculture damages evaluated based on variations in crop yields.
Hsiang (73)	Carribean and Central America	annual mean temperature	different work sectors	1970–2006 by season	change in production due to temperature increases (% change for 1°C increase)	Empirical models of the relationship between the production of value in individual industries and interannual variations in climate. The production of goods and services is measured by per capita value added. Regression models of production with temperature, rainfall, and cyclones evaluated in non-linear models.	Heat impact on total production of—2.5% per 1°C increase. Wholesale, retail, restaurants and hotels (-6.1% per 1°C increase), and other services (-2.2% per 1°C increase) exhibit significant production losses. Output losses occurring in non-agricultural production (−2.4% per 1°C increase) substantially exceed losses occurring in agricultural production (−0.1% per 1°C increase).

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TABLE 2 (Continued)

References	Country	Heat exposure	Work sectors	Study period	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Hübler et al. (87)	Germany	perceived temperature (Laschewski, 2002)	all work sectors	2071–2100 (A1B SRES high emission scenario and B1 low emissions) compared to 1971–2000 (baseline)	Average GDP loss per year	Macroeconomic model of the impact of heat on labor output. Predictions of GDP losses for future temperature scenarios are estimated as function of heat-related GDP loss in baseline year (2004), predicted days with temperature exceeding safety threshold, mean relative productivity reduction when temperature threshold are exceeded, GDP in baseline year, wage share in baseline year.	Considering the worst scenario (A1B), future (2071–2100) losses are 2.5 billion Euros (0.12% of GDP) or 10.4 billion Euros (0.48% of GDP) with labor productivity losses of 3% and 12% for strong (32–38°C) and extreme heat (equal or above 38°C), respectively. Actual losses are 540 million Euros and 2.4 billion Euros with labor productivity loss of 3% and 12% for strong and extreme heat, respectively. Using IPCC scenario B1 (low emissions) and a 12% heat impact on labor productivity yields an additional loss of ca. 4.2 billion Euros, which is significantly lower than in the A1B scenario (almost 8 billion Euros, representing the expected emissions development).
Kershaw (88)	UK	predicted mean vote (PMV)	indoor work sectors	2030s, 2050s, and 2080s under SRES A1F1 scenario vs. 1970s	Relative productivity losses (%) Cost of lost productivity per square meter as a result of thermal discomfort	The loss of productivity due to thermal stress for each hour of occupancy is derived from physiological model of productivity and PMV. The cost of lost productivity per square meter as a result of thermal discomfort over the year is estimated based on the productivity per worker within a given sector. This is calculated by dividing the Gross Value Added (GVA) for that sector by the number of people employed in that sector measured as full-time equivalent (FTE). The change in relative productivity as a function of user thermal comfort is then applied to the economic output of a worker. A typical office building is used.	As the climate warms then the cost of lost productivity increases from 134 pounds per square meter in 1970s (3.2% lost productivity) to 148, 164, and 181 pounds (and 3.5%, 3.9%, and 4.3% lost productivity) per square meter in 2030, 2050, and 2080, respectively.
Kjellstrom et al. (89)	Southeast Asia	Wet-bulb Globe Temperature (WBGT)	all work sectors both non cooled indoor (or shade) and outdoor (or sun), for heavy (400W) and moderate (300W) work in the shade and in the sun	1975 (1961–1990) and 2035–2065. No climate change scenarios.	Work loss in percent of available afternoon working hours in March	Projections of future labor productivity losses (in terms of lost labor days) (% loss at specific WBGT level) from dose–response function between WBGT and work capacity for moderate and heavy work estimated in literature and based on safety standard (ISO) function (work hours lost due to rest and slower work due to heat)	In 1975 in the hottest locations 30–40% of afternoon worktime is lost in the shade and 60–70% lost in the sun. In 2050 in hottest areas, afternoon worktime is lost due to heat up to 80% for heavy work and up to 50% for moderate work.

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TABLE 2 (Continued)

References	Country	Heat exposure	Work sectors	Study period	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Kopp et al. (90) Gray literature	US	daily maximum temperature	all work sectors for high-risk (agriculture, construction, utilities, and manufacturing) and low-risk labor sectors	2020–2039, 2040–2059, 2080–2099 climate change scenarios (RCP 2.6, 4.5, and 8.5) compared to 2012 baseline	Relative (%) and absolute (full-time equivalent workers at current employment levels) change in labor productivity	Changes in productivity estimated using the dose–response functions between temperature and working time obtained by literature (91). Number of minutes individuals work from survey data. The dose–response functions accounted for cross-county patterns in labor markets, as well as trends over time and over seasons. Dose–response functions were used to predict future changes in labor productivity under different climate scenarios relative to a future with no climate change.	In RCP 8.5, high-risk labor likely declines by 0.2% to 0.9% by 2040–2059 and by 0.8% to 2.4% by 2080–2099. For low-risk labor supply, losses are more modest, with 2080–2099 losses in RCP 8.5 of 0.1% to 0.5%, with a 1-in-20 chance that labor supply falls more than 0.8% or less than 0.01%. Projected changes are smaller in magnitude for RCP 4.5 and RCP 2.6.
Kovats et al. (92) Gray literature	Europe	Wet-bulb Globe Temperature (WBGT)	all work sectors (agriculture, industry, and service) at different work intensities (400W for agricultural labor, 300W for industrial labor, and 200W for service industry)	2020, 2050, 2080 under SRES A1B (medium–high emission) and E1 (low emission) climate change scenarios compared to 1961–1990 (baseline)	Labor productivity losses (in terms of lost labor days) Economic costs (Million Euro/year) related to productivity losses	Changes in productivity estimated using the dose–response functions between temperature and working time obtained by literature (67). Loss of labor productivity, derived from the GDP per labor force member using EU27 average productivity cost value of 287 euros per day. Projections of productivity loss estimated by combining a global temperature rise of 1.5°C by the end of the twenty-first century with labor force trends compared to baseline climate. The model is based on a scenario in which current labor distributions are maintained over time and a scenario in which there is a shift among sectors in Europe.	Under the current climate, the only impacts are in Southern Europe, where losses were estimated to be 0.14% days lost. Higher impacts are projected for Mediterranean countries with climate change. Under A1B scenario, for Southern Europe a 0.4–0.9% loss in productive days by the 2080s. Total productivity losses (whole European area) are estimated at 120–320 million euros in the 2050s, rising to 300–740 million euros in the 2080s under A1B scenario. Impacts are significantly lower under the E1 mitigation scenario. According to the scenario of productivity distributions change, future impacts in Europe are lower.
Lee et al. (93)	South Korea	Wet-bulb Globe Temperature (WBGT)	outdoor laborers in construction, agriculture, forestry, and fisheries (moderate, 234–407 W and heavy intensity, 407–581 W)	2011–2040, 2041–2070, 2071–2100 under RCP 8.5 (high emission) and 4.5 (moderate emission) compared to 1981–2005 (baseline) summer season (June to September)	Labor productivity (days with reduced labor productivity as percentage of total working days) Relative productivity loss in future scenarios compared to baseline.	Projections of future labor productivity losses (in terms of lost labor days) compared to baseline climate, applying dose–response function between WBGT and work capacity (work–rest ratio) estimated in literature for moderate and heavy labor. Population-weighted future labor productivity estimated from the number of days with reduced labor productivity multiplied for reduction ratio expressed as percentage change of the total number of working days. The relative productivity loss was calculated as difference between future and current labor productivity by period.	Future productivity losses for moderate work of 4.8% and 15.8% by 2071–2100 under RCPs 4.5 and 8.5, respectively, compared to the baseline. Productivity losses for heavy work are 12% (RCP4.5) and 26.1% (RCP8.5) compared to the baseline. Areas with larger productivity losses are those with higher proportion of outdoor workers.

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References	Country	Heat exposure	Work sectors	Study period	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Licker et al. (94)	US	maximum heat index	outdoor workers (included agriculture, construction, and transportation) for moderate and light workload	2036–2065 and 2070–2099 (RCP4.5, +2°C and RCP 8.5, +4°C) vs. 1971–2000 (baseline)	Worktime at risk of being lost Annual earnings (Billions USD) at risk (%)	Calculation of the number of hours would be unsafe to work (in terms of lost labor days) based on dose–response function between heat index and work capacity (work–rest ratio) estimated by NIOSH for light and moderate workloads. These findings were coupled with the future annual average number of days projected to exceed heat index thresholds by occupational category and scenario and multiplied by the number of people in each occupational category (e.g., protective service) and refer to this exposure metric as "person-days" per year. Economic losses in terms of earnings at risk (assuming that workers are not paid for the hours during which it is too hot to work) calculated based on unsafe workdays, annual median earnings, and total workdays per year. Two potential adaptation options—using an adjusted work schedule that shifts work hours to cooler times of day and lightening workloads—were also assessed.	Assuming normal work schedules and moderate workloads, nationwide nearly 3 million outdoor workers already experience 7 or more unsafe workdays per year—primarily across Southwest, Southern Great Plains, Midwest, and Southeast. This number will grow by late century to 17.1 million workers (RCP4.5) and 27.7 million workers (RCP8.5). In terms of earning loss 4.7% of earnings (or a total of $49.2 billion) would be at risk under RCP4.5 and 10.2% (or a total of $107.5 billion) under RCP8.5 by the end of the century. Both adaptation scenarios are able to reduce the number of workers at risk, especially the second measure reducing workloads to light levels. By late century, universal implementation of both adaptation measures combined with emissions reductions consistent with the RCP4.5 pathway would reduce the number of workers experiencing 7 or more unsafe workdays per year to virtually none compared with 27.7 million workers who would experience such losses with the higher emissions RCP8.5 scenario and no adaptation measures implemented.

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TABLE 2 (Continued)

References	Country	Heat exposure	Work sectors	Study period	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Liu (95)	China	Wet-bulb Globe Temperature (WBGT)	outdoor workers and work intensity for light, moderate, and heavy	near future (2021–2050) and the end of the century (2071–2099) under RCP scenarios 8.5 (high emission) and 2.6 (low emission) compared to baseline (1981–2010) in July and August	Changes in labor capacity (%) Relative productivity loss in future scenarios compared to baseline.	The labor capacity is estimated in terms of lost labor days based on dose–response function between WGBT and work capacity (work–rest ratio) estimated in the literature. Projections of future labor productivity losses compared to baseline climate.	Under RCP8.5, the labor capacity of China would decrease by 5.5–5.6% and 16–17% during the 2021–2050 and 2071–2099 periods, respectively. Large decreases (more than 40%) in labor capacity of heavy work due to increased WBGT were found for many areas of China in future, particularly in northern China especially at the end of the century under RCP8.5 compared to baseline. In South and East China, labor capacity of light work would also experience a significant decrease (by 40% to 50%) under RCP8.5 compared to baseline. Under RCP2.6, the labor capacity in the 2071–2099 period would be generally similar to that during the 2021–2050 period, showing slightly less labor capacity than the baseline period. The large decreases in labor capacity generally would occur in the regions with high population densities and developed economies.
Martinich and Crimmins (96)	US	Daily maximum temperature	all work sectors for high-risk (agriculture, construction, utilities, and manufacturing) and low-risk labor sectors	RCP4.5 and RCP8.5 in 2050 and 2090 vs. 2003–2007 (baseline)	Lost Labor Hours (millions) Lost wages (USD)	Changes in productivity estimated using the dose–response functions between temperature and working time obtained by literature (91). Number of minutes individuals work from survey data. Losses calculated also due to changes in cold temperature, including extreme temperatures. Economic losses in terms of wages lost calculated by lost labor supply hours, Number of workers adjusted by ICLUSv2 projected population and wages scaled by economic growth.	Lost labor hours under RCP8.5 are 880 (500 to 1, 400) millions in 2050 and 1, 900 (1, 000 to 2, 700) millions in 2090. In economic terms, 44, 000 USD in terms of wages lost in 2050 and 160, 000 USD wages lost in 2090 under RCP8.5. Stronger losses in labor hours and economic losses in Southeast, Midwest, Southern Plains.

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TABLE 2 (Continued)

References	Country	Heat exposure	Work sectors	Study period	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Orlov et al. (97)	10 European countries	Wet-bulb Globe Temperature (WBGT)	Outdoor workers (agriculture and construction) for high (400W) and moderate (300W) intensity work	Heat waves August 2003, July 2010, and July 2015 (no climate change scenarios)	Monthly average changes in worker productivity during heat waves (%) Direct economic losses from heat-related reductions in worker productivity (USD 2015 per worker)	Changes in productivity estimated using the dose–response functions between WGBT and working time using the Hothaps exposure-response functions and the ISO standards under. Direct economic losses (or direct private costs) calculated using the sectorial average economy-wide earnings multiplied by relative reductions in worker productivity. Also social costs resulting from heat-related decreases of output were calculated by using a computable general equilibrium (CGE) model	In August of 2003, the mean value of heat-induced reductions in worker productivity in the top fifteen most adversely affected European countries accounted for approximately 3%. In the same month, the mean value of direct economic losses resulting from heat-induced reductions in worker productivity in the agricultural sector in the top ten most affected European countries accounted for approximately 83 USD per worker, whereas in July of 2010, it was 59 USD per worker, and in July of 2015, it was 90 USD per worker. Country specific estimates could be larger, e.g., in the agricultural sector of Italy in 2015 could be large than 1100 USD per worker. With respect to the construction sector, the mean value of direct economic losses in August of 2003 amounted to 61 USD per worker, in July of 2010, it was 41 USD per worker, and in July of 2015, it was 72 USD per worker
Parks and Xu (98) Gray literature	US	Daily mean temperature	Low- and high-risk sectors (farming, fishing and forestry, construction and extraction, Installation Maintenance and Repair, Transportation, and Material Moving Occupations)	1983–2016 (no climate change scenarios)	total cost of lost labor (billions USD and percent of GDP)	Changes in productivity (time lost per day per worker) estimated using the dose–response functions between temperature and working time obtained by literature (91) Number of minutes individuals work from survey data. Labor lost translated into cost by multiplying lost days per worker by the number of workers in each sector and mean wage per minute.	In high-risk sectors, total cost of lost labor from 0.3% in 1983 to 0.58% in 2016 as percentage of total GDP. The total loss of labor productivity in the farming, fishing, and forestry sector was nearly 3 billion USD in 2016. California accounted for 82.60% of the total national loss. In the construction and extraction sector, the total loss amounted up to $34 billion in 2016. Similarly, most of the loss took place in California, Texas and Arizona. Losses in 2016 were 29 billion USD in the installation maintenance and repair occupation and 41 billion USD in the Transportation and Material Moving Occupations sector.

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TABLE 2 (Continued)

References	Country	Heat exposure	Work sectors	Study period	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Rao et al. (99)	India	Steadman Heat Index	not specified	2016–2035, 2046–2065, 2080–2099 (RCP4.5 low emission, RCP8.5 high emission) vs. 1986–2005 (baseline) during summer	Decrements in summertime work performance (%)	Labor productivity losses (work hours) estimated using the dose–response functions between temperature and work performance obtained by literature in each grid cell and each region. Projections of future labor productivity losses estimated.	Our assessment showed a decline in work performance to up to 40% under the RCP8.5 and 35% under the RCP 4.5 scenario. The coastal regions of India (east and west coast) are found to be more vulnerable to heat stress impacts by showing a perceptible increase in the heat impact days and a decline of 30 to 40% in the work performance, particularly in east coast region.
Somanathan et al. (100) Gray literature	India	Wet-bulb Globe Temperature (WBGT)	manufacturing industry (weaving, Garment Manufacturing, rail production, diamond polishing, panel of manufacturing industries)	1971–2009 (no climate change scenarios)	Actual efficiency (daily worker output) Absenteeism Annual plant manufacturing output	Empirical estimate of the dose–response functions between WBGT and actual efficiency measured as the actual hourly output averaged over each day, as a measure of the combined productivity of each line of workers based on daily production output and attendance data for workers in local farms. Empirical estimate of the dose–response functions between WBGT and work absenteeism. Empirical estimate of the dose–response functions between WBGT and plant manufacturing Output (by wage share and electricity intensity)	Ambient temperatures have non-linear effects on worker productivity, with declines on hot days of 4 to 9 percent per degree rise in temperature. Sustained heat also increases absenteeism, at the rate of approximately 1 to 2 percent with every additional day of elevated temperatures. Regarding plant output, it declined by between 3 and 6% per degree above 25 °C.
Somanathan et al. (101)	India	Wet-bulb Globe Temperature (WBGT)	manufacturing industry (weaving, Garment Manufacturing, rail production, diamond polishing, Steel mill, panel of manufacturing industries)	1998–2009 (no climate change scenarios)	Change in average worker daily efficiency (%) Absenteeism Annual plant manufacturing output	Empirical estimate of the dose–response functions between WBGT and actual efficiency measured as the actual hourly output averaged over each day, as a measure of the combined productivity of each line of workers based on daily production output and attendance data for workers in local farms. Empirical estimate of the dose–response functions between WBGT and work absenteeism. Empirical estimate of the dose–response functions between WBGT and plant manufacturing Output (by wage share and electricity intensity)	The clearest effects are found for weaving workers, where an additional day above 35°C in the six preceding days causes a 2.7% decrease in contemporaneous daily output and a 0.005 increase in the probability of missing work. The impact of a 1°C increase in temperature on district output was a declines of 3% per 1°C. Declines in daily output on hotter days are seen only in sites without climate control.

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References	Country	Heat exposure	Work sectors	Study period	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Suzuki-Parker et al. (102)	Tokio and Osaka (Japan)	Wet-bulb Globe Temperature (WBGT)	Outdoor light and heavy labor work	2030s, 2050s, 2070s, and 2090s under SRES A1B vs. 2000 (baseline)	Labor hour loss Percent hour losses in climate change scenarios compared to baseline (%)	Labor productivity losses (work hours) estimated using the dose–response functions between temperature and work performance obtained by literature in each grid cell and each region. Projections of future labor productivity losses estimated.	For heavy intensity work, the estimated loss in the hours in the 2070s corresponds to a roughly 60% in Tokyo and 75% in Osaka reduction relative to the 2000s. The reduction rate of labor hours is larger in Osaka than in Tokyo possibly since Osaka there will be a larger temperature increases. The number of heavy labor restricted days (days with minimum daytime WBGT exceeding the safe level threshold for heavy labor) is projected to increase from∼5 days in the 2000s to nearly two-thirds of the days in August in the 2090s.
Szewczyk et al. (103)	Europe	Wet-bulb Globe Temperature (WBGT)	4 classes based on occupational vulnerability to heat stress: cognitive and physical work divided in light (200W), moderate (300W), and heavy (400W) labor	2020, 2050, and 2080 for RCP8.5 vs. 1990 (baseline)	Labor productivity change (%) Annual economic losses (euros or proportion of GDP)	Labor productivity losses (work hours) estimated using the dose–response functions between temperature and work performance by occupational category. The regional employment in the four occupational groups, is used to aggregate the occupational losses into a single metric representing regional labor productivity loss by period. A macroeconometric model of the European economy is then used to assess implications of change in productivity in monetary terms. In addition to the direct effect of the labor productivity shock, the model also captures the dynamic, long-term cumulative effects that operate through the capital investment processes. Economic impacts are presented as changes in annual GDP in 2013 Euros. Adaptation was also considered: diffusion of space cooling and increase in the use of robotic exoskeletons.	Productivity of labor can be 1.6% lower in the worst-case scenario (RCP8.5), with the largest reductions in southern European regions. Adaptation can reduce the productivity losses by around 40%, with higher rates of reduction for the lower warming levels. The annual economic losses in Europe could reach 563 billion euros or 1.15% of GDP by the 2080s in the worst-case scenario.

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References	Country	Heat exposure	Work sectors	Study period	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Vivid Economics (104) UK 2017 Gray literature	Ethiopia, Ghana, India, Jordan, Tanzania	Wet-bulb Globe Temperature (WBGT)	Outdoor and indoor: agriculture, manufacturing, construction, other industry, wholesale and retail trade, transport, storage and communication, and other services.	2020 to 2039 and 2040 to 2059 for RCP2.6 (low emission) and RCP8.5 (high emission) vs. 1986–2005 (baseline)	Productivity loss (%) Total employment and 'equivalent effective workers' lost due to heat stress (percent of GVA)	Labor productivity losses (work hours) estimated using the dose–response functions between WGBT and remaining productivity (%) by different work intensities from Hothaps models and safety standards. Adaptation solutions were also considered (i) a decrease in the supply of labor (total hours worked), (ii) a reduction in the effort applied per hour worked, (iii) a reduction in productivity, per hour worked, for a given level of effort.	These losses are 1–5% of productivity for a 1.5 °C temperature. In all countries except Jordan, the first and second largest absolute reductions in labor productivity loss are in the agriculture and construction sectors, respectively. In India the reduction is 20% of total workforce hours lost due to heat stress, the other countries losses are lower. Changing working hour patterns will be most effective in countries where temperatures are high during 'normal' working hours, and lower at other times. The split shift reduces productivity losses by between 0.9 and 8 percentage points, equivalent to reductions in lost productivity between 40% and 70% across all five countries.
Xia et al. (105)	Nanjing, China	Humidex	all work sectors (indoor and outdoor)	14-days heat wave 2013 (no climate change scenarios)	Industrial Reduced Productive Working Time (percentage) Economic losses (billion Yuan and proportion of the city Gross Value of Production, GVP)	Interdisciplinary approach by combining meteorological, epidemiological and economic analyses to investigate the macroeconomic impacts of heat waves on the economy. Labor productivity losses (work absences) estimated using the dose–response functions between Humidex and working time loss by different work intensities. Direct losses were inputted in the supply-driven Input-Output model to measure the total indirect economic loss incurred along the production supply chain, which is measured as the total loss in output. Economic loss estimated from monetary value of sector outputs taking into account interdependencies between sectors.	Each heat induced death results in 250 working days lost. Extreme heat also results in a 12% loss of daily working time for indoor workers in the manufacturing and service sectors during the heat wave, while it induces a daily loss of 6 h (45 min times 8 h per day) of working time for outdoor workers in the agricultural, mining, and construction sectors during the heat wave due to the occupational health safety plan. The average percentage reduction in industrial productive working time is 2.50% across all 42 industries in Nanjing in 2013 compared with full productivity and capacity without any heat effect. The greatest losses in industrial productive working time occur in the agricultural (4.50%), mining (4.22%), and construction (4.20%) sectors, where most laborers work outdoors. In economic terms, 27.49 billion Yuan due to the heat wave, 3.43% of Nanjing's GVP in 2013.

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TABLE 2 (Continued)

References	Country	Heat exposure	Work sectors	Study period	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Zhang and Shindell (106)	US	Wet-bulb Globe Temperature (WBGT); daily maximum temperature	light, medium, and heavy work	2050 and 2100 (RCP8.5 and RCP4.5) vs. 1980–2016 (baseline)	Economic losses (billions USD in 2016) from reduced labor supply due to extreme heat Economic losses as percentage of GDP (%)	Labor productivity losses (work absences) estimated using the dose–response functions between WBGT (or daily maximum temperature) and working time loss by different work intensities from literature. The calculated work loss was multiplied by the working population in each country to get the annual total labor loss due to heat and by the county-specific hourly wages for each sector.	In the baseline period, on average 421 (95% confidence interval (CI): 70–561) million hours of work were lost annually due to extreme heat across the USA (1.2% of total billion work hours). The average market cost was 14 (2.3–18.7) billion USD. Under the RCP8.5 scenario, 1.5 (0.3–2.1) billion US workforce hours per year will be lost by the end of this century. The market cost associated reach $50 (8.3–66.7) billion per year, more than triple the losses with current climate conditions. The costs increase to 0.18% and 0.30% of the total GDP by the 2050s and the end of the century without accounting for any changes in GDP itself over time. Impacts greater in Southern states.
Zhao et al. (107)	China	High-temperature days: daily maximum temperature exceeding the temperature threshold for high-temperature subsidies to workers (indoor and outdoor)	all work sectors (indoor and outdoor)	2030, 2040, 2090 (RCP2.6, RCP4.5, RCP 8.5) vs. 1979–2005 (baseline)	Labor losses (billions Yuan) Losses as percentage of GDP (%)	High-temperature subsidies (HTSs) are estimated based on the formal employee to total population ratio, the daily subsidy at the jth class in yuan per person per day, the frequency of HTDs at the jth class and ith grid point in days per year. The daily HTS are then summed up per year over grid points. The HTS values in yuan per employee per year are calculated from annual HTS per grid cell, divided by the national total number of formal employees.	On average, the total HTS in China is estimated at 38.6 billion yuan/y (6.22 billion USD per year) over the 1979–2005 period, which is equivalent to 0.2% of the gross domestic product (GDP). Assuming that the HTS standards (per employee per hot day) remain unchanged throughout the 21st century, the total HTS may reach 250 billion yuan/y in the 2030s and 1, 000 billion yuan/y in 2100. Without specific adaptation, the increased HTS cost is mainly determined by population growth until the 2030s and climate change increase in hot weather.

(Continued)

TABLE 2 (Continued)

References	Country	Heat exposure	Work sectors	Study period	Productivity or cost calculation (unit measure)	Heat-related economic loss analysis	Results
Zivin and Neidell (91)	US	daily mean temperature	Outdoor and indoor high- and low-risk sectors. High-risk industries: agriculture, forestry, fishing, and hunting, mining, construction, manufacturing, and transportation and utilities industries; Low risk: remaining industries	2003–2006 (no climate change scenario evaluated)	Time allocated to labor market activities or leisure activities (min)	Econometric model of percent of time allocated to labor market activities and percent of time allocated to outdoor/indoor leisure activities as a function of temperature. Adaptation contribution (e.g., shifting activities across days) was also evaluated for outdoor work.	In high-risk industries, for labor supply, there is little response to temperatures below 80 degrees, but monotonic declines in labor supply above 85 degrees. At temperatures over 100 degrees, labor supply drops by a statistically significant 59 min as compared to 76–80 degrees. At high temperatures, workers appear to substitute their labor supply for indoor leisure, with surprisingly no decline in outdoor leisure. For low-risk industries while there is a decrease in labor supply at temperatures above 95 degrees, this effect is modest and not statistically significant. Little or no role for adaptation measure (intertemporal substitution in the workplace) to mitigate the decrease in labor supply in high-risk industries.

PPP, GDP per capita, purchasing power parity (PPP) per capita.; CGE, computable general equilibrium model; USD, US dollars; RCP, Representative Pathway Concentration Scenarios.; SSP, Shared Socioeconomic Pathways Scenarios.; BaU, Business-as-Usual Scenario.; SRES, IPCC Special Report Emission Scenarios.; GDP, gross domestic product.; GVP, gross value of production.; GVA, gross value added.; GRP, gross regional product.

78, 91, 97, 98, 100, 101, 105). Studies based on economic models have used different approaches to estimate the economic costs associated with heat-associated reductions in worker productivity. The majority of studies starts from the working time losses estimated based on occupational health and safety standards at different work intensities and sectors. Most included studies estimated productivity as a function of the ISO 7243 standard on the risk associated with thermal stress, by considering exceeding a threshold of the Wet Bulb Globe Temperature indicator (WBGT) at the workplace or on the basis of the standard of indoor thermal comfort, the Predicted Mean Vote Index, and associating climate data with economic data or on the basis of previous studies (e.g., Hothaps models) (65, 67, 69, 91, 108). Worktime losses per day/worker are then rescaled to the entire worker population and expressed in terms of percent productivity loss, converted into monetary terms (e.g., by multiplying for average wages) or as portion of gross domestic product (GDP) considering the share to which each labor sector contributes to GDP. For studies on climate change scenarios, the incremental change relative to baseline is estimated compared to future scenarios usually at the middle (2050) and the end of the century (2100) comparing low and high emissions scenarios. With regards of studies focusing on farm production output, some of them applied structural economic models based on the so-called computable general equilibrium (CGE) model or general equilibrium models that allowed to consider the relationships and influence between economic sectors (70, 73, 74, 87, 97, 105). General equilibrium models are a class of economic models that use actual economic data to estimate how an economy might react to changes in policy, technology, or other external factors (109). Other studies quantified production output using empirical or literature data (66, 72, 100, 101). Some studies included in the economic modeling also an adaptation measure such as air conditioning for indoor work, or shifting work hours or lightening workloads (83, 84, 91, 94, 103, 104).

3.3.1. Global studies

Studies evaluating global economic impacts of current and future occupational heat ($n = 21$) were both scientific publications (59, 60, 63–65, 67–70, 72, 74–80) and gray literature (16, 61, 62, 66), providing evidence of heat-related reductions in work productivity at the global level. Productivity losses associated with climate change by 2100 under the worst-case scenario (high emissions) range from nearly 10% (68) to 30–40% (15, 65, 67, 97) at the global level. GDP losses for the same period and scenario varied between 1.8% compared to baseline (75) to 23% (59). In specific sectors such as agriculture, the loss of productivity expressed as a percentage reduction in GDP is even >30–50% (64, 74). Global studies provided also estimates for the different world regions, by highlighting higher impacts from both current and future climates in low- and middle-income countries (60–62, 67, 68, 78), like sub-Saharan Africa (63, 64, 80), very hot countries (59, 66), and high-intensity work in low-latitude countries (75).

3.3.2. Regional studies

Regional studies ($n = 28$) were also considered both from peer-reviewed journals (73, 81, 82, 87–89, 91, 93–97, 99, 101–103, 105–107) and the gray literature (83–86, 90, 92, 98, 100, 104) confirming a heterogeneous impact of heat on work productivity not only among countries but also within the same country (82, 95, 99, 102). As seen in the global studies, low-latitude, high-intensity labor settings were the most affected such as West Africa, Southeast Asia, and Central and South America. Moreover, specific local studies suggest an impact also in other regions such as southern European countries (92, 97, 103), some parts of the US (especially agricultural areas in Southeast and Southwest) (94, 96, 106), and Australia (86). For example, under medium-high emission scenario by the end of the century, a 0.4–0.9% loss in productive days was shown for Southern Europe (92), 10.2% of wages lost were estimated in the US (94), and a 16–17% labor capacity loss was predicted in China (95). Agriculture was the sector most affected by heat stress, both considering the current climate and future scenarios and among non-agricultural sectors, construction, manufacturing, transportation, service, and mining (73, 83, 86, 98, 104, 105). Agriculture (97) and manufacturing sector are also expected to be impacted in terms of farm production output losses (100, 101).

The evaluation of adaptation measures was marginally evaluated: Air conditioning was effective in reducing labor productivity losses in indoor settings in two European studies (84, 103), with one study suggesting also a potential role for technological measures such as robotic exoskeletons (103), while measures affecting the work/rest schedule have been shown to reduce productivity loss in outdoor workers in one study in Ethiopia, Ghana, India, Jordan, and Tanzania (104) and in one US study (94) while another US study provided uncertain results (91).

4. Discussion

This literature review provides an updated summary of the evidence on socioeconomic impacts of occupational heat exposure and confirms the results of previous reviews (7, 11, 12, 14–16) and of the latest IPCC report (8). The review also provides further evidence on the association between indoor and outdoor heat exposure and socioeconomic impacts in terms of productivity loss or costs. Throughout the different study types, a coherent picture of the social and economic impacts of heat exposure in the workplace emerges, highlighting the main pathways for heat-related productivity losses. One pathway is in common with the general population and is related to the increased risk of acute heat-related illnesses and deaths (1) and the emergence of chronic illnesses consequences such as renal impairment (5, 6). Underlying biological mechanisms include thermoregulatory failure with cardiovascular fatigue and respiratory distress, dehydration with progressive kidney dysfunction in case of sustained chronic exposure. Another pathway is related to changes in vigilance and cognitive performance that may enhance the risk of distraction, impairment in risk perception, and reaction time leading to improper operation and injury (3). The third pathway directly related to work productivity and physical performance reductions and to the physiological need to rest during heat exposure, leading to a reduction in work hours and work output (16). All these pathways are strongly interconnected, and it is difficult to identify which plays a major role in productivity loss.

The most robust evidence in the present review derives from time-series or case-crossover studies (53, 54, 58). Such methods are the "gold-standard" study design to evaluate the short-term effects of environmental exposures at the population level while controlling for time-varying confounders. Field studies represent an important piece of evidence about heat-related productivity loss, but they have the limitation of providing evidence on a small sample and related to given setting at a specific time interval (110) and only a limited number of studies adjust for potential confounders (22, 39, 40, 47). Studies are consistent in reporting labor productivity loss perceived by the workers (19, 20, 23, 29, 32–35, 43, 45, 46, 48, 49) and have negative impacts in terms of physical performance (42) and work output (21, 25).

The largest body of evidence from the present review comes from economic modeling studies. These are mostly global or regional studies which apply modeled spatially resolved temperature data for the current or future climate change scenarios to risk functions from physiological studies (65, 71, 89, 91, 108) to obtain an estimation of loss in working hours which is then converted to economic costs *via* workers' wages or as portion of gross domestic product (GDP). Studies combining economic and climate modeling have the added value of providing current and future impact estimates which are useful for the definition of adaptation and mitigation actions. However, these models are dependent on the scenarios selected and assumptions made; thus, it is important that the uncertainty is adequately reported (71). More complex economic models, i.e., the general equilibrium models (109), are able to account for the interdependencies among sectors but also have a number of methodological challenges in particular in accounting for societal welfare changes (different by GDP), non-linear damages, and micro- and macro-adaptation processes (8). Although methodological differences limit comparability, actual productivity losses at the global level are nearly 10% (62, 65) and under the worst-case scenario (high emissions) by 2100 are expected to increase up to 30–40% (62, 65, 67, 75). GDP losses for the same period and scenario varied between 1.8% compared to baseline (75) and 23% (59). Scenarios suggest that in regions like sub-Saharan Africa, India, Southeast Asia, and South America, productivity losses may be even greater as they will experience significant warming and a high share of the economy entails labor-intensive occupations (59–64, 66–68, 75, 78, 80), experiencing over a 10 times increase in work hours lost under the worst emission scenario (62). Some studies also report substantial reductions in work capacity in the United States, Europe, and Australia (86, 92, 94, 96, 97, 103, 106).

Vulnerability factors increasing the risk of heat-related productivity loss may differ according to the underlying causal pathway, with potential differences among factors increasing vulnerability for heat-related diseases, heat-related injuries, and heat-related productivity loss. However, the link with socioeconomic impacts is less clear. Individual factors such as age (53, 56), gender (31, 37, 45, 49), race (52), education level (37, 53), immigration status (34), and comorbidities such as kidney failure or other conditions (21, 22) have been related to higher reduction in work productivity in some studies, but the evidence is limited. The work environment may also affect worker susceptibility to productivity losses related to heat, as consistently shown in the literature. Some occupational sectors, primarily agriculture and construction, appear more affected than others, suggesting a higher impact on productivity loss due to more intense physical activities. The agricultural sector alone accounts for two-thirds of all labor hours lost globally in 2021 at the global level (78). Other sectors or workers affected include transportation and utilities (83, 98), miners (37, 58, 83, 86, 105), and indoor workers with no air conditioning (19, 100, 101). Furthermore, performing heavy tasks (45, 48, 68, 70, 75, 89, 93), direct sunlight exposure (36, 63, 89), and use of personal protective equipment (PPE) (23, 29, 35) have been associated with productivity loss. In some cases, the work sector and task may be a multiplier of existing individual vulnerabilities, as in the case of migrant agricultural workers (34) or young manual workers (51).

Awareness of heat-related risks, health and safety actions and training, as well as workers behaviors play a key role productivity loss due to heat among workers (37). The heterogeneous perception of heat-related occupational risks and causes of productivity loss (35, 37, 45, 46) suggests that more efforts are needed to enhance risk perception and heat-protective behaviors. Work management policies need to have a holistic approach by addressing all potential pathways linking heat exposure to workers' health, safety, and productivity (37). Specific information tools aimed to increase adaptive capacity and protective behavior especially in the most vulnerable workers can reduce impacts on productivity, as suggested by the work carried out in Italy within the Worklimate project (https://www.worklimate.it/en/home-english/).

Some strengths and limitations are worth mentioning: the quality of studies was not formally evaluated, and the search was restricted to only two bibliographic databases (PubMed and Web of Science) and only to English language studies that may have restricted the geographical coverage of some areas of the world such as Central and South America and Africa. To partially counterbalance this, the inclusion of a significant number of studies (14 out of 89) from the gray literature (from academia, NGOs, or economic or policy organizations) (16, 46, 61, 62, 66, 83–86, 90, 92, 98, 100, 104) retrieved from reviews in the field (7, 11, 12, 14–16) ensures to include a greater number of studies from low- and middle-income countries where the issue is particularly relevant. Moreover, the scoping review was limited to studied published since 2010, but this was also the publication horizon from previous reviews (11, 12, 14).

Due to the heterogeneity of studies in terms of methodologies used, heat exposure indicators, and economic cost measures, a quantitative synthesis was not possible. However, the present literature review provides a clear and consistent indication of the effects of heat on productivity and costs for employers and employees, economic sectors, social security systems, and national economies. The impacts are coherent across a range of study designs and study areas although we cannot exclude that some relevant papers are missing, the possibility that publication bias could distort these results is low thanks to the inclusion of a relevant piece of gray literature as specified above. This large body of evidence can support decision-making process in terms of improving and protecting worker safety, health, and wellbeing following the Total Worker Health approach (111) also in the context of climate change resilience and response by involving all relevant stakeholders both at the policy level and at the workplace level (i.e., nurses or other healthcare practitioners and workers' compensation professionals) (112). A number of initiatives in this field have been taken, but more efforts are needed in terms of prevention, employer and employee information, and training to raise awareness and increase resilience and behavioral adaptation. The evidence suggests that the expected impacts of climate change may be even greater and that investing resources in prevention actions in occupational settings has both social and economic benefits. Despite the consistent evidence on productivity impacts, some knowledge gaps emerge. Future research needs to address them such as the role of individual and work-related factors in increasing worker's vulnerability to productivity losses, and the evaluation of adaptation measures such as work schedule adjustments and work-level reductions only little evaluated in terms of productivity improvements (91, 94, 104).

5. Conclusion

In conclusion, much knowledge has been accumulated about heat-related reduction in work capacity in recent years. There is an urgent need for holistic work management policies such as the Total Worker Health approach and for climate change adaptation and mitigation efforts to protect workers' health from future warming and climate extremes, especially in most vulnerable agriculture, manufacturing, and construction sectors and in very hot countries with high-intensity work.

Author contributions

MDS: literature review, conceptualization, and paper writing. Fd'D: literature review, conceptualization, design, supervision, interpretation, and paper writing. MB, ML, and MM: interpretation and paper writing. AM and FA: paper writing. PM: conceptualization, supervision, and interpretation. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2023.1173553/full#supplementary-material

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Article

Development of a Prototype Observatory of Heat-Related Occupational Illnesses and Injuries through the Collection of Information from the Italian Press, as Part of the WORKLIMATE Project

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Abstract: Exposure to heat is a recognized occupational risk factor. Deaths and accidents at work caused by high temperatures are underestimated. With the aim of detecting and monitoring heat-related illnesses and injuries, a prototype database of occupational events attributable to critical thermal conditions reported in Italian newspapers was created. Information was analyzed from national and local online newspapers using a web application. The analysis was conducted from May to September during the three-year period 2020–2022. Articles concerning 35 occupational heat-related illnesses and injuries were selected; 57.1% of the events were reported in 2022, and 31.4% of total accidents occurred in the month of July 2022, when the Universal Thermal Climate Index daily mean values corresponded to "moderate heat stress" (51.0%) and "strong heat stress" (49.0%). Fatal heat-related illnesses were the most frequent conditions described. In most cases, workers had been involved in outdoor activities in the construction sector. A comprehensive report was created by compiling all relevant newspaper articles to enhance awareness of this issue among relevant stakeholders and promote heat-risk prevention strategies in the current context where heatwaves are becoming increasingly frequent, intense and long-lasting.

Keywords: heat-related illness; heat stress; news; occupational injuries; press; workers' health; workplace

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1. Introduction

Climate change is the primary cause of the increased frequency of extreme weather conditions such as heatwaves, floods and wildfires [1]. Events such as heatwaves play an important role in population health, and studies confirm a general increase in heat-related mortality [2–5]. Indeed, a reduced capacity to respond and adapt to extreme heat increases the risk of organ damage due to exceeding physiological thermoregulatory capacity [6]. Exposure to excessive heat is also a well-known occupational hazard. Workers under heat stress conditions appear to be four times more likely to experience heat strain compared to individuals working in an environment with neutral temperatures [7]. Heat-related occupational health risks are exacerbated during activities carried out in sunny outdoor environments and in indoor workplaces when lack of ventilation, a poor cooling system or processes that generate heat do not allow proper regulation of temperatures [8]. Workers in agricultural and construction sectors are among those most exposed, with clear evidence also at the Italian level [9–11], especially those with jobs requiring high levels of physical exertion, the use of personal protective equipment and/or heavy clothes that prevent heat loss [12]. Negative health effects arising on account of dehydration and overheating, such as sweating, dizziness, poor sleep quality, and physical and mental exhaustion, with impairment of reasoning and increased reaction times, may increase the risk of injury [13]. Moreover, short-term heat-related illnesses, such as heat cramps, heat exhaustion and heat stroke may also arise [14]. If not adequately and promptly treated, heat stroke is a fatal condition. Some workers have a greater susceptibility to heat-related illness; factors such as pre-existing heart and respiratory diseases, taking certain medications (hypotensive drugs, diuretics, sedatives, etc.) [15], or being pregnant or disabled increase the risk associated with exposure to high temperatures [16].

Heat exposure makes workers a vulnerable population; depending on the work situation, they often lack the authority to control their exposure time, find a shaded area [17], arrange for refreshing breaks, and maintain constant access to water. Additionally, in cases of undeclared work, they are often not covered by employment injury insurance. Such occupational conditions make certain categories of workers more subject to the negative effects of heat exposure in the workplace and contribute to heat-related productivity losses [18]. Occupational exposure to extreme temperatures exacerbates social inequalities, especially in relation to conditions such as low income, ethnic status, low literacy and education. Workers employed in precarious, strenuous, risky, low-tech, and unskilled jobs, such as migrant workers, may suffer greater job insecurity, which is associated with increased heat-related morbidity and mortality [16,19].

As part of the WORKLIMATE Project ("Impact of environmental thermal stress on workers' health and productivity: intervention strategies and development of an integrated heat and epidemiological warning system for various occupational sectors") [20], a study was conducted during the warmer months of 2020–2022 to assess the effectiveness of using online newspapers as a tool for promptly detecting and monitoring heat-related illnesses and injuries in the workplace in Italy, as well as for fostering interventions to protect the health of workers exposed to heat.

2. Materials and Methods

News articles regarding the effects of extreme thermal conditions on workers' health published in the Italian daily press during the warm months (May to September) in the three-year period 2020–2022 were quantitatively and qualitatively assessed. The search for articles was set up using a web application accessible via web browser (VALIRIA, developed by the Joint Laboratory of Technological Solutions for Clinical Pharmacology, Pharmacovigilance and Bioinformatics of the University of Florence), that allows the configuration and execution of customized queries to be launched on the Google search engine. The search strategy performed was the following: [*("climate change" OR "killer heat" OR "scorching heat" OR temperature* OR "global warming" OR sultriness OR hot OR drought) AND (work OR worker* OR "construction site" OR "day laborer" OR farmer OR company OR tractor OR farming OR garden) AND ("heat stroke" OR accident OR injury OR "sudden illness" OR dead OR die OR fall)]*. A daily report of search results was automatically sent by email to two researchers (G.I. and M.L.). The search was conducted in both national and local online newspapers, chosen because of their large readership as assessed by ADS, the association that publishes data on the circulation of the daily and periodical press in Italy [21]. According to October 2022 data from Audipress, the official reference survey of readership of the daily and periodical press in Italy, 21.8% of Italians, corresponding to more than 11 million readers, read one of the main newspapers on paper or digital every day. The steady growth in the reading of digital editions was also confirmed, with an estimated audience of 6.5 million readers [22]. Articles were included if they focused on heat-related illnesses and injuries among workers due directly to high temperature exposure. In addition, a manual search was conducted every two weeks to verify that all relevant news had been captured by the web application. Articles with no mention of extreme hot conditions or work environment were excluded.

The events were classified as "injuries" in the case of traumatic events, or as heat-related illnesses, based on the description provided in the article. For each article, whenever available, information about sex, age, nationality, Italian region in which the accident occurred, labour sector in which the worker was employed, activity performed immediately before the event and severity (fatal versus non-fatal) of heat-related illnesses/injuries was collected. The occupational sector of each worker was classified according to the ATECO classification of economic activities adopted by the Italian National Institute of Statistics-Istat [23]. Descriptive statistical analyses were performed using frequency measures and contingency tables.

Data on air temperature (°C), relative humidity (%), wind speed (m s^{-1}) and solar global radiation (W m^{-2}) on the relevant days were collected from meteorological stations located near the municipality where the heat-related events (illnesses or injuries) were reported by the Italian daily press. Hourly meteorological data were gathered from "Weather Underground" [24] and were used to calculate a thermal comfort index, the Universal Thermal Climate Index (UTCI) (by using the UTCI software code "version a 0.002", freely available online, http://www.utci.org/), currently considered the state of the art for outdoor biometeorological indices [25]. UTCI is an equivalent temperature (°C) referring to a person generating 135 W m^{-2} (therefore a value on the border between a low and moderate metabolic rate) based on the most recent scientific progress in human thermophysiology, biophysics, and heat exchange theory [26]. UTCI categorizes thermal stress in ten classes (from extreme cold to extreme heat stress conditions) relating to heat stress, starting from a situation of "no thermal stress" (9 °C < UTCI $\leq$ 26 °C), through "moderate heat stress" (26 °C < UTCI $\leq$ 32 °C), "strong heat stress" (32 °C < UTCI $\leq$ 38 °C), "very strong heat stress" (38 °C < UTCI $\leq$ 46 °C) and "extreme heat stress" (UTCI > 46 °C). For the days in which heat-related events occurred, the daily average and maximum UTCI values and the respective categories are shown.

3. Results

On average, the web application mail report showed five to thirty daily articles, with peaks detected during heatwaves. The final report containing selected articles was published on the WORKLIMATE project homepage (https://www.worklimate.it/ (accessed on 7 February 2023)) for free access [27,28].

Cases that appeared in newspapers from May 2020 to September 2022 were selected. If reported in multiple articles, the event was counted only once. All links to articles in which the incident was mentioned were reported in the final reports. According to web-based press and inclusion criteria, 35 workers suffered from health outcomes related to occupational heat stress in Italy in the three-year period considered. The days on which the selected events occurred were characterized in 51.0% of cases by daily mean UTCI values corresponding to "moderate heat stress" (daily mean UTCI of 29.6 °C ± 1.5 °C) and in the remaining 49.0% on days with daily mean UTCI values corresponding to "strong heat stress" (daily mean UTCI of 33.7 °C ± 1.1 °C). Furthermore, the maximum daily UTCI values were predominantly (80.0% of days) values corresponding to the "very strong heat stress" class (the average daily maximum UTCI value was 42.7 °C ± 1.9 °C) and on 14.0% of days the daily maximum UTCI values were in the "extreme heat stress" class (the average daily maximum UTCI value was 48.7 °C ± 0.9 °C) (Table 1).

Table 1. Summary table of heat-related illnesses and injuries in the workplace reported in the Italian national press. Details of published data—years 2020–2022. (All website accessed on 7 February 2023).

	Year, Month	Age (Years)	Sex	Nationality	Occupational Sector, Activity	Region (Municipality)	Event (Illness or injury) and Severity	Link to Online Newspaper	Daily Average Heat Stress Category and UTCI (°C)	Daily Maximum Heat Stress Category and UTCI (°C)
1	2020, July	55	Male	Italian	Agriculture and forestry, gardener	Lazio (Latina)	Illness, fatal	http://bit.ly/3ERtz05	Moderate 29.4	Very strong 41.5
2	2020, July	53	Male	Polish	Construction activities, worker engaged in canal reclamation	Emilia-Romagna (Bologna)	Illness, fatal	http://bit.ly/3B2RWqG	Strong 35.2	Extreme 49.6
3	2020, July	36	Male	Romanian	Construction activities, fiber optic placement	Friuli-Venezia Giulia (Pasiano)	Illness, fatal	http://bit.ly/3B1epUO	Moderate 27.9	Very strong 40.7
4	2020, August	-	Female	Italian	Public administration, municipality employee	Tuscany (Viareggio)	Illness, non-fatal	http://bit.ly/3ulSiEQ	Strong 32.4	Very strong 41.5
5	2021, June	-	Male	-	Construction activities, worker on construction site	Apulia (Taranto)	Illness, non-fatal	http://bit.ly/3B0Vs4P	Strong 32.3	Very strong 42.6
6	2021, June	-	Male	-	Construction activities, worker on construction site	Apulia (Taranto)	Illness, non-fatal	http://bit.ly/3B0Vs4P	Strong 32.9	Very strong 44.3
7	2021, June	-	Male	-	Construction activities, worker on construction site	Apulia (Taranto)	Illness, non-fatal	http://bit.ly/3B0Vs4P	Strong 32.9	Very strong 44.0

Table 1. *Cont.*

	Year, Month	Age (Years)	Sex	Nationality	Occupational Sector, Activity	Region (Municipality)	Event (Illness or injury) and Severity	Link to Online Newspaper	Daily Average Heat Stress Category and UTCI (°C)	Daily Maximum Heat Stress Category and UTCI (°C)
8	2021, June	-	Male	-	Construction activities, worker on construction site	Apulia (Taranto)	Illness with onset of coma, non-fatal	http://bit.ly/3B0Vs4P	Strong 33.5	Very strong 44.0
9	2021, June	38	Male	Italian	Transport and storage, tanker truck driver	Apulia (Brindisi)	Illness, fatal	http://bit.ly/3UDMNMR	Moderate 31.9	Extreme 47.4
10	2021, June	27	Male	Mali	Agriculture and forestry, day labourer	Brindisi (Apulia)	Illness, fatal	http://bit.ly/3VFtmUC	Strong 34.6	Extreme 48.3
11	2021, June	35	Male	Italian	Other service activities, leafleting	Apulia (Galatina)	Illness, fatal	http://bit.ly/3it03pY	Moderate 30.6	Very strong 42.1
12	2021, June	-	-	-	Agriculture and forestry, harvesting of agricultural products	Veneto (Province of Verona)	Illness, fatal	http://bit.ly/3VIqpCN	Moderate 29.6	Very strong 41.5
13	2021, June	-	-	-	Agriculture and forestry, harvesting of agricultural products	Veneto (Province of Verona)	Illness, non-fatal	http://bit.ly/3VIqpCN	Moderate 29.8	Very strong 41.7
14	2021, July	42	Male	Italian	Construction activities, working on a scaffold	Sicily (Palermo)	Injury (Fall), fatal	http://bit.ly/3ueoU3B	Moderate 31.6	Very strong 42.2
15	2021, August	62	Male	Italian	Agriculture and forestry, forestry worker	Apulia (Bitonto)	Illness, fatal	http://bit.ly/3ugMWLb	Strong 36.1	Extreme 49.6

Table 1. *Cont.*

	Year, Month	Age (Years)	Sex	Nationality	Occupational Sector, Activity	Region (Municipality)	Event (Illness or injury) and Severity	Link to Online Newspaper	Daily Average Heat Stress Category and UTCI (°C)	Daily Maximum Heat Stress Category and UTCI (°C)
16	2022, May	-	Male	-	Construction activities, working on a scaffold	Umbria (Terni)	Illness, non-fatal	http://bit.ly/3W5Zh0Y	Moderate 26.1	Very strong 43.4
17	2022, June	47	Female	Italian	Water supply; sewerage, waste management and sanitation activities, ecological worker	Tuscany (Prato)	Illness, fatal	http://bit.ly/3Vr97KK	Moderate 31.2	Very strong 46.1
18	2022, June	65	Male	Italian	Construction activities	Lombardy (Jerago con Orago)	Injury (Fall), non-fatal	http://bit.ly/3hx5mVo	Moderate 30.1	Very strong 43.0
19	2022, June	-	Female	Italian	Public administration, judge	Lombardy (Bergamo)	Illness, non-fatal	http://bit.ly/3v2wgY5	Strong 32.2	Very strong 45.3
20	2022, June	49	Male	Italian	-	Campania (Casagiove)	Illness, fatal	http://bit.ly/3HCP33X	Strong 33.3	Very strong 44.2
21	2022, June	45	Male	-	Manufacturing activities	Emilia-Romagna (Castelvetro di Modena)	Illness, non-fatal	http://bit.ly/3VHTldZ	Moderate 28.2	Very strong 39.2
22	2022, July	59	Male	Italian	Agriculture and forestry, day labourer	Calabria (Rossano)	Illness, fatal	http://bit.ly/3uTATUz	Strong 34.1	Very strong 43.9
23	2022, July	-	Male	-	Public administration, municipal employee	Campania (Battipaglia)	Illness, non-fatal	http://bit.ly/3WFUZxx	Moderate 29.5	Strong 37.0

Table 1. *Cont.*

	Year, Month	Age (Years)	Sex	Nationality	Occupational Sector, Activity	Region (Municipality)	Event (Illness or injury) and Severity	Link to Online Newspaper	Daily Average Heat Stress Category and UTCI (°C)	Daily Maximum Heat Stress Category and UTCI (°C)
24	2022, July	-	Female	French	Other service activities, model for fashion shows	Sicily (Siracusa)	Illness, non-fatal	http://bit.ly/3VoR481	Moderate 30.4	Very strong 40.8
25	2022, July	20	Male	Albanian	Agriculture and forestry, day labourer in a greenhouse	Campania (Falciano del Massico)	Illness, fatal	https://bit.ly/3XSDknp	Moderate 27.9	Very strong 40.5
26	2022, July	54	Male	Romanian	Construction activities, electrician working on a roof	Liguria (La Spezia)	Illness, fatal	http://bit.ly/3GZVNsn	Strong 33.6	Very strong 43.2
27	2022, July	61	Male	Italian	Manufacturing activities	Piedmont (Rivoli)	Illness followed by head injury, fatal	http://bit.ly/3BI5R5T	Moderate 31.0	Very strong 42.6
28	2022, July	-	Male	-	Manufacturing activities	Trentino—Alto Adige (Arco)	Illness followed by head injury, fatal	http://bit.ly/3Up1fI8	Strong 35.0	Very strong 43.8
29	2022, July	47	Male	Moroccan	Accommodation and food service activities, dishwasher	Liguria (Diano Marina)	Illness, fatal	http://bit.ly/3V3g83e	Strong 33.5	Very strong 44.6
30	2022, July	-	Male	-	Transport and storage, bicycle rider	Lombardy (Milan)	Illness, non-fatal	http://bit.ly/3FibcTp	Strong 33.2	Very strong 45.5

Table 1. *Cont.*

	Year, Month	**Age (Years)**	**Sex**	**Nationality**	**Occupational Sector, Activity**	**Region (Municipality)**	**Event (Illness or injury) and Severity**	**Link to Online Newspaper**	**Daily Average Heat Stress Category and UTCI (°C)**	**Daily Maximum Heat Stress Category and UTCI (°C)**
31	2022, July	67	Male	-	Construction activities, worker on a roof	Emilia-Romagna (San Donnino)	Illness, fatal	http://bit.ly/3gLhvFW	Strong 32.9	Very strong 44.3
32	2022, July	-	Male	African origin	Agriculture and forestry, day labourer in a greenhouse	Campania (Parete)	Illness, fatal	http://bit.ly/3XSDknp	Strong 34.7	Extreme 48.4
33	2022, August	50	Male	-	Manufacturing activities, worker in a shed	The Marche (Ancona)	Illness, non-fatal	http://bit.ly/3uX2Hre	Moderate 29.2	Strong 38.0
34	2022, August	30	Male	-	Manufacturing activities, shipyard worker	The Marche (Ancona)	Illness, non-fatal	http://bit.ly/3uX2Hre	Moderate 29.6	Very strong 38.3
35	2022, August	-	Male	-	Other service activities, airport baggage loading/unloading attendant	Veneto (Venezia)	Injury (ankle fracture), non-fatal	http://bit.ly/3gROBUp	Moderate 28.9	Very strong 40.9

UTCI: Universal Thermal Climate Index.

Heat-related illnesses were the most reported (*n* = 32; 91.4% of all reported events), with only three being injuries (Table 2). There were 19 fatal events, corresponding to 54.3% of all heat-related events. Among the fatal events, all except one were caused by heat-related illnesses, the remaining death being ascribed to a fall. Both the daily mean (32.1 °C) and maximum (44.3 °C) UTCI values on days with fatal events were on average higher by 1.4 °C and 2.5 °C respectively than the mean and maximum UTCI values on days with non-fatal events (30.8 °C and 41.8 °C for mean and maximum daily UTCI values, respectively). Furthermore, all the events that occurred on days when the maximum daily value of UTCI reached "extreme" heat stress levels (UTCI > 46 °C) resulted in fatalities.

Table 2. Severity of heat-related illnesses and injuries as reported by Italian online newspapers in the years 2020 to 2022.

	Fatal		**Non-Fatal**		**Total**	
	N	**%**	**N**	**%**	**N**	**%**
Heat-related Illnesses	18	51.4%	14	40.0%	32	91.4%
Injuries	1	2.9%	2	5.7%	3	8.6%
Total	19	54.3%	16	45.7%	35	100.0%

In 26 cases (74.3% of all reported cases) the activities were carried out outdoors and in nine cases the laborers were working in indoor environments, mainly sheds. For one event, neither the activity nor the occupational sector in which the victim was involved were indicated.

In terms of the distribution of events over time, four heat-related illnesses/injuries were reported in 2020, corresponding to 11.4% of the events that occurred in the three-year period considered (Figure 1). In 2021, 11 cases were reported (31.4% of the events that occurred in the three-year period 2020–2022); of these, almost all (*n* = 9; 81.8%) occurred during a heatwave in June. Finally, 20 events (57.1% of the events that occurred in the three-year period) were reported in 2022, particularly during heatwaves in July, when 11 events were reported (55.0% of events occurred in 2022 and 31.4% of events occurred in 2020–2022).

Only one event was reported in May 2022 and no events were reported in the month of September during the three-year period.

Of the 35 workers involved, 31 (88.6%) were men and only 4 (11.4%) were women. Regarding nationality, 12 (34.3%) were Italian, 8 (22.9%) were of foreign nationality and for 15 workers (42.9%) their nationality was not mentioned in the news.

Almost half (40.0%) of the events involved middle-aged workers (30–59 years) (Table 3). Only two workers (5.7%), both of them foreigners, were younger than 30. No worker was older than 70. The ages of 12 men and 3 women (corresponding to 42.9% of all workers) were unknown.

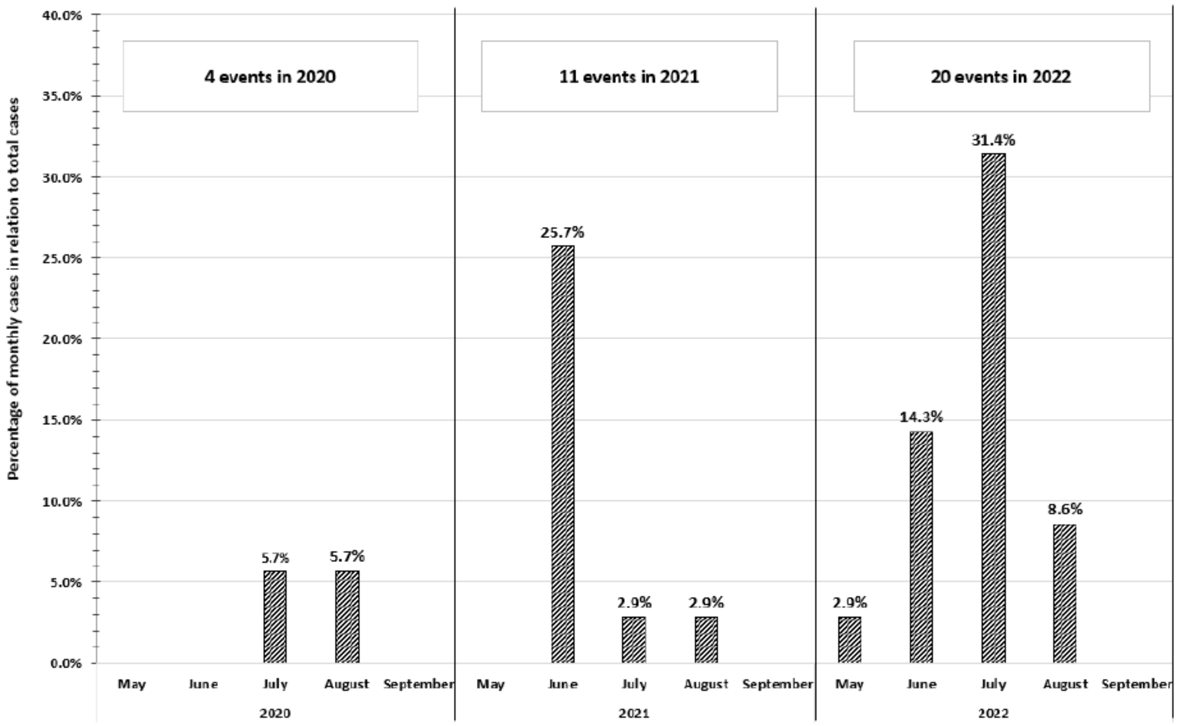

Figure 1. Distribution of events reported by Italian online newspapers in the years 2020 to 2022, by month and year of publication.

Table 3. Demographic characteristics (gender, age and nationality) as reported by Italian online newspapers in the years 2020 to 2022, by age group.

Age Groups	**Nationality**						**Gender**				**Total**	
	Italian		**Foreigner**		**Unknown**		**Male**		**Female**			
	N	**%**	**N**	**%**	**N**	**%**	**N**	**%**	**N**	**%**	**N**	**%**
<30 years	0	0.0%	2	5.7%	0	0.0%	2	5.7%	0	0.0%	2	5.7%
30–39 years	2	5.7%	1	2.9%	1	2.9%	4	11.4%	0	0.0%	4	11.4%
40–49 years	3	8.6%	1	2.9%	1	2.9%	4	11.4%	1	2.9%	5	14.3%
50–59 years	2	5.7%	2	5.7%	1	2.9%	5	14.3%	0	0.0%	5	14.3%
60–69 years	3	8.6%	0	0.0%	1	2.9%	4	11.4%	0	0.0%	4	11.4%
Unknown	2	5.7%	2	5.7%	11	31.4%	12	34.3%	3	8.6%	15	42.9%
Total	12	34.3%	8	22.9%	15	42.9%	31	88.6%	4	11.4%	35	100.0%

Events occurred throughout Italy, except for five regions (Aosta Valley, Abruzzo, Molise, Basilicata, Sardinia), where no events were reported in the online newspapers. Apulia recorded the highest number of heat-related illnesses/injuries in the examined period (n = 8; 22.9%) (Figure 2).

Figure 2. Number of occupational heat-related illnesses and injuries as reported by Italian online newspapers in the years 2020 to 2022, by region.

The highest number of events was reported in the construction sector (n = 11; 31.4% of all recorded events), followed by agriculture and forestry (n = 8; 22.9% of all recorded events) and manufacturing activities (14.3%). Traumatic events (injuries) were recorded in construction activities and for an airport service worker (included in "other service activities") (Figure 3).

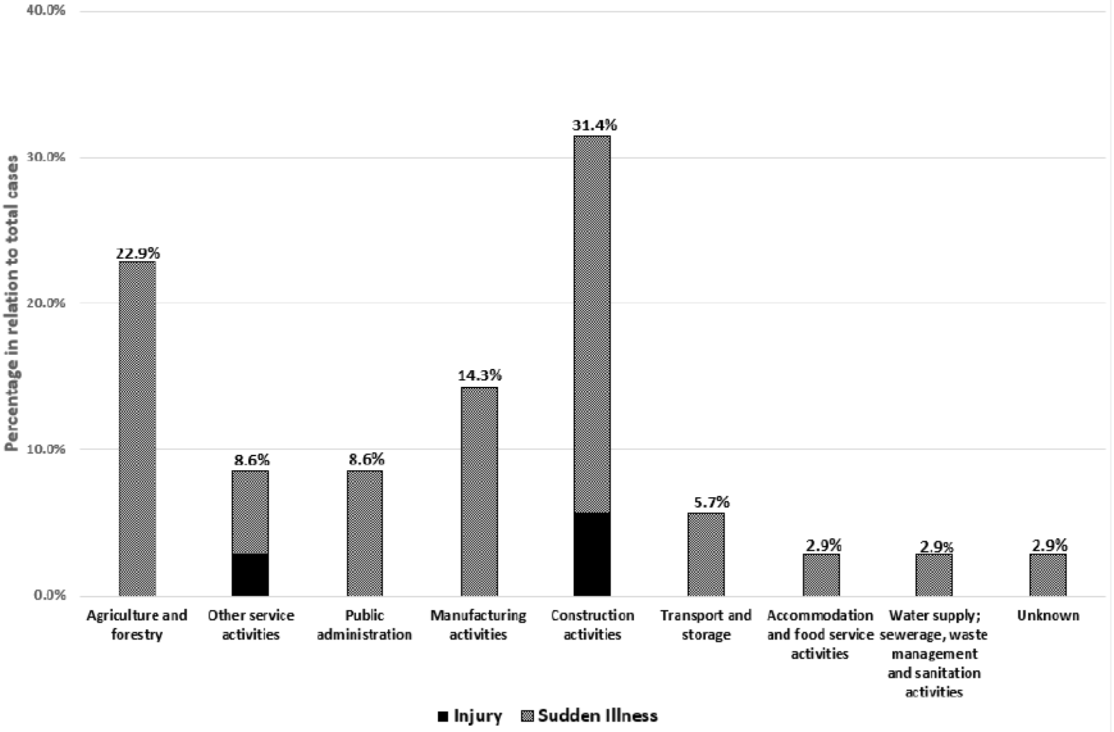

Figure 3. Number of occupational heat-related illnesses and injuries as reported by Italian online newspapers in the years 2020 to 2022, by occupational sector.

4. Discussion

Environmental temperatures and the number of heatwaves have been increasing each year, and the three years in which we conducted the study (2020–2022) were among the warmest on record, according to the World Meteorological Organization [29]. Although exposure to high temperatures is considered an occupational risk factor and preventive measures for reducing the hazard of developing heat-related pathologies are often easy to implement, 35 events were reported by the Italian press in the studied period. As demonstrated by this study, all 35 events occurred on critical thermal stress days, characterized by daily average UTCI values classified as "moderate" or "strong" heat stress conditions and maximum daily UTCI values prevalently characterized by "very strong" or "extreme" heat stress conditions. Furthermore, all events that occurred on days with "extreme" heat stress conditions resulted in fatalities. Most of the workers involved were males employed in the construction sector and performing their tasks in an outdoor environment, which is in agreement with findings from the scientific literature [30–32]. However, no information is provided regarding workers' prior work experience, individual training level [33,34] or degree of heat acclimatization, despite studies reporting that most fatalities occur during the first week of work in the heat, when the body has not yet adapted to high temperatures [15,35]. Our findings related to occupational sectors are consistent with the existing literature, which indicates that outdoor male workers face a higher risk of injuries during heatwaves [36]. Although it is well known in the scientific literature that young, less experienced workers are particularly susceptible to heat-related occupational injuries [10], only two workers were younger than 30 among the reported cases. As with cases involving women, the proportion of events in this age group was minimal, since older age groups and men are still more represented in at-risk jobs. In addition to the cases reported in Table 1, several additional events indirectly linked to global warming occurred as well. In August 2021, two deaths occurred in the agricultural sector. These involved a 30-year-old man who was crushed by a tractor while putting out a fire in Sicily and a 42-year-old man swept away by a landslide while draining water after a flood in the Trentino-Alto Adige region. In June 2022, in Piedmont (Northern Italy), a 57-year-old man experienced a heat stroke while burning brushwood that resulted in an organ failure requiring him to undergo a liver transplant. In the province of Florence in Tuscany (Central Italy), several healthcare workers fell sick in the operating room of a hospital due to a cooling system malfunction. In July 2022, due to abnormal heat, an avalanche occurred on the Marmolada massif in the Alps (Trentino-Alto Adige), killing three mountain guides.

The number of heat-related occupational illnesses and injuries reported in the news appreciably increased from 2020 to 2022, so much so that the number of reported events in July 2022 alone was equivalent to that of the entire previous year.

This trend testifies to the progressive recovery of commercial and industrial activities in Italy after the lockdowns caused by the COVID-19 pandemic, as well as to the fact that the summer of 2022 was the hottest in history in Europe, according to the Copernicus Global Climate Highlights 2022 report [37]. In Italy, however, the summer of 2022 was the second hottest ever (second only to 2003), with an average temperature of just over 2 °C higher than the period 1991–2020, as highlighted by the Institute of Atmospheric Sciences and Climate of the National Research Council. One event occurred in May 2022, the hottest since 2003, with record drought across many Italian regions [38].

During the three-year observational period, only four news articles described an event as a "heat stroke". Furthermore, for the events that occurred in the summer of 2022, which was characterized by prolonged and intense heatwaves, not a single article used this term. Instead, the majority of the articles used the term "*malore*", which translates to "sudden illness". With the aim of communicating news more effectively to laypeople, journalists use terms that are easily understood, even if they are not entirely appropriate [39]. Many articles among those emailed daily were disregarded, as they lacked explicit mention by the reporters of the association between the events and heat, despite circumstances such as the time of the day implying a possible link. Even during heatwaves, some journalists resorted to the phrase "for reasons yet to be ascertained", perhaps due to infrequent interviews with the workers involved or their colleagues [33]. This dearth of information could lead readers to underestimate the risks associated with heat exposure in the workplace.

Unfortunately, it is not possible to accurately identify heat-related occupational illnesses or injuries in Italian administrative healthcare databases, such as hospital discharge or emergency records, as they generally only report the ICD code of the health condition affecting the patient, with no indication of the environmental factors that may be involved [40].

By examining the INAIL database for the period of 2010–2021 and taking into account the causes of injuries or acute illnesses resulting directly from heat exposure, such as heat strokes, sunstrokes, and other effects of extreme temperatures, a total of 569 cases were identified. Among these cases, 25 were fatal, accounting for 0.014% of all occupational injuries and 0.35% of fatalities during the same period [41].

Those direct effects do not capture all heat-related injuries. In particular, there may be indirect links, due, for example, to the reduction of attention caused by the heat.

For this reason, it is necessary to study the general correlation between ambient temperature and overall injury rates to correctly consider all the numerous ways in which heat can impact the health of workers. In a study assessing the correlation between ambient temperature and occupational injuries in Italy, considering injuries occurring from 2006 to 2010, extreme heat temperature exposure resulted in a 0.14% attributable fraction of work-related injuries for outdoor workers [10].

A recent systematic review confirmed that the risk of occupational injuries increases by 1% for every 1 °C rise in environmental temperature and by 17.4% during heatwaves, defined as several consecutive days with temperatures above the average for the period [42].

The present study has some limitations. It was not possible to monitor all newspapers, especially local ones and those requiring a subscription to access. Also, only newspaper coverage data were considered, excluding other mass media that provide information to the public, such as radio programs.

Nonetheless, we have showed that the monitoring of newspapers represents a valuable tool for tracking heat illnesses, which were given less attention in recently published estimates that mainly focused on traumatic events [9,10].

The monitoring of newspapers has also been useful for raising awareness about heat-related illnesses in the workplace among workers themselves and relevant stakeholders, thanks to the strong and extensive information capacity of the media, with the ultimate goal of prompting the implementation of heat stress prevention measures in occupational settings. This was the case in Italy where, in 2021, a young agricultural worker's demise was widely reported, drawing the attention of stakeholders. In response, the Governor of Apulia passed an ordinance prohibiting fieldwork between 12.30 pm and 4.00 pm until the end of August, leveraging the heat stress forecasting system developed in WORKLIMATE [30] for identifying potential risks among outdoor laborers. Subsequently, agricultural activities were banned on days identified as "high risk" based on the project's findings. The measure was adopted by three other southern Italian regions, namely Basilicata, Calabria, and Molise, in the same year, and the ordinances were renewed in 2022.

Given the impact of heat stress on health [43], the development of prevention measures is fundamental. Awareness, correct perception and knowledge of the risks related to exposure to high temperatures is necessary to be able to effectively implement prevention and management measures in the workplace [44]. Implementing preventive measures can minimize health risks associated with exposure to heat. These measures are supported by clinical evidence [45] and can be enhanced through the use of technology to facilitate the development of recommendations and guidelines. Key strategies for preventing heat-related health problems in workers include [43,45]: limiting direct exposure to heat, scheduling breaks, consuming adequate amounts of water regularly, using appropriate personal protective equipment compatible with the thermal environment, identifying workers vulnerable to heat stress who may benefit from temporary work restrictions, and promoting mutual supervision among workers [15]. In Italy, operational guidance was issued in summer 2021 for the prevention of occupational risk due to physical factors, such as microclimates, to enhance the effectiveness of preventive measures [46]. The WORKLIMATE project also developed operational strategies, such as a forecasting alert platform based on the Wet Bulb Globe Temperature (WBGT) parameter, which provides regional and sub-regional heat stress predictions for up to three days and recommendations to mitigate health effects for workers engaged in outdoor work [47]. In addition, informational brochures were developed [48] to educate workers on how to deal with occupational risk conditions. These interventions have been proven to effectively reduce the risk of heat-related illness. In fact, a randomized trial found that the group that received an "intervention package" with behavioral preventive measures experienced a 63% reduction in the risk of heat stress compared to the group not receiving the intervention [49].

5. Conclusions

In summary, we have examined how the media portrays the workplace, including its associated risks and problems. Media outlets may emphasize certain aspects over others, which can influence public perception and understanding of an issue [33]. How the media frames critical public health concerns, such as injuries and illnesses related to heat stress among workers, is crucial in informing the public about hazards [50]. Wakefield et al. argue that the reporting of an event "diagnoses, evaluates, and prescribes solutions to social problems" [51]. In their study, the authors view newspaper reports as a means to quickly draw attention to heat-related injuries and fatalities in the workplace among official bodies, the public, and workers themselves, as official statistics on occupational illnesses and injuries are not updated frequently enough. Furthermore, newspaper articles can promote preventative measures, which can lead to positive changes in minimizing high-risk behaviors [52].

The aim of the working group is to extend the monitoring of heat-related injury news coverage to social media platforms, such as Twitter or Facebook, in the near future.

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Full length article

Association between extreme temperature exposure and occupational injuries among construction workers in Italy: An analysis of risk factors

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ABSTRACT

Background/Aim: Extreme temperatures have impact on the health and occupational injuries. The construction sector is particularly exposed. This study aims to investigate the association between extreme temperatures and occupation injuries in this sector, getting an insight in the main accidents-related parameters.

Methods: Occupational injuries in the construction sector, with characteristic of accidents, were retrieved from Italian compensation data during years 2014–2019. Air temperatures were derived from ERA5-land Copernicus dataset. A region based time-series analysis, in which an over-dispersed Poisson generalized linear regression model, accounting for potential non-linearity of the exposure- response curve and delayed effect, was applied, and followed by a *meta*-analysis of region-specific estimates to obtain a national estimate. The relative risk (RR) and attributable cases of work-related injuries for an increase in mean temperature above the 75th percentile (hot) and for a decrease below the 25th percentile (cold) were estimated, with effect modifications by different accidents-related parameters.

Results: The study identified 184,936 construction occupational injuries. There was an overall significant effect for high temperatures (relative risk (RR) 1.216 (95% CI: (1.095–1.350))) and a protective one for low temperatures (RR 0.901 (95% CI: 0.843–0.963)). For high temperatures we estimated 3,142 (95% CI: 1,772–4,482) attributable cases during the studied period. RRs from 1.11 to 1.30 were found during heat waves days. Unqualified workers, as well as masons and plumbers, were found to be at risk at high temperatures. Construction, quarry and industrial sites were the risky working environments, as well as specific physical activities like working with hand-held tools, operating with machine and handling of objects. Contact with sharp, pointed, rough, coarse 'Material Agent' were the more risky mode of injury in hot conditions.

Conclusions: Prevention policies are needed to reduce the exposure to high temperatures of construction workers. Such policies will become a critical issue considering climate change.

1. Introduction

Climate change and extreme temperatures are risk factors not only for health of population but also for workers carrying out heavy labor duties employed in specific jobs. Evidence from literature has shown how exposure to extreme temperatures is associated with an increase in occupational injuries (Marinaccio et al., 2019; Bonauto et al., 2007; Gubernot et al., 2015; Martínez-Solanas et al., 2018). The increase of awareness and the identification of actions for preventing or reducing occupational health effects of extreme temperature, have to be become a priority in occupational health and safety agenda. Climate change is likely to result in increasing prevalence, distribution, and severity of occupational hazards, where the increased frequency and intensity of extreme weather-related events, the air pollution, the occupational exposure to ultraviolet radiation and to vector-borne disease, seem to represent the main environmental risk factors for workers associated to climate change scenarios [Schultze, 2016]. Others emerging risk factors could be substantial in the next years, including the mental health effects

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induced by the occupational stressors and the extreme anxiety reactions, such as post-traumatic stress disorders for workers involved in actions against extreme weather disasters, such as floods, forest fires, heat waves, cyclones [Fritze, 2008].

The occupational health effects of exposure to extreme temperatures have been recently highlighted in epidemiological studies conducted in Australia (Varghese et al., 2019; Xiang et al., 2014), Spain (Martinez-Solana et al., 20189, Italy (Marinaccio et al., 2019) and in other countries, using occupational injuries as health outcome. Systematic reviews (Bonafede et al., 2016a, Varghese et al., 2018) and *meta*-analyses (Fatima et al., 2021; Binazzi et al., 2019) confirmed the significant risk of injuries during exposure to extreme temperatures in the occupational setting. The increasing perceived fatigue and decreasing reaction capacities are generally considered as the causal driver such as the cognitive impairment, mental confusion, impaired judgment, and poor coordination (Dutta et al., 2015). Furthermore, more critical situation can also occur in the case of migrant workers, as demonstrated in a recent work on heat stress perception among native and migrant construction workers employed in Italian industries (Messeri e al., 2019).

Comprehensive assessments of injuries associated to outdoor extreme temperature exposure by sector, job type and working conditions are limited. However, the definition of prevention action plans and consistent recommendations and awareness campaigns require solid evidence-based on the potential risk factors by economic sector and work settings.

The construction industry is recognized globally as severely affected by heat and cold stress. A recent review about construction workforce addressed 21 and 20 health challenges under hot and cold weather conditions respectively, and strategies to limit them (Karthick, et al., 2022). Recently, an analysis based on the U.S. Census of fatal occupational injuries accounted for 36 % of heat related deaths in U.S. occurring among construction workers (Dong et al., 2019). Previous studies have estimated a mortality risk of 13-time fold higher from a heat-related illness among construction workers in U.S., with respect to other working sectors, showing roofers and road construction workers as the jobs majorly affected (Bonauto et al., 2007, Gubernot et al., 2015). The need to increase preventive measures and the absence of structured regulations for heat exposure in this sector has been underlined (Acharya et al., 2017).

The aim of this study was to investigate the effect of extreme temperatures on occupation injuries in the construction sector in Italy, identifying the determinants of risk to provide additional evidence for defining policies and prevention measures.

2. Materials and methods

2.1. Occupational injuries data

Data on Occupational injuries were retrieved from the Italian National Institute for Insurance against Accidents at Work (INAIL) archive of insurance compensation claims for accidents that occurred in the construction sector during the period 2014–2019. Information contained in the archive follows the European Statistics on Accidents at Work (ESAW) structure for data collection of accidents at work: worker information (gender, age, nationality, profession, employment status, geographical localisation), workplace information (working environment, working process), sequence of events (specific physical activity and associated material agent, deviation and associated material agent, contact mode of injury and associated material agent), effects of injury (type of injury, body part injured, days lost). Moreover, it contains insurance information, such as grade of invalidity and type of compensation. ESAW variables were aggregated at their highest level of classification and, in some cases, they were aggregated even more at a higher level of abstraction to ensure a high numerousness in the class (see paragraph 2.3 for classes details). Professions were classified according to the National Institute of Statistics (ISTAT) classification of professions CP2011, linkable to the international classification of occupations ISCO-08.

Based on data provided by ISTAT, during the period 2014–2019 on average 1,32 M workers were employed in the 505 K firms of the construction sector (ISTAT, 2022). The majority of these firms (96 %) are small with less than 9 workers, and 65 % (865 K) of total workers are employed in small enterprises. About 544 K construction firms are registered in the INAIL archive, including around 1.29 M workers (INAIL, 2019). The consistency between the two national archives about the size of the construction business makes the claims for compensation received by INAIL due to occupational injury, representative of this sector and eligible for this study.

2.2. Meteorological data

Air temperatures data were derived from ERA5-land Copernicus dataset (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=overview), which provides land meteorological variables with 9 km horizontal resolution from 1950 to present, by replaying the land component of the ECMWF ERA5 climate reanalysis. Hourly 2 m height temperature and dew point temperature data, a measure of air humidity, were retrieved at grid level for the study period (2014–2019) for the Italian domain, and then used to obtain daily mean values for each of the 8,090 municipalities of Census 2011 by means of geostatistical techniques, based on grid cells overlapping the municipality boundaries. Such data were then merged with the daily counts of occupational injuries occurred in the construction sector in each municipality to provide a full time series of outcomes and exposure levels.

2.3. Statistical analysis

The relationship between air temperature and injuries was evaluated using a time-series approach, based on a protocol already applied in a former study about temperature and occupational injuries (Marinaccio et al., 2019). For each of the 8,090 Italian municipalities the daily count of injuries was retrieved together with the daily mean temperature. As Italy is characterized by different climates, with cold humid subtropical or mild continental climate in the Northern regions and a Mediterranean climate in the central and southern regions, different temperatures ranges can be found across the country, which might produce regional variability in the impact of occupational injuries due to acclimatization and resilience. To take this into account it, we conducted a regional base analysis with a two-stage analytical protocol.

In the first stage the 20 regions in which Italy is divided, were analysed individually, by means of a specific over-dispersed Poisson generalized linear regression model, run for each region, including all municipalities here located, which were pooled analyzed. A Distributed Lag Nonlinear Model (DLNM) approach was used to take into account both the potential non-linearity of the dose response curve and a delayed effect of the exposure on the outcome (Gasparrini, 2014). The relationship between temperatures and injuries was modelled with a quadratic B-spline with one internal knot, placed at the 50th percentile of the region-specific temperature distributions. The lag–response was modelled with a natural spline with two degrees of freedom, considering a lag duration of four days. To control for long time trends and seasonality, a quadruple interaction between municipality, year, month and day of the week was included in the models. A few confounders were also included in the model as categorical variables, such as holidays (four levels including bank holiday and long weekends) and decrement of population during summer (a 3-levels variable: 1 from July 16th to August 8th; 2 from 9th to 31th of August; 0 elsewhere).

In the second stage, we applied a random-effects *meta*-analysis to combine the regional estimates to derive a national estimate, and a multivariate *meta*-analytical regression to obtain an overall national exposure–response curve (Gasparrini et al, 2012).

Based on values used in former studies (Marinaccio et al., 2019;

Varghese et al., 2019; Martínez-Solanas et al., 2018), we defined the effect of high temperatures as the Relative Risk (RR) of injury for temperature increases between the 75th and the 99th percentile, while the effect of low temperatures was estimated for a decline in mean temperature between the 25th and the 1st percentile. We also estimated the impact of temperatures in terms of the number of attributable cases, within the same above intervals, using a methodology previously described (Gasparrini and Leone, 2014). For both effect and impact, 95 % Confidence Intervals (CI) were estimated.

As sensitivity analyses, we evaluated the potential role of different functions and parameters to model the exposure–response relationship. For temperature, we tested B-spline and natural spline as a variable function, and integer, as well as natural spline, function for the lag effect. As for temperature, we tested different degrees of freedom in the natural spline function (3 and 4), and degrees for B-spline one (2 and 4). Finally, we tested the effect at different lags (2, 3 and 4 days), using a quadratic B-spline and a natural spline functions with 2 degrees of freedom for temperature and lag effect respectively.

Effect modification was evaluated for different characteristics of occupational injuries. We investigated the effect by age groups, profession and severity, the latter measured in terms of number of days of temporary allowance and percent of temporary or permanent incapacity. In addition, some ESAW variables were also considered for the study of effect modification such as: working environment, working process, specific physical activity and its material agent, deviation from the norm and leading to the accident, contact-mode of injury. The modalities of each variable included in the effect modification study are reported in Table 1.

We finally investigated the effect during heat waves events. According to the definition used by Gasparrini and Armstrong (2011) for epidemiological purposes, heat wave days were defined as those with temperature above the 97th, 98th and 99th percentiles of the year-round region-specific distribution. A criterion for the persistence of heat waves of 4 days was used (Anderson et al, 2009; Hajat et al, 2006). In practice, the usual indicator (1/0) defines heat wave days as those with temperature above the selected intensity criterion defined above for at least 4 days of duration, and 0 elsewhere. This heat-wave indicator is then included in the model in place of the temperature cross-basis function described above, to derive its coefficient as an overall effect. The region-specific effect was estimated as the exponential of the coefficient for the heat wave indicator variable. As done previously, a random-effects *meta*-analysis was then applied to combine the region-specific estimates into a national estimate.

All the analysis were run using R software (version 3.5.2) with the packages *gnm*, *dlnm* and *mvmeta.*

3. Results

In the period 2014–2019 almost 185 k occupational injuries occurred in Italy in the construction sector. Table 1 shows the characteristics of this dataset. A decreasing trend in the number of injuries was observed across the years (from 34,480 in 2014 to 27,738 in 2019). Most of the involved workers were aged 35–60 (131 k events), followed by younger ones (aged 15–34 years with about 44 k events). The great majority of injuries were among males (181 k vs 3 k for men and women respectively). Accidents were quite spread among professions with most of injuries occurring for artisans and qualified workers such as electricians, masons, plumbers and carpenters (85 K events). Construction site, quarry and industrial sites were the most frequent working environments (121 k events), with excavation, construction, repair and demolition as the most frequent working processes carried out just before the accidents (58 k events). Movement and handling of objects were the two most frequent specific physical activities conducted at the time of accident (61 k and 29 k respectively) and loss of control, as well as slipping, stumbling and falling, were found as the most frequent deviation from the normal operations leading to the accidents. About one third of

Table 1
Descriptive statistics and Relative Risks (RRs, 95% CI) of occupational injuries for high and low temperatures in the construction sector in Italy, for the period 2014–2019 by age, profession, ESAW variables based on ICSE-93 classification of ILO, and severity. Data are included in the Italian national workers compensation authority (INAIL) archive.

Variable	Occupational injuries	High temperatures	Low temperatures
	n	RR (95 %CI)	RR (95 % CI)
Overall	184,936	1.216 (1.095–1.350)	0.901 (0.843–0.963)
Age class			
15–34	43,977	1.246 (1.046–1.484)	0.758 (0.635–0.906)
35–60	131,229	1.237 (1.137–1.347)	0.926 (0.852–1.006)
>60	9,730	0.948 (0.646–1.391)	0.945 (0.533–1.674)
Profession			
Electrician	14,122	0.968 (0.687–1.365)	0.770 (0.498–1.191)
Mason	42,231	1.309 (1.164–1.473)	0.768 (0.620–0.952)
Plumber	18,076	1.193 (0.988–1.441)	1.135 (0.750–1.716)
Carpenter	11,184	1.147 (0.820–1.603)	1.053 (0.721–1.538)
Other qualified worker	45,915	1.181 (1.026–1.359)	0.981 (0.737–1.305)
Unqualified worker	26,439	1.413 (1.187–1.682)	0.690 (0.582–0.818)
Plant conductor, machinery worker, vehicle driver	14,434	1.285 (0.928–1.779)	0.911 (0.693–1.196)
Other professions	12,533	0.900 (0.669–1.211)	0.885 (0.656–1.194)
N.A	2		
Working Environment			
Construction site, quarry	77,471	1.247 (1.061–1.466)	0.746 (0.630–0.885)
In the home	12,359	1.091 (0.692–1.720)	1.362 (0.920–2.017)
Public area	25,290	1.089 (0.901–1.317)	1.075 (0.876–1.319)
Industrial site	44,070	1.240 (0.993–1.549)	0.920 (0.747–1.133)
Other Working Environments	8,551	0.887 (0.416–1.893)	0.889 (0.592–1.334)
N.A.	17,195		
Working Process			
Movement, including aboard means of transport	26,199	1.204 (0.997–1.454)	1.316 (1.029–1.681)
Excavation, Construction, Repair, Demolition	58,576	1.281 (1.067–1.538)	0.661 (0.550–0.795)
Setting up, preparation, installation, mounting, disassembling, dismantling, maintenance, repair, tuning, adjustment	41,906	1.197 (1.042–1.375)	0.955 (0.813–1.122)
Production, manufacturing, processing, storing	35,015	1.211 (0.981–1.496)	0.921 (0.756–1.121)
Others working processes	4,867	1.134 (0.730–1.761)	0.654 (0.305–1.400)
N.A.	18,373		
Specific Physical Activity			
Working with hand-held tools	29,293	1.292 (1.133–1.473)	0.700 (0.490–1.001)
Carrying by hand	27,529	1.066 (0.844–1.347)	0.784 (0.568–1.084)
Operating machine, driving/being on board a means of transport	14,482	1.459 (1.201–1.771)	0.788 (0.386–1.612)
Movement	61,028		

(*continued on next page*)

Table 1 (*continued*)

Variable	Occupational injuries	High temperatures	Low temperatures
		1.104 (0.853–1.427)	0.975 (0.844–1.127)
Handling of objects	34,137	1.435 (1.265–1.628)	0.884 (0.708–1.104)
Presence, other specific activity	1,832	N.D.	N.D.
N.A.	16,635		
Deviation from the norm and leading to the accident			
Body movement without any physical stress (generally leading to an external injury)	27,531	1.524 (1.162–2.001)	0.837 (0.653–1.073)
Body movement under or with physical stress (generally leading to an internal injury)	33,337	1.047 (0.806–1.361)	0.738 (0.604–0.903)
Loss of control (total or partial) of machine, means of transport or handling equipment, hand-held tool, object, animal	42,141	1.165 (0.950–1.427)	0.912 (0.794–1.047)
Breakage, bursting, splitting, slipping, fall, collapse of Material Agent	17,448	1.531 (1.314–1.784)	0.669 (0.402–1.113)
Slipping - Stumbling and falling - Fall of persons	39,176	1.085 (0.946–1.244)	1.019 (0.833–1.245)
Other deviation	7,409	1.096 (0.836–1.436)	0.711 (0.445–1.137)
N.A.	17,894		
Contact-Mode of injury			
Contact with sharp, pointed, rough, coarse Material Agent	41,032	1.547 (1.299–1.842)	0.763 (0.552–1.053)
Trapped, crushed	13,042	0.967 (0.663–1.410)	0.916 (0.616–1.361)
Horizontal or vertical impact with or against a stationary object	47,815	1.156 (0.959–1.394)	1.025 (0.860–1.220)
Physical stress - on the musculoskeletal system	32,322	0.904 (0.630–1.296)	0.726 (0.563–0.936)
Struck by object in motion, collision with	25,887	1.199 (0.960–1.497)	0.816 (0.676–0.986)
Other contact	6,414	1.287 (1.021–1.623)	1.153 (0.830–1.601)
N.A.	18,424		
Material agent			
Buildings, structures, surfaces - above ground level (indoor or outdoor)	20,320	1.118 (0.949–1.317)	0.892 (0.658–1.208)
Building materials, Loads – handled by hand	41,125	1.181 (0.969–1.438)	0.823 (0.711–0.953)
Land vehicles	19,002	1.143 (0.803–1.627)	1.085 (0.809–1.454)
Buildings, structures, surfaces - below ground level (indoor or outdoor)	26,314	1.127 (0.963–1.320)	1.006 (0.718–1.409)
Machines and equipment; Conveying, transport and storage systems; Systems for the supply and distribution of materials; Motors, systems for energy transmission and storage	18,428	1.477 (1.151–1.896)	0.923 (0.690–1.235)
Hand tools; Hand-held or hand-guided tools, mechanical; Hand tools	26,625	1.231 (1.043–1.454)	0.802 (0.573–1.123)
- without specification of power source			
Other material agent	12,167	1.220 (0.950–1.566)	0.616 (0.304–1.250)
N.A.	20,955		
Severity			
Permanent incapacity (to work) higher than 16 % or fatal accident	5,578	0.902 (0.522–1.559)	0.719 (0.489–1.058)
Permanent incapacity (to work) between 6 % and 16 %	16,050	1.361 (1.068–1.733)	1.148 (0.796–1.655)
Permanent incapacity (to work) between 1 % and 6 %	27,757	1.301 (1.085–1.560)	0.803 (0.622–1.038)
Temporary allowance higher than 40 days	19,016	1.138 (0.998–1.297)	0.787 (0.576–1.076)
Temporary allowance between 31 and 40 days	11,776	1.304 (0.835–2.036)	0.860 (0.663–1.116)
Temporary allowance between 21 and 30 days	19,751	1.079 (0.804–1.447)	0.922 (0.660–1.287)
Temporary allowance between 8 and 20 days	53,933	1.150 (0.945–1.399)	0.880 (0.804–0.963)
Temporary allowance between 4 and 7 days	27,365	1.409 (1.077–1.845)	0.619 (0.467–0.820)
Without temporary allowance	3,710	N.D.	N.D.

accidents had an average severity between 8 and 20 days of leave (54 k events).

Figure S1 of Supplementary Material (SM) shows the time series of the total daily occupational injuries in the construction sector occurring in Italy during years 2014–2019. Seasonal and weekly patterns can be identified. Figure S2 in the SM shows both the mean monthly and weekly behaviors. The mean number of injuries increases during winter, spring up to early summer. The absolute minimum number of injuries is reached in August, during the summer holyday period followed by a rapid increase in late summer and early autumn before the second minimum of December. As for weekly trends, an average of 110 accidents per working day was identified, as well as a different trend on weekends (Saturday and Sunday) with much lower values (30 and 10 injuries respectively).

Fig. 1 shows the geographical distributions of daily mean air temperatures across the Italian municipalities for the first, the 25th, the 75th and 99th percentiles. A clear north–south gradient can be observed, with warmer temperatures in the south and colder ones in the north. Furthermore, altitude and mountain (Alps in the north and Apennines in central areas) also create a thermal gradient. At municipal level, the 25th percentile ranges between −7.32 °C and 14.43 °C, while the 75th one ranges between 5.37 °C and 24.60 °C. Extreme temperatures ranges between −19.31 and 9.87 °C for the first percentile, and between 13.27 °C and 31.71 °C for the 99th one.

The exposure–response relationship between daily mean temperatures and occupational injuries among construction workers is shown in Fig. 2. A non-linear significant risk gradient is estimated for high temperatures, while a significant protective effect is estimated for low temperatures with a nearly linear behavior. The lowest point of exposure–response curve has been estimated at about 10th percentile of temperature range (4 °C). The lag structure for high temperatures (Fig. 3) addresses for an increment of risk at the same day of accident (lag 0) and continues to be significant for the following three days (lag 1, lag 2, lag 3). Conversely, the lag structure for low temperatures (figure S3 of SM) shows a not significant risk at the same day and the day after that of the accident (lag 0 and lag 1), and a protective behavior in the following days (lag 2–4).

The overall cumulative Relative Risks (RR) of occupational injuries

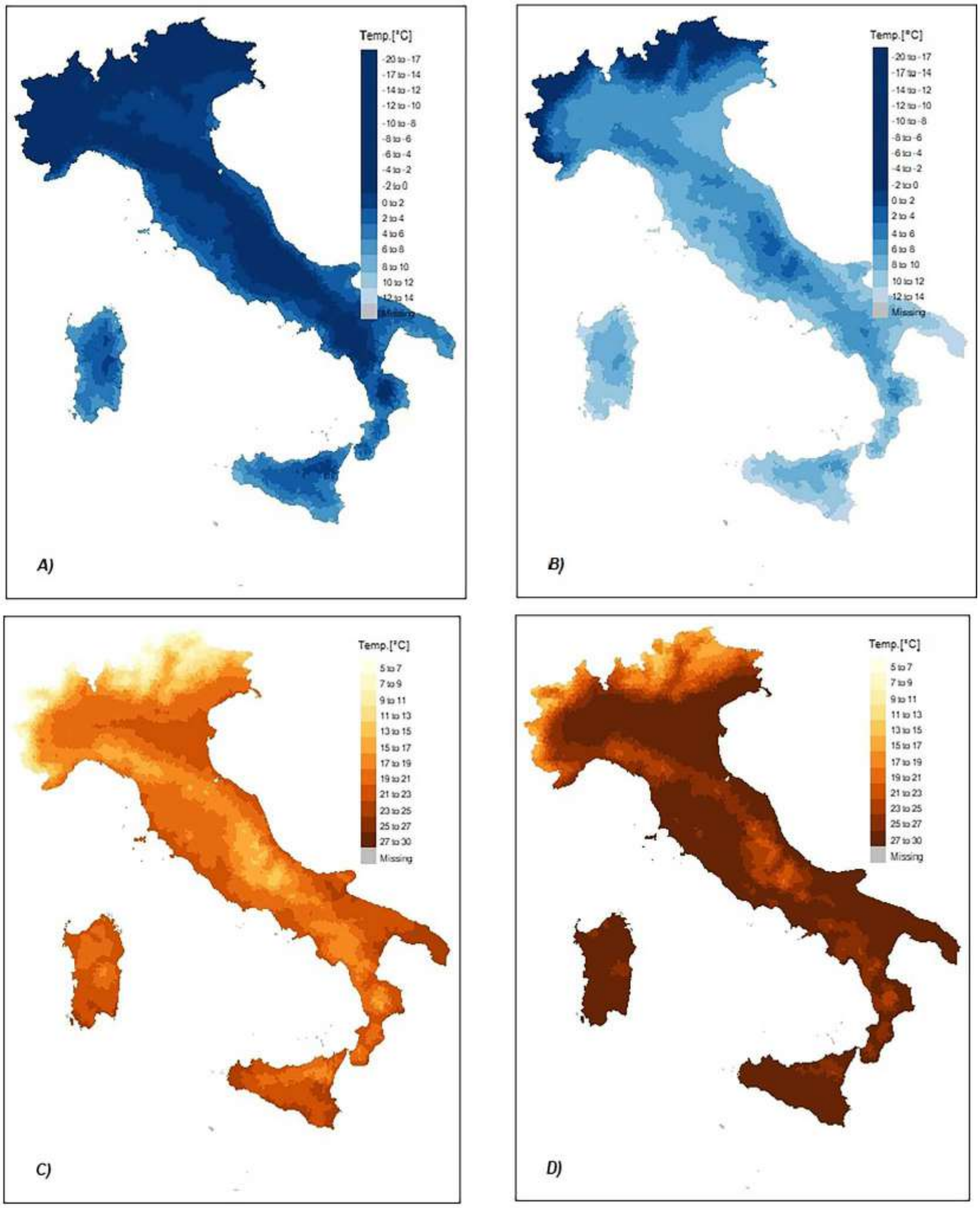

Fig. 1. Maps of the first (A), 25th (B), 75th (C) and 99th (D) percentiles of mean daily air temperature at municipal level based on ERA5 data from year 2014 to 2019.

occurred in the construction sector for high and low temperatures are shown in Table 1. For high temperatures (between 75th and 99th percentiles) and low temperatures (between 25th and 1st percentiles) the RRs were 1.216 (95 % CI: 1.095–1.350) and 0.901 (95 % CI: 0.843–0.963) respectively. Region specific estimates for high temperatures are shown in figure S4 of SM. A certain degree of heterogeneity in increment of risk (IR) was detected, with a few small regions deviating with respect to overall mean effect (Valle D'Aosta, Molise and Basilicata). The number of attributable cases of injuries associated to high temperatures was estimated to be 3,142 (95 % CI: 1,772–4,482) during the whole period (2014–2019).

The results by age, profession and ESAW variables provided interesting findings for analysis of effect modification (Table 1). As a risk was found for high temperatures only, the results are presented to this effect only. The analysis by age showed the greater risk of injury among the youngest age group (15–34 years of age) with a RR of 1.246 (95 % CI: 1.046–1.484), which is slightly lower in the 35–60 year age group (RR 1.237 (95 % CI: 1.137–1.347)) and becomes non-significant among older workers (over 60 years). Considering specific professions, unqualified workers exhibited the highest significant risk (RR 1.413 (95 % CI: 1.187–1.682)), followed by masons (RR 1.309 (95 % CI: 1.164–1.473)) and other qualified workers (RR 1.181 (95 % CI: 1.026–1.359)). For the remaining professions the risk of injury for exposure to high temperatures was non-significant or at the very border line (eg. Plumber). Construction sites and quarries are the working environments most at risk (RR 1.247 (95 % CI: 1.061–1.466)). The analysis by working process, defined as the main type of work or task being performed by the workers at the time of the accident, indicated a risk during excavation, construction, repair and demolition general activity (RR 1.281 (95 % CI: 1.067–1.538)), as well as during some setting up, preparation, installation and general maintenance activities (RR 1.197 (95 % CI: 1.042–1.375)). Within these working processes, there were

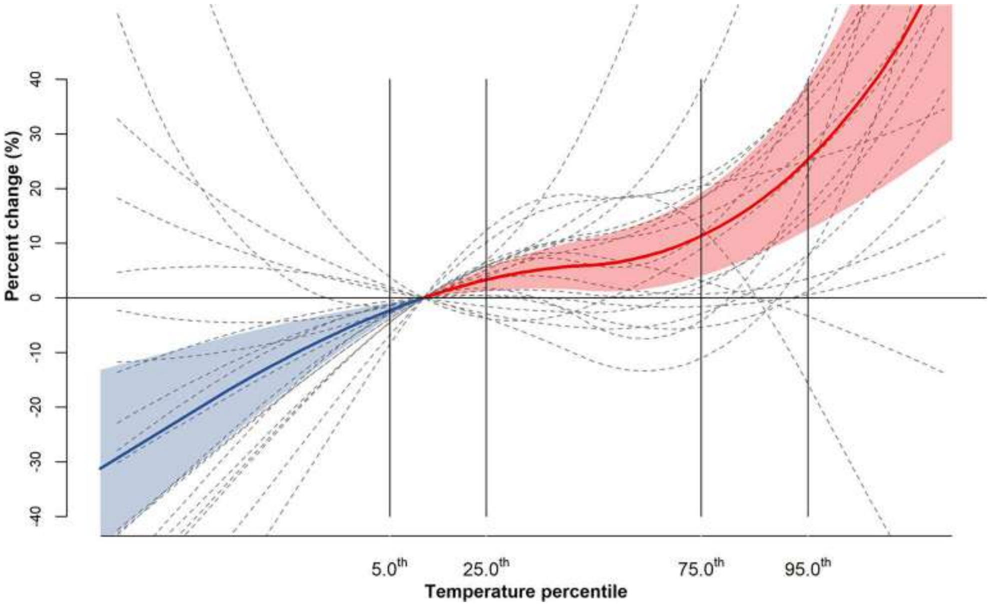

Fig. 2. Exposure-response relationship. Percent change in occupational injuries in the construction sector by temperature percentile. Blue and red areas correspond to low and high temperature effects. Dashed lines represent the region specific functions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

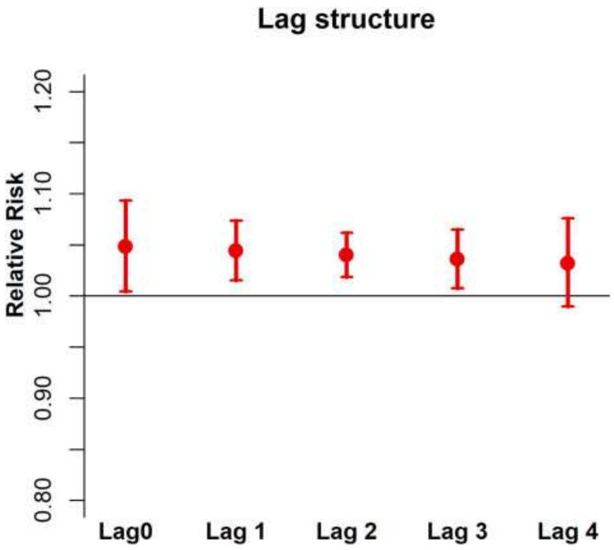

Fig. 3. Lag specific effects for the overall cumulative exposure–response relationship between outdoor temperature and occupational injuries in the construction sector for heat effects. Italy, 2014–2019.

specific physical activities which had a greater risk of injury for exposure to high temperatures, such as: working with hand-held tools (RR 1.292 (95 % CI: 1.133–1.473)), operating machine or driving/being on board a means of transport (RR 1.459 (95 % CI: 1.201–1.771)), and handling of objects (RR 1.435 (95 % CI: 1.265–1.628)). When data were analyzed by the last event differing from the norm and leading to the accident (deviation), results show that body movements without any physical stress were at greater risk for injuries (RR 1.524 (95 % CI: 1.162–2.001)). Furthermore, deviations like breakage, bursting, splitting, slipping, fall or collapse of 'Material Agent' were also at risk for high temperatures (RR 1.531 (95 % CI: 1.314–1.784)). As far the mode of injury is concerned, which describes how the victim came into contact with the 'Material Agent', we found at significant risk of injury for contact with sharp, pointed, rough, coarse 'Material Agent' (RR 1.547 (95 % CI: 1.299–1.842)), as well as other unclassified contacts (RR 1.287 (95 % CI: 1.021–1.623)). As for 'Material Agent', we found machines, equipment and miscellanea of systems to be categories at risk of injury under high temperatures (RR 1.477 (95 % CI: 1.151–1.896)). Another risky 'Material Agent' was identified among hand tools and hand-held or hand-guided tools (RR 1.231 (95 % CI: 1.043–1.454)). Finally, considering severity of injuries, in terms of the days of sick leave\disability given to the worker following injury, the highest risk was observed for minor severity (between 4 and 7 days leave) with an RR of 1.409 (95 % CI: 1.077–1.845). Exposure to high temperatures was also associated to more severe injuries associated to permanent physical disability with a RR of respectively 1.361 (95 % CI: 1.068–1.733) and 1.301 (95 % CI: 1.085–1.560) for permanent physical disability of 6–16 % and 1–6 % respectively.

We also investigated the overall effect of extreme events considering three definitions of heat waves. Results are shown in Table 2. When the threshold level for 4 days duration of temperature above yearly municipal specific is set to 97th percentile, we found an increase of risk (RR 1.11 (95 % CI: 0.99–1.25)) in heat waves days with respect to not heat waves ones. Correspondent figures for threshold of 98th and 99th

Table 2
Relative Risks (RRs, 95% CI) of occupational injuries during heat waves (HW) for different definitions of heat waves.

HW code	Description	RR (95 % CI)	HW days	Number of HW days over the studied period
HW4.97		1 (Ref)	NO	
	4 days duration of temperature above yearly municipal specific 97th percentile	1.11 (0.99–1.25)	YES	137
HW4.98		1 (Ref)	NO	
	4 days duration of temperature above yearly municipal specific 98th percentile	1.19 (1.06–1.33)	YES	102
HW4.99		1 (Ref)	NO	
	4 days duration of temperature above yearly municipal specific 99th percentile	1.30 (1.06–1.58)	YES	56

percentiles of temperatures distributions were RR 1.19 (95 % CI: 1.06–1.33) and RR 1.30 (95 % CI: 1.06–1.58) respectively.

The results of the sensitivity analyses are summarised in table S1 of SM. The use of alternative functions in the cross-basis of DLNM model for both temperatures and lag structure, the use of different degrees of function, degrees of freedom and knots in the above functions, different lag values, as well as the use of dew point temperature instead of air temperature, did not alter the main analysis results.

4. Discussion

The effects of extreme temperatures on general occupational injuries have been investigated in several studied, most of them using a time-series analysis (Martínez-Solanas et al., 2018; Marinaccio et al., 2019; Varghese et al., 2019), while few focused on specific industrial sectors.

Each sector may have a specific degree and risk profile due to typical labor activities and environmental working conditions. In construction, workers usually carry out their physical activities outdoors with little protection against extreme temperatures, which, in combination with a potentially hazardous working environment can lead to injury (Rameezdeen and Elmualim, 2017; Kjellstrom et al., 2016; Kakamu et al., 2021).

A few studies have investigated the relationship and impact of heat exposure on construction workers (Li et al., 2016; Acharya et al., 2018; Al-Bouwarthan et al., 2019; Dong et al., 2019; Han et al., 2021). The impacts of high-temperature conditions on construction labor productivity in China has been studied by Li et al. (2016), addressing for a decreasing of direct work time by 0.57 % for an increase of temperature of 1 °C. Acharya et al. (2018) assessed heat stress and health among construction workers in a review paper. Al-Bouwarthan et al. (2019) conducted an analogous study about the intensity and duration of heat stress exposure among workers performing residential construction in southeastern Saudi Arabia, addressing for an excessive heat stress, both indoors and outdoors, over a large part of the work day, which a midday outdoor work ban was not effective in reducing it. Dong et al. (2019) explored heat-related deaths among U.S. construction workers, accounting for 36 % of all occupational heat-related deaths from 1992 to 2016 in the U.S. Han et al. (2021) carried out a study, based on cross-sectional online questionnaire provided to a sample of Chinese construction workers, about the perceptions of workplace heat exposure, finding that most respondents stated that work efficiency declined during extremely hot weather. Although the above mentioned studies are relevant to understand workers' perception of heat and impact of heat on productivity or deaths in general terms, it is important to quantify the risk of injury and its impact in number of attributable injuries for increases of temperature, considering individual and working characteristics in order to define adequate prevention measures for workers. The literature in this field is very limited. Calkins et al. (2019) carried out a case-crossover study to assess the relationship between heat exposure and occupational traumatic injuries claims among outdoor construction workers, using Washington State Fund workers' compensation claims data. They found maximum daily humidex to be associated with increasing traumatic injury risk. The same kind of data were used for a study carried out in a subalpine region of Northeast of Italy to assess the heat-occupational injuries relationship among construction workers, by means of a Poisson regression model (Riccò et al., 2020). Higher risk was reported during summer days (temperature higher than 25 °C) and in those with maximum temperatures higher than 95th percentile. Two previous studies stratified the analysis by economic sector and found a greater risk of injury for exposure to high temperatures in the construction sector (Martínez-Solanas et al., 2018; Marinaccio et al., 2019).

Our study found a positive association between high temperatures (between the 75th and 99th percentiles of daily mean temperatures) and occupational injuries in the construction sector, in agreement with previous studies. Results were robust for different parameters to model exposure–response nonlinearity and lag structure. The effect of heat is observed up to 3 days after exposure consistently with the results obtained in Spain (Martínez-Solanas et al., 2018) and in Italy (Marinaccio et al., 2019) for general occupational injuries. It might be due to the persistence of hot days in summer seasons, with a prolonged effect, which can significantly alter the state of hydration, affecting the attention during working activities, the ability to react to anomalous events and generally favoring distress of workers involved. This situation predisposes to the risk of accidents at work and the onset of heat diseases. The positive association with high temperatures is in agreement with results of the recent literature (Calkins et al., 2019; Riccò et al., 2020), as well as for cold effect (Riccò et al., 2020). However, the RR obtained in this study cannot be directly compared with those obtained in the above studies, either for the different metric used or for the different reference of temperatures. We found an attributable fraction of number of injuries of 1.7 % due to high temperatures. Furthermore, we assessed the impact of heat waves on occupational injuries in the construction sector for different definition of it. The higher is the temperature threshold level the higher is the risk of injuries. This result is in agreement with previous studies (Riccò et al., 2020; Rameezdeen and Elmualim, 2017).

This study found a protective association for low temperatures (between 1st and 25th percentile of daily mean temperatures) in agreement with results of a study carried out in a northern region of Italy about the occupational injuries occurred in the construction sector (Ricco et al., 2020). Marinaccio et al. (2019) also estimated non-significant effect for cold for occupation injuries occurred in the construction sector in Italy. A few colder regions (Piemonte, Trentino A.A, Umbria and Sardinia) were found positive associated with low temperatures (results not shown). As the construction sector has a strong seasonal behavior (see figure S2), with many working activities carried out during warmer seasons and much lower one during winter, the number of occupational injuries reflects this behavior especially during days with very low temperatures, as those analyzed in this study (1st to 25th percentiles of temperatures). This could have affected the identification of an association with low temperatures.

This study estimated the exposure–response function specifically for the construction sector, for the first time.

The national context of this study allows collecting a large number of occupation injuries, increasing its representativeness and accuracy, and providing information about the geographical heterogeneities of the studied phenomena. As for the latter, we found a medium degree of heterogeneity among the risks by regions of Italy for hot effect (figure S4 of SM). For most of them, the increment of risk (IR) was close to the overall one. Sicily, Emilia-Romagna and Liguria regions were at the lowest level of risk for high temperatures. As for the first two regions, this lower risk could be due to an effect of acclimatization to heat, a physiological response to repeated exposure to hot environments (Acharya et al., 2018). We also found some regions with the highest positive effect for high temperatures (Valle d'Aosta, Friuli V.G., and Basilicata), two with a strong (Molise) and moderate (Marche) protective effect. For some regions (Valle d'Aosta, Basilicata and Molise) these results might be due to the low number of injuries occurred (0.3–0.8 % of total accidents) with a likely impact on the effectiveness of the study.

The region-specific thresholds identified in this study could be implemented in the national occupational heat-warning system developed as part of a recent national project (Worklimate, https://www.worklimate.it/en/home-english/) as well as represent a valid support to the current legislation in force in the Italian territory to counter the effects of heat in the construction sector and which is currently based on exceeding an absolute daily temperature threshold of 35 °C.

Previous studies assessed the risk of injuries in the construction sectors for different individual and working characteristics (Rameezdeen and Elmualim, 2017; Calking et al., 2019; Dong et al., 2019; Riccò et al., 2020). However, none of these studies assessed the risk for the full accident related path, as included in the ESAW variables, such as: where it occurred (working environment); worker involved (age, profession, employement status); process in progress at the time of accident (working process); sequence of events (specific physical activity, deviation from the norm, contact - mode of injury and associated material agent); victim (day lost, permanent inhability). These factors are important for defining key determinants of heat-related accidents and to improve safety and prevention policies. As for age, we found the highest risk among youngest workers, decreasing with increased age, in agreement with other studies (Calkins et al., 2019; Riccò et al., 2020; Acharya et al., 2018). This result is of great importance given that younger workers underestimate the risk of heat, as emerged from a national survey on the perception and knowledge of this risk (Bonafede et al., 2022). We found construction sites, quarries and industrial sites, as those at greater risk for injuriy in hot conditions. Unqualified worker and mason were the two professions at higher risk for injury. The latter is in agreement with results by Dong et al. (2019). Injury is likely to occur during the progress of different processes like excavation, construction, repair and demolition, as well as during procedures of setting up, preparation, installation, mounting and disassembling. Among the specific physical activity carried out at the time of the accident, we found that machine operation, included the transportation, handling of objects and working with hand-held tools were the more likely to be involved during hot related accidents. Riccò et al. (2020) found the use of tools/machinery to be at risk during summer days in agreement with the results of this study. During the above specific activities, the most likely and risky deviations from the norm were breakage, bursting, splitting, slipping, fall, collapse of 'Material Agent' as well as body movement leading to an external injury, and the modalities at risk were the contact with sharp, pointed, rough, coarse 'Material Agent'. As far as the severity is concerned, we found low consequence accidents (4 to 7 days lost) as those at higher risk of accident under hot conditions. Calkins et al. (2019) also obtained similar results for less than 7 days time loss. Significant risks are also estimated in this study for up to 16 % of permanent incapacity to work.

The above risk profiles provide useful information to focus prevention policies for specific risky activities. According to the review published by (Acharya et al., 2018) and herein literature, the construction industry is one of the most affected by heat stress. The rising of temperatures produce thermal discomfort which impact on carelessness, fatigue, lack of alertness, loss of concentration, disorientation and reduced vigilance with possible morbidity effects (Varghese et al., 2018; Marinaccio et al., 2019; Acharya et al., 2018). These conditions during working activities contribute to increase the risk of injury. Hovewer, according to a study conducted in the United States, about the hazard recognition among the construction workers, roughly 47 % of the safety hazards in the gravity, electrical, motion, and temperature hazard categories were recognized (Uddin et al., 2020). At the same time a chinese study about the perception of workplace heat exposure, found that workers were concerned about it (Han et al., 2021). In addition, the high frequency of migrant workers in the construction sector, the harder work required to them, the poor knowledge about heat-health issues and the associated cultural aspects (religious, linguistic, adaptation), contribute to further increase the heat-related occupational vulnerability, although less impact from heat on productivity and thermal discomfort are reported (Rosano et al., 2012; Messeri et al., 2019). This study suggests that particular professions (unqualified and mason) and specific physical activities (machine operation, handling of objects, working with hand-held tools) carried out in particular working processes (excavation, construction, repair, demolition and setting up procedures), should be prioritized when prevention policies have to be applied in hot conditions and heat waves days (Acharya et al., 2018).

This study has a few limitations. The study, being based on municipal data, used municipal averaged temperature exposure data, which could not be representative of the actual exposure at the location of the accident. This study used the daily value as exposure indicator in agreement with a previous study (Marinaccio et al., 2019). However, it has been shown that the predictive ability of different temperature indicators in epidemiological studies is comparable (Barnett et al., 2010). The effect of humidity on temperature exposure has been partially considered by using the dew point temperature as sensitivity analysis. As outlined by recent studies, the strong correlation between different measures of temperature means that, on average, they have the same predictive ability on estimating mortality, and potentially also on occurrence of injuries (Barnett et al.,2010; Varghese et al., 2018, 2019; Marinaccio et al., 2019). The role of socio-cultural conditions, of not registerded irregular workers, and of nationality were not considered in the risk of occupational injuries. These might have a role in the evaluation of effect on occupational accidents (Riccò et al., 2019). The contribution of irregular workers on occupational injuries could not be quantified. According to recent estimates, in Italy irregular workers have been estimated to be 3.2 M with a rate of irregularity beetween 8.8 % and 21.5 % depending on the region (CGIA, 2021). These workers are expected to produce occupational injuries that are not accounted for, with a possible contribution in the evaluation of heat-related effects. This study, by considering only outdoor exposure, did not take into account indoor effects, or the combined effect, which could provide additional insights on workers for exposures to extreme temperatures. Data at individual level at the time of the accident, like the type of clothing, the idratation status and pregress morbidity status were not available. These factors affect the risk of heat related health effect (Kjellstrom et al., 2016; Parsons and Human, 2014; Morioka et al., 2006; Chan et al., 2013).

5. Conclusions

In conclusion, our study provides evidence of a significant risk of injuries due to the exposure to high temperatures and heatwaves among workers in the construction sector. Conversely, exposure to low temperatures does not seem to be a risk factor in the construction sector. The nationwide study and the availability of high quality accident related data allowed the identification of additional risk factors associated to heat-related injuries. Young age of workers and the jobs involved in the excavation, construction, repair and demolition appear the most relevant risk factors. The identified pattern of subgroup at high risk could help to guide regulators and governments for developing targeted injury prevention measures. Public education campaigns and governmental guidelines, optimizing of work–rest cycles according to meteorological conditions, heat-alert program, air ventilation, cool water dispensers and ice machines, are identified as proper prevention measures. Future scenarios of climate change and the predicted increase of intensity and frequency of heatwaves prioritizes the definition of policies and safety regulations for the occupational setting and specific for construction.

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CRediT authorship contribution statement

Claudio Gariazzo: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Luca Taiano:** Resources, Data curation, Writing – review & editing. **Michela Bonafede:** Writing – review & editing. **Antonio Leva:** Data curation, Writing – review & editing. **Marco Morabito:** Writing – review & editing. **Francesca de' Donato:** Methodology. **Alessandro Marinaccio:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2022.107677.

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Article

Effects of Temperatures and Heatwaves on Occupational Injuries in the Agricultural Sector in Italy

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Abstract: The effects of heat on health have been well documented, while less is known about the effects among agricultural workers. Our aim is to estimate the effects and impacts of heat on occupational injuries in the agricultural sector in Italy. Occupational injuries in the agricultural sector from the Italian national workers' compensation authority (INAIL) and daily mean air temperatures from Copernicus ERA5-land for a five-year period (2014–2018) were considered. Distributed lag non-linear models (DLNM) were used to estimate the relative risk and attributable injuries for increases in daily mean air temperatures between the 75th and 99th percentile and during heatwaves. Analyses were stratified by age, professional qualification, and severity of injury. A total of 150,422 agricultural injuries were considered and the overall relative risk of injury for exposure to high temperatures was 1.13 (95% CI: 1.08; 1.18). A higher risk was observed among younger workers (15–34 years) (1.23 95% CI: 1.14; 1.34) and occasional workers (1.25 95% CI: 1.03; 1.52). A total of 2050 heat-attributable injuries were estimated in the study period. Workers engaged in outdoor and labour-intensive activities in the agricultural sector are at greater risk of injury and these results can help target prevention actions for climate change adaptation.

Keywords: work-related injuries; occupational injuries; agricultural sector; temperatures; heat waves; timeseries studies

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1. Introduction

Temperatures across Europe and the Mediterranean basin are constantly rising, with the last ten summers registering above-average values, as reported by Copernicus Climate Services [1]. Summer 2022 registered a record +2.8 °C above the climatological average (1991–2020) and +0.4 °C higher than the previous year on record. As reported in the latest IPCC report, climate change is a matter of fact, and extreme climatic events, and increasing temperatures have been shown to have adverse impacts on human health in terms of increased mortality and morbidity with different impacts depending on age, gender, and socioeconomic characteristics, and will continue in the future with more frequent occurrences [2]. There is a growing body of emerging studies on the impact of climate change on the occupational sector, and the negative consequences concern capacity and costs in the production process, health injuries, and workers' health [3,4].

Adverse effects of heat and climate change on human health have been documented in numerous epidemiological studies all over the world [5,6] and some of them posed the question of the impact of extreme heat on workers' health [7–9]. In fact, workers employed in specific occupational sectors working outdoors can be particularly exposed to extreme events and physical fatigue for prolonged periods of time, which can lead to heat stress [10–13], with consequences not only on productivity and occupational costs [14–16], but also on work capacity [17], with possible consequences on occupational injuries [18]. Moreover, a series of surveys were conducted [19–21] and found that the perception of heat-related risk in workplaces is underestimated by workers, so it is crucial to strengthen their awareness of the risks and define adequate prevention strategies.

Evidence of the increasing risk of occupational injuries associated with high temperatures has been found in different geographical settings [22–30]. More recently, reviews have not only confirmed the association between occupational injuries and heath exposure but also summarized the evidence on vulnerability factors and sectors most at risk [31–38].

In Italy, several studies have been conducted on heat-related occupational injuries. A study conducted in Tuscany evaluated the association between heat and hospital admissions due to work-related accidents and found an increase in admissions on days with high apparent temperature [39]. A study conducted in three Italian cities (Rome, Milan, and Turin) showed an association between high temperatures and occupational injuries among workers employed in the construction, transportation, and energy sectors [40]. Most recently, Marinaccio et al. conducted a national study on temperature-related occupational injuries and found a significant relative risk of 1.17 (95% CI: 1.14–1.21) for increases in mean temperature above the 75th percentile and highlighted differences in risk estimates among economic sectors [22]. Moreover, Gariazzo et al. focused on occupational injuries related to heat waves and high temperatures in the construction sector and found significant relative risks for the particular type of workers, production processes, and specific activities performed before the accident [41]. Nevertheless, an Italian study on the evaluation of both occupational risks and impacts in the agricultural sector has not been carried out.

The aim of this study is to estimate the association between daily air temperatures and occupational injuries in the agricultural sector at the municipal level in Italy using national compensation claims. Furthermore, the study estimates the relative risk and attributable injuries for heat and heatwave exposures identifying individual vulnerability factors among agricultural workers.

2. Materials and Methods

2.1. Workers' Compensation Data

Data on 150,422 work-related injuries occurring in Italy between 2014–2018 were extracted from the Italian workers' compensation authority (INAIL) archives. Occupational injury claims related to the agricultural sector were selected and daily counts of events were calculated for each of the 8068 municipalities of Italy. Anonymization procedures were applied in order to ensure privacy.

Data includes information on gender, age at injury, professional qualification (labourer, self-employed, occasional), and duration of leave, considered as a proxy of severity of the injury.

Occupational injuries occurring while travelling (road accidents) and injuries occurring among individuals aged less than 15 years and over 85 were excluded. Data were also stratified by different variables (gender; age group: 15–34, 35–60, 61+; professional qualification: labourer, self-employed, occasional; duration of leave: 0–14, 15–29, 30–60, 61+ days); working process: crop production and harvesting, plant breeding, livestock farming and breeding, land preparation, auxiliary preparation, forestry, other).

2.2. Meteorological Data

Daily mean air temperature data for the study period were retrieved from ERA-5 Land climate reanalysis data [42] available from the Copernicus Climate data Store (CDS) and were considered as exposure variable.

For each of the 8068 Italian municipalities, the daily mean air temperature was calculated as the average mean temperature of all the grid cells included in the spatial domain of the municipality weighted by the area of inclusion.

A time series dataset of daily injuries and daily mean temperatures for each municipality for the entire 5-year study period (2014–2018) was constructed.

2.3. Statistical Analysis

Analyses of this work were produced with three different methodologies but with the common background of Distributed Lag Non-linear Model (DLNM) approach to take into account both the potential non-linear shape of the dose-response curve and the delayed effect of the exposure on the outcome [43,44].

The relationship between mean air temperature and injuries was modelled with a B-spline with one internal knot at the 50th percentile of region-specific temperature distributions, and the lag response with a categorical variable (lag window 0–2). An over-dispersed Poisson generalized regression model was used for the analyses, and time-varying covariates were fitted:

- summer population decrease (a 3-levels variable with value "2" for the 2-week period around 15 August; "1" from 16 July to 31 August with the exception of the aforementioned 2-week period; "0" elsewhere);
- public holidays (a 4-levels variable with value "1" on isolated days; "2" on Christmas, Easter and New Year's Day; "3" on the days surrounding Christmas, Easter, and New Year's Day; "0" elsewhere);
- a four-way interaction by municipality, year, month, and day of the week to control for long-term time trends and seasonality.

2.4. Effect Estimates

To estimate the exposure-response curve and the relative risks, a two-stage approach was considered. Firstly, for each of the 19 Italian regions (Valle d'Aosta region was excluded due to limited observations), specific over-dispersed Poisson generalized linear regression models were applied, while, in the second stage, the regional estimates were combined to obtain an overall dose–response curve, and effect-estimates by applying a multivariate meta-analytical regression [45].

Results for high temperatures are reported as the Relative Risk (RR) and 95% Confidence Intervals (95% CI) of work-related injuries in the agricultural sector for increases in mean temperature between the 75th and 99th percentile.

Effect modification was evaluated by stratifying the analysis by age group (15–34, 35–60, and 61+ years), injury severity (defined as the duration of leave in days and categorized as 0–14, 15–29, 30–60, and 61+ days), professional qualification (labourer, self-employed, occasional) and working process (crop production and harvesting, plant breeding, livestock farming and breeding, land preparation, auxiliary preparation, forestry, other).

2.5. Impact Estimates (Attributable Injuries)

In order to account for the impact of heat on occupational injuries in the agricultural sector, the number of attributable injury cases associated with the same temperature interval and relative 95% empirical Confidence Interval (95% eCI) were estimated, according to the methodology described in Gasparrini and Leone [44]. Moreover, the number of attributable cases by age, injury severity, and professional qualification variables were also estimated.

2.6. Heatwaves

To evaluate the effect of extreme events in summer, the analysis was restricted to the warm months (May to September), and the risk of occupational injury for heatwave days was estimated.

Firstly, heatwaves (HWs) were defined as three or more consecutive days of mean air temperature above the municipality-specific 90th percentile in the warm months. Secondly, the regional risk of injury on heatwave days, compared to non-heatwave days was estimated. Similarly to the previous analysis, the model was adjusted for day of the week, a two-way interaction term between municipality and year, and controlled for seasonal time trends with a spline modelled on the days of the warm period. Thirdly, regional estimates were meta-analysed to obtain an overall RR and relative 95% CI, and the attributable number of injuries occurring during HWs was calculated.

All analyses were performed using the R statistical software version 4.1.3 (http://R-project.org, accessed on 16 September 2022).

3. Results

During the study period (2014–2018) a total of 150,422 occupational injuries in the agricultural sector were reported in the 19 Italian regions (Table 1), with a decreasing trend over time both for annual and summer counts. The same trend was observed in each region (Table A1). Figure 1 shows the total number of occupational injuries for each region during the study period with the highest percentage of injuries in the Northern regions of Emilia-Romagna, Lombardia, Veneto, Toscana in the Centre and Puglia in the South (regional values are reported in Appendix A Table A1). The gender distribution of injuries is predominantly male (78%) reflecting the higher proportion of males employed in the agricultural sector in Italy. The majority (over 50%) of injuries occurred in the 35–60 years old age group in all the regions, while in a few of them (Friuli-Venezia Giulia, Lombardia, Puglia, and Sicilia) a higher number of injuries was observed among the youngest age group (15–34 years). As for the duration of leave, considered as a proxy of injury severity, 30% of the agricultural injuries were non-severe (<14 days leave) with a declining trend by increasing severity. Injury claims by professional qualification were heterogeneous among regions, with more than 50% of total injuries occurring among self-employed workers, with the highest proportion in Abruzzo (80%) and Molise (84%), and lowest in Calabria (16%), where the occasional workers had the highest proportion of injury claims (around 46% compared to a national average of 14%). Labourer injury claims were around 27% nationally, ranging from 12% in Abruzzo and Molise to 42% in Lombardia.

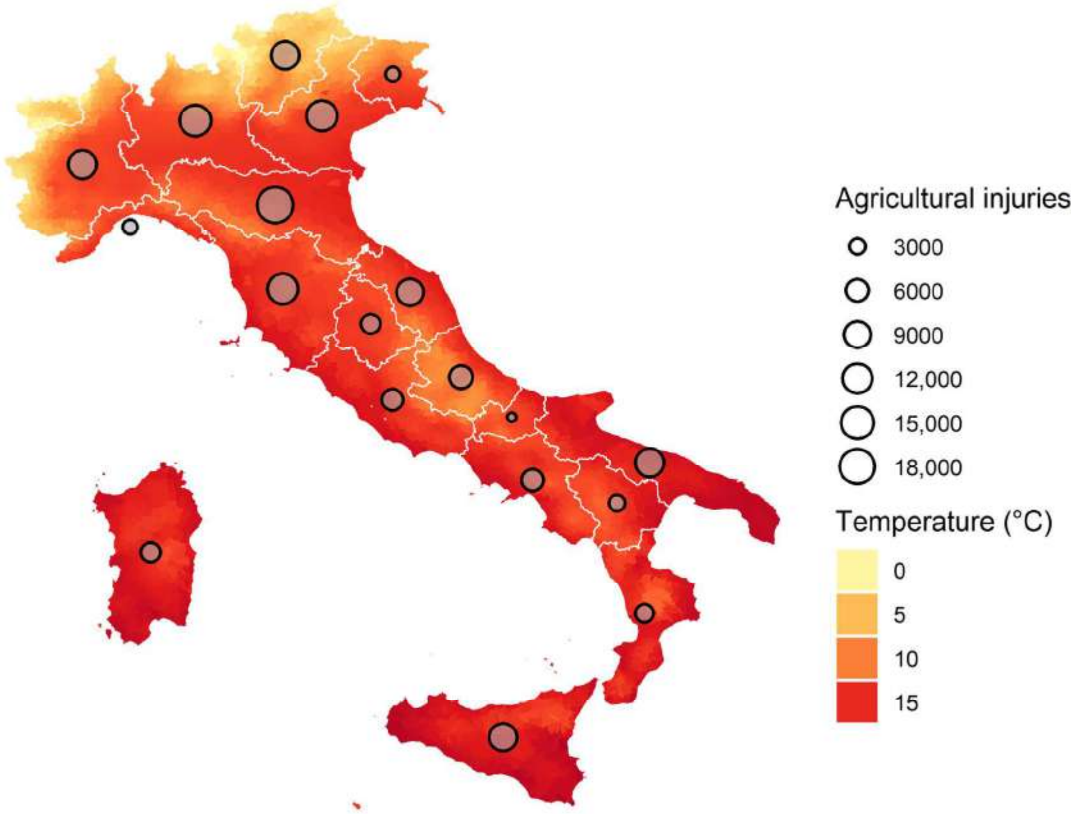

Figure 1. Daily mean air temperature and occupational injuries in the agricultural sector in Italy in the period 2014–2018. Air temperature is expressed at municipal resolution, while injuries are at the regional level.

Table 1. Descriptive statistics of occupational injuries in the agricultural sector, mean temperature and heatwaves in Italy in the study period (2014–2018).

		Full Period		**Summer (May–September)**	
		Frequency	**Percentage**	**Frequency**	**Percentage**
Overall		150,422	100	66,025	100
Year	2014	33,362	22.2	14,555	22.0
	2015	31,846	21.2	14,002	21.2
	2016	30,033	20.0	13,126	19.9
	2017	28,453	18.9	12,342	18.7
	2018	26,728	17.8	12,000	18.2
Sex	Male	117,874	78.4	51,339	77.8
	Female	32,548	21.6	14,686	22.2
Age group (years)	15–34	27,085	18.0	12,103	18.3
	35–60	94,122	62.6	41,243	62.5
	61+	29,215	19.4	12,679	19.2
Days of leave	0–14	45,421	30.2	20,636	31.3
	15–29	36,413	24.2	16,001	24.2
	30–60	36,054	24.0	15,507	23.5
	61+	32,534	21.6	13,881	21.0
Professional qualification	Labourer	41,377	27.5	18,896	28.6
	Occasional	21,687	14.4	9690	14.7
	Self-employed	87,345	58.1	37,434	56.7
		Annual average		**Summer (May-September) Average**	
Termperature °C	Mean	13.0		19.7	
	Min	−24.7		-5.8	
	1°	−4.6		7.0	
	25°	7.2		16.6	
	50°	12.9		19.7	
	75°	19.0		23.2	
	99°	28.0		29.1	
	Max	35.0		35.0	
				N (%)	**Average Temperature °C**
Heatwaves *	Yes	-	-	118 (15.4)	24.9°C
	No	-	-	647 (84.6)	18.7°C

* Heatwaves are defined as three or more consecutive days of mean temperature above the 90th percentile in summer months (May–September).

Figure 1 illustrates the mean air temperature in the study period at the municipal level showing a North–South gradient with higher temperatures in the Southern regions. The mean air temperature in the five-year period was of 12.9 °C, with the highest value in 2018 and the lowest in 2016 (Table 1 and Appendix A Table A2). The complex orography and its geographical location in the Mediterranean influence the climate of Italy and its regions. Mean temperatures in the Northern regions vary from 6.4 °C in Trentino-Alto Adige, 13.5 °C in Central regions, and 15.6 °C in the South, with the maximum value in Puglia (16.8 °C). Similarly, the percentiles considered in the analysis range from 12.6 °C to 22.4 °C for the 75th percentile and from 21.5 °C to 29.8 °C for the 99th, respectively in the coldest (Trentino-Alto Adige) and in the warmest (Puglia) region (Table 1).

Considering heatwaves during the warm season (May to September), around 15% of the days were identified as heatwaves, with an annual average of 24 HWs per year ranging between 5 in 2014 and 38 in the summer of 2015. The average temperature during a heatwave was of 24.9 °C.

Figure 2 shows the exposure-response curve of the association between daily mean air temperature and the risk of agriculture-related injuries.. The vertical lines represent the mean temperature percentile interval (75th and 95th) between which the risk of heat-related occupational injuries has been estimated. The figure shows a linear association between temperature and agricultural injuries with increasing risks as temperatures rise.

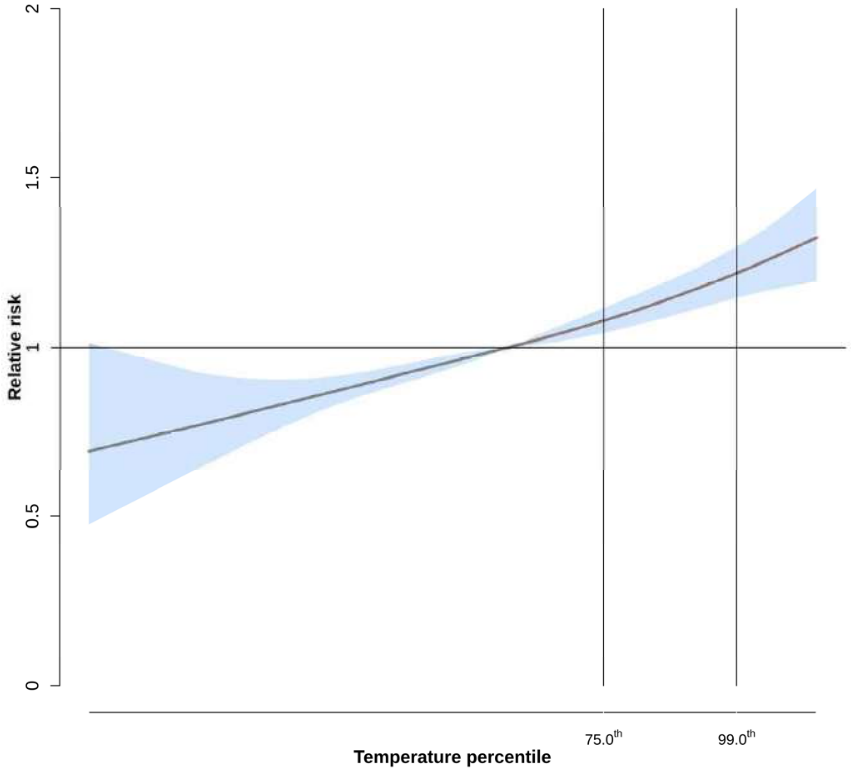

Figure 2. Meta-analytical exposure-response curve between daily mean air temperature and occupational injuries in the agricultural sector in Italy in the period 2014–2018. Estimates are expressed as Relative Risks (thick lines) and 95% confidence bands.

The cumulative relative risks (RR) of work-related injuries in the agricultural sector, associated with an increase in temperature between the 75th to 99th percentile, are reported in Figure 3. The overall RR was 1.13 (95% CI 1.08–1.18) and a greater risk of injury was observed among young workers aged from 15 to 34 years (RR 1.23, 95% CI: 1.14–1.34), occasional and self-employed workers (RR 1.25, 95% CI: 1.03–1.52 and RR 1.15, 95% CI: 1.08–1.23, respectively). Furthermore, agricultural workers have a greater risk of experiencing a non-severe (RR 1.21, 95% CI: 1.10, 1.33) or a mild injury (RR 1.14, 95% CI: 1.02, 1.29) than severe ones (RR 1.13, 95% CI: 1.01, 1.25 for 30–60 days of leave and RR 1.04, 95% CI: 0.93, 1.16 for more than 60 days). Considering working processes, a significant risk was found for workers carrying out land preparation (RR 1.18, 95% CI: 1.08, 1.30) and other agricultural processes (RR 1.16, 95% CI: 1.05, 1.27) (Table A4).

The risk of work-related injuries in the agricultural sector during HWs (3 or more consecutive days above the warm season 90th percentile) was 6% higher than on non-HW days (Figure 3).

Table 2 shows the number of injuries attributable to increases in daily mean air temperature between the 75th to 99th percentile. Over the entire 5-year study period, a total of 2050 heat-attributable injuries were estimated with an average of 410 per year. Considering worker subgroups, the greatest impact was observed among those aged 35–60 years and considering employment type, as expected, the self-employed category had the greatest number of heat-related injuries.

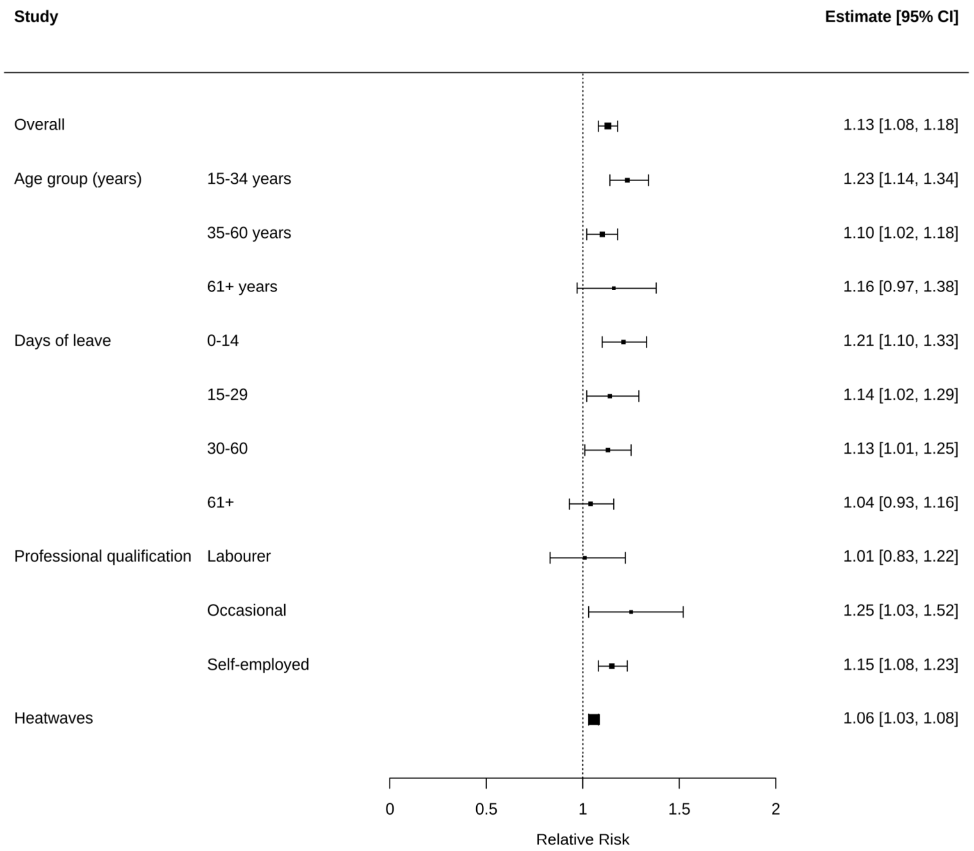

Figure 3. Relative Risks (and 95% confidence intervals) of work-related injuries in the agricultural sector for increases in daily mean temperature between 75th to 99th percentile (period 2014–2018). Square size represents the robustness of the estimates.

Table 2. Relative Risks (and 95% confidence intervals) and number of heat attributable injuries (and 95% empirical confidence intervals) in Italy for increases in mean temperature between the 75th to 99th percentile in the full period 2014–2018.

		RR (95% CI)	Attributable Injuries	95% eIC	
Overall		1.13 (1.08–1.18)	2050	1632	2455
Age group (years)	15–34	1.23 (1.14–1.34)	396	346	446
	35–60	1.10 (1.02–1.18)	1258	1024	1487
	61+	1.16 (0.97–1.38)	464	405	521
Days of leave	0–14	1.21 (1.10–1.33)	739	618	852
	15–29	1.14 (1.02–1.29)	578	492	660
	30–60	1.13 (1.01–1.25)	485	404	565
	61+	1.04 (0.93–1.16)	337	260	409
Professional qualification	Labourer	1.01 (0.83–1.22)	748	664	831
	Occasional	1.25 (1.03–1.52)	405	352	460
	Self-employed	1.15 (1.08–1.23)	1051	801	1300
Heatwaves *		1.06 (1.03–1.08)	608	−72	1237

* Heatwaves are defined as 3 or more consecutive days of mean temperature above the 90th percentile in summer months (May–September).

4. Discussion

This study explored the relationship between daily mean air temperature and the risk of occupational injuries among agricultural workers in Italy from 2014 to 2018. A relative risk of 1.13 (95% CI 1.08–1.18) for exposures between the 75th and 99th percentile of air temperature in the whole study period was found.

Several studies have evaluated the association between air temperature and occupational injuries, with the majority of these considering heat stress and HWs, but few of them focused on the agricultural sector [31–38]. Although all studies found a positive association between high temperatures and work-related injuries, comparisons are difficult because of differences in study design, statistical techniques, HW definitions, geographical or climatological settings, and sectors/activities included.

The physiological link between heat exposure and workers concerns both health and productivity [11] and depends on individual characteristics [10] as well as outdoor working conditions [46], that can be, however, mitigated by practices like hydration, work-time shifting, work-rest cycles and ventilated clothing [15,47–49]. In this context, the recent Italian Worklimate project has developed a heat stress forecasting system for different outdoor working scenarios [50], developing informative and training material for employers and workers to help raise awareness and prevent heat stress and injuries among workers (https://www.worklimate.it/en/, accessed on 17 November 2022).

An increasing risk of injuries for agricultural workers has been previously shown in Italy, especially in the North, both in the autonomous province of Trento in the first decade of 2000s [26], and in the Po River Valley in the second one [51]. Similarly, a study conducted in Spain, which has both similiar climatic conditions and agricultural activities to Italy, showed the highest percent risk difference (almost 30%) of injury associated with extreme temperatures in the 99th percentile versus the minimum occupational injury percentile among agricultural workers [23]. In Australia, studies conducted in different cities and regions confirm a significant risk of heat-related injuries among agricultural workers [29,52]. A study conducted in Brisbane reported a RR of 1.91 (95% CI: 0.72–5.03) for "agriculture, forestry and fishing" for exposures to high temperatures (99th percentile) while in Adelaide, the RR for "agriculture, forestry, fishing and hunting" category was even higher (4.01 (95% CI: 1.24–12.9) [29]. A study conducted in Washington State, USA [27], found an odds ratio of 1.10 (95% CI 1.01, 1.20) for outdoor traumatic injuries among agricultural workers due to apparent temperature values above 33 °C compared to lower ones (<25 °C). Findings from our study, in terms of risk estimates and the positive association between heat and occupational injuries in the agricultural sector are consistent with the evidence in the literature and meta-analytical results [31].

Although several studies on occupational injuries investigated the effect modification of the association with high temperatures, few of them focused on risk factors for agricultural workers. Riccò et al. reported the highest odds ratio in very young workers (<20 years old) related to >95th percentile of mean air temperature with a fluctuating trend among other age groups [51]. The estimates of this work report higher risks in the 15–34 and 61+ years age groups, respectively of 1.23 and 1.16, statistically significant only in the first case and consistently with the variability of Riccò's trend. A meta-analysis reported a higher risk (RR: 1.009, p-value: < 0.001) for young workers (age <35 years), possibly attributable to inexperience [31] but, on the other hand, there is evidence of higher risks among elderly workers, due to physiological mechanisms [11,53] and comorbidities [54]. In Italy, a greater risk for the under 35s is reported by both Marinaccio et al. [22] and Gariazzo et al. [41], probably due to an underestimation of the risk or a lack of training on specific risks [21]. In 35–60 year old workers, although a lower risk was found, the highest impact in terms of the number of attributable injuries was estimated, as the greatest proportion of workers are in this age group, suggesting the need to enhance prevention measures and awareness campaigns for both workers and employees. When considering the severity of injuries, only one case-crossover study, previously mentioned, on agricultural workers in Washington State [27], found a greater risk in mild-severe and severe injuries (25–29, 30–33, 34 or more days of leave) which is in contrast to findings from our study, in which a decreasing risk at increasing severity of injury was observed. In the context of professional qualification of agricultural workers, a higher risk was estimated for occasional and self-employed workers, and self-employers also showed the highest impact (attributable injury cases). It is plausible that both these categories could be the less trained and experienced, in the first one because of the temporary nature of work, in the second one due to the absence of colleagues with more experience to learn from.

The definition of HWs varies among studies and sensitivity analyses suggested to not directly compare studies that use different definitions [6]. However, two studies investigated the effect of HWs on occupational injuries in Australia, both defining HWs as three consecutive days with maximum temperature over 35 °C, and obtained contrasting results. In fact, the first one, conducted in Adelaide [55], found a positive incidence rate ratio of 1.45 (95% CI 1.13–1.86) for "agriculture, forestry and fishing" while a second study [56] found a non-significant relative risk of 0.98 (95% CI 0.62–1.54) for "agriculture, forestry, fishing and hunting" workers. Contrasting results came out also when considering the severity of HWs defined by a newly proposed metric of heatwave severity, the Excess Heat Factor (EHF) index [57], with negative risks for low and high-severity HW days and positive for moderate ones. The definition chosen for HWs considered in this study is consistent with previous studies conducted in Italy and with the definition used in the Italian Heat Health Watch Warning System (HHWWS) [58,59].

The strengths of this work lie in the coverage of the outcome, which includes injury claims at the national level in the agricultural sector and on the high spatial resolution of the exposure. Moreover, both injuries and temperature data are detailed at the municipal level. For the first time, this study provides estimates of attributable injuries in the agricultural sector by age, days of leave, professional qualification and HWs. However, it is also worth mentioning the limitations of the impossibility of including the irregular workers not registered in the INAIL database, underestimating the number of injuries, and a great heterogeneity in agricultural activities and processes carried out between regions.

In summary, the study shows that high temperatures are a significant risk factor for occupational injuries, with stringer effects among the young, occasional, or self-employed workers.

In coming years we can expect that climate change and a warming climate will enhance the adverse impacts on occupational health and work productivity around the world [2,12]. A recent study estimated that Under RCP8.5 by 2100, global GDP declines by 1.4% due to heat stress [4]. It was estimated that in Italy, the labour productivity loss will more than double in 20 years from 300 million dollars in 2010 to 650 in 2030 [59]. Furthermore, it has been estimated that in Southern Europe in 2030 the total hours of work lost due to heat stress will double with respect to 1995 and for Italy, the same result is expected in the agricultural sector [3]. Specific adaptation and protective strategies to protect workers in the context of climate change need to be promoted. Warning systems for specific occupational settings, improving thermal characteristics of working environments, reducing physical activity in work settings, use of protective clothing, hydration, and cooling spaces need to be implemented and provided as well as research on monitoring heat exposure and physiological heat stress and evaluating preventive actions need to be enhanced. Future studies in the occupational sector should address region-specific area and individual worker risk factors and develop sector-specific response measures, in order to define more effective prevention strategies.

5. Conclusions

Heat has a significant impact on occupational injuries in the agricultural sector and adequate prevention measures need to be introduced to reduce risks and respond to future climate change. The results of this study could be useful in the awareness of such problems and fruitful in implementing prevention actions and working conditions in the agricultural sector, which is one of the sectors at highest risk due to climate change.

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Appendix A

Table A1. Descriptive statistics of occupational injuries in the agricultural sector by region, in Italy in the study period (2014–2018).

		Year									
		2014		**2015**		**2016**		**2017**		**2018**	
Regions	**Total**	**Freq**	**%**	**Freq**	**%**	**Freq**	**%**	**Freq**	**%**	**Freq**	**%**
Piemonte	10,710	2414	22.5	1040	22.0	968	20.2	882	18.6	821	16.7
Lombardia	13,771	1414	23.1	1281	20.9	1271	20.0	1132	18.8	1079	17.2
Trentino-Alto Adige	10,533	1089	22.8	984	20.5	916	18.9	893	18.6	958	19.3
Veneto	13,114	1298	22.0	1262	21.5	1182	19.9	1103	18.7	1084	17.9
Friuli-Venezia Giulia	2444	243	20.6	247	22.4	221	20.4	216	18.9	205	17.8
Liguria	2466	247	22.4	233	21.9	204	19.9	197	18.9	169	16.9
Emilia-Romagna	19,299	1989	22.2	1872	21.6	1760	19.7	1603	18.4	1668	18.1
Toscana	12,794	1215	22.3	1174	21.8	1045	19.7	996	18.5	1006	17.6
Umbria	4301	418	22.4	399	21.9	360	19.2	295	18.6	317	18.0
Marche	9574	886	22.7	922	21.2	816	20.1	723	18.9	699	17.0
Lazio	5367	511	23.3	513	22.4	383	18.5	434	18.9	406	16.9
Abruzzo	6590	612	22.4	611	22.0	532	19.8	517	19.3	455	16.4
Molise	1619	174	24.1	149	20.0	136	20.5	118	17.5	136	17.9
Campania	5631	513	22.2	510	19.7	517	20.6	505	19.0	488	18.5
Puglia	11,136	899	20.4	984	20.5	968	20.9	850	18.9	905	19.2
Basilicata	2909	308	22.4	290	21.2	258	19.6	251	20.9	201	15.8
Calabria	3726	345	20.4	319	20.1	368	22.1	375	20.8	279	16.6
Sicilia	10,043	817	20.2	836	19.7	856	20.9	856	20.1	817	19.2
Sardegna	4395	500	24.5	376	20.5	365	19.3	396	19.4	307	16.3

		Age Group (Years)						**Professional Qualification**					
		15–34		**35–60**		**31+**		**Labourer**		**Occasional**		**Self-Employed**	
Regions	**Total**	**Freq**	**%**	**Freq**	**%**	**Freq**	**%**	**Freq**	**%**	**Freq**	**%**	**Freq**	**%**
Piemonte	10,710	2043	19.1	6023	56.2	2644	24.7	1880	17.6	548	5.1	8281	77.3
Lombardia	13,771	3111	22.6	8523	61.9	2137	15.5	5783	42.0	696	5.1	7292	53.0
Trentino-Alto Adige	10,533	1917	18.2	6115	58.1	2501	23.7	1867	17.7	593	5.6	8073	76.6
Veneto	13,114	2455	18.7	7825	59.7	2834	21.6	4186	31.9	566	4.3	8361	63.8
Friuli-Venezia Giulia	2444	555	22.7	1458	59.7	431	17.6	844	34.5	152	6.2	1447	59.2
Liguria	2466	451	18.3	1668	67.6	347	14.1	633	25.7	169	6.9	1664	67.5
Emilia-Romagna	19,299	3302	17.1	11,361	58.9	4636	24.0	5022	26.0	2872	14.9	11,404	59.1
Toscana	12,794	2319	18.1	7759	60.6	2716	21.2	4885	38.2	1068	8.3	6839	53.5
Umbria	4301	676	15.7	2638	61.3	987	22.9	1295	30.1	446	10.4	2558	59.5
Marche	9574	932	9.7	5486	57.3	3156	33.0	2025	21.2	537	5.6	7012	73.2
Lazio	5367	1072	20.0	3399	63.3	896	16.7	1477	27.5	696	13.0	3191	59.5
Abruzzo	6590	651	9.9	4264	64.7	1675	25.4	799	12.1	542	8.2	5249	79.7
Molise	1619	170	10.5	1157	71.5	292	18.0	188	11.6	74	4.6	1357	83.8
Campania	5631	808	14.3	4154	73.8	669	11.9	1413	25.1	850	15.1	3368	59.8

Table A1. *Cont.*

		Age Group (Years)						Professional Qualification					
		15–34		35–60		31+		Labourer		Occasional		Self-Employed	
Regions	**Total**	**Freq**	**%**	**Freq**	**%**	**Freq**	**%**	**Freq**	**%**	**Freq**	**%**	**Freq**	**%**
Puglia	11,136	2435	21.9	7675	68.9	1026	9.2	2358	21.2	4782	42.9	3996	35.9
Basilicata	2909	440	15.1	2061	70.8	408	14.0	748	25.7	752	25.9	1409	48.4
Calabria	3726	785	21.1	2663	71.5	278	7.5	1398	37.5	1718	46.1	610	16.4
Sicilia	10,043	2291	22.8	6757	67.3	995	9.9	2913	29.0	4451	44.3	2677	26.7
Sardegna	4395	672	15.3	3136	71.4	587	13.4	1663	37.8	175	4.0	2557	58.2

Table A2. Descriptive statistics of air temperature and heatwaves by region, in Italy in the study period (2014–2018).

Regions	Temperature °C				Heatwaves *	
	Mean	SD	Percentiles 75th	Percentiles 99th	N	Mean Temperature °C
Piemonte	11.1	8.0	17.4	26.6	116	23.4
Lombardia	12.1	8.0	18.5	28.0	117	24.8
Trentino-Alto Adige	6.4	7.9	12.6	21.5	109	18.5
Veneto	12.7	8.0	19.1	28.6	116	25.4
Friuli-Venezia Giulia	11.8	7.7	18.0	26.9	116	24.0
Liguria	13.2	6.4	18.6	25.4	114	23.7
Emilia-Romagna	13.7	7.7	19.8	29.0	118	26.5
Toscana	13.9	6.9	19.5	27.5	122	25.5
Umbria	13.4	7.2	19.1	27.9	123	25.9
Marche	13.9	7.1	19.6	28.1	119	26.0
Lazio	13.8	7.0	19.5	27.7	128	25.6
Abruzzo	12.0	7.3	17.7	26.9	117	24.0
Molise	12.9	7.1	18.6	27.2	117	24.9
Campania	14.7	6.7	20.2	27.9	125	25.9
Puglia	16.8	6.7	22.4	29.8	123	28.2
Basilicata	13.7	7.2	19.5	28.6	118	26.0
Calabria	15.3	6.3	20.5	27.9	117	25.8
Sicilia	16.2	6.4	21.6	28.9	112	26.9
Sardegna	15.9	6.4	21.4	28.6	109	27.0

* Heatwaves are defined as 3 or more consecutive days of mean temperature above the 90th percentile in summer months (May–September).

Table A3. Relative Risks (and 95% confidence intervals) of work-related injuries in the agricultural sector for increases in daily mean temperature between 75th to 99th percentile (period 2014–2018), by region.

Regions	RR	95% CI	
Piemonte	1.16	1.13	1.19
Lombardia	1.23	1.21	1.26
Trentino-Alto Adige	1.17	1.12	1.23
Veneto	1.16	1.12	1.20
Friuli-Venezia Giulia	0.90	0.86	0.95
Liguria	1.17	1.11	1.23
Emilia-Romagna	1.22	1.17	1.27
Toscana	1.06	1.00	1.11
Umbria	0.97	0.89	1.07
Marche	1.07	1.01	1.13
Lazio	1.34	1.28	1.40
Abruzzo	1.29	1.23	1.35
Molise	1.15	1.07	1.23
Campania	1.00	0.97	1.04
Puglia	1.14	1.09	1.20
Basilicata	1.15	1.08	1.23
Calabria	0.97	0.93	1.01
Sicilia	1.09	1.05	1.13
Sardegna	1.29	1.24	1.34

Table A4. Relative Risks (and 95% confidence intervals) of work-related injuries in the agricultural sector for increases in daily mean temperature between 75th to 99th percentile (period 2014–2018), by working process.

Working Process *	RR	95% CI	
Crop production and harvesting	0.92	0.60	1.41
Plant breeding	0.97	0.67	1.39
Livestock farming and breeding	1.11	0.85	1.47
Land preparation	1.18	1.08	1.30
Auxiliary preparation	1.07	0.77	1.49
Forestry	1.67	0.97	2.86
Other	1.16	1.05	1.27

* Crop production and harvesting: Harvesting, Cutting, Reaping, Threshing; Plant breeding: Seeding, Stratification, Planting; Livestock farming and breeding: Farming, Insemination, Milking, Shearing; Land preparation: Ploughing, Tillage, Drainage, Fertilization; Auxiliary preparation: Mechanical activities, Woodworking, Cleaning, Surveillance Forestry: Cutting down tall trees, Cutting of coppice, Cutting of plants at the height of the stump or collar, First processing of lumber on the spot; *Other*: Other preparations before harvesting, Different activities of reclamation, Special plantations, Further preparations after seeding.

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Article

Workers' Perception Heat Stress: Results from a Pilot Study Conducted in Italy during the COVID-19 Pandemic in 2020

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Abstract: Many workers are exposed to the effects of heat and often to extreme temperatures. Heat stress has been further aggravated during the COVID-19 pandemic by the use of personal protective equipment to prevent SARS-CoV-2 infection. However, workers' risk perception of heat stress is often low, with negative effects on their health and productivity. The study aims to identify workers' needs and gaps in knowledge, suggesting the adaptation of measures that best comply with the needs of both workers and employers. A cross-sectional online questionnaire survey was conducted in Italy in the hottest months of 2020 (June–October) through different multimedia channels. The data collected were analyzed using descriptive statistics; analytical tests and analysis of variance were used to evaluate differences between groups of workers. In total, 345 questionnaires were collected and analyzed. The whole sample of respondents declared that heat is an important contributor to productivity loss and 83% of workers did not receive heat warnings from their employer. In this context, the internet is considered as the main source of information about heat-related illness in the workplace. Results highlight the need to increase workers' perception of heat stress in the workplace to safeguard their health and productivity. About two-thirds of the sample stated that working in the sun without access to shaded areas, working indoors without adequate ventilation, and nearby fire, steam, and hot surfaces, represent the main injuries' risk factors.

Keywords: risk perception; risk knowledge; heat stress prevention measures; heat exposure; occupational injuries

1. Introduction

Mean annual air temperatures are getting hotter globally due to climate change [1]. The year 2021 was the 7th consecutive year (2015–2021) where the global temperature had been over 1 °C above pre-industrial levels (1850–1900), with 2016, 2019, and 2020 constituting the top three ones [2,3]. Because of climate change, a substantial increase in the frequency and intensity of heat waves has been observed in the hottest months of the year, and it has been estimated that around 30% of the world population is currently exposed to climatic conditions particularly critical for human health for at least 20 days a year [4]. Workers, in particular those who spend most of their activities outdoors, are among the individuals the most exposed to the effects of heat and in general to extreme temperatures [5,6]. The situation has further deteriorated during the current COVID-19 pandemic due to the widespread use of personal protective equipment (PPE) to prevent SARS-CoV-2 infection, which tends to increase heat stress [7–9]. The challenges derived from heat exposure to workers' health and productivity [10] have already been identified as significant problems in tropical areas and are becoming more and more common also in the USA and in EU countries; not only outdoor workers, such as farmers and construction workers [11,12], but also indoor workers performing tasks nearby heat-generating equipment [13,14], such as iron and steel workers, boiler room workers, bakers, firefighters, especially if involved in moderate or high-intensity activities, are at the higher risk of heat illnesses, injuries, and even heat stress-related death [15].

Occupational heat stress is a risk factor for medical conditions collectively defined as heat illnesses, which include minor symptoms such as heat rash, heat cramps, and heat edema, and more serious conditions such as heat syncope and heat exhaustion [4]. The most severe form of heat illness is heatstroke. Contrary to a classic heatstroke, which more commonly occurs among the elderly, children and people with underlying chronic diseases, the exertional heatstroke, the one occurring among workers, typically affects healthy young individuals. Heatstroke is a potentially life-threatening health condition that is facilitated by carrying out strenuous activities in severe heat and/or humidity [16]. Kidney diseases are also often diagnosed in otherwise healthy young adults commonly exposed to heat and dehydration in the workplace [17,18].

Heat-related illnesses and injuries are largely preventable. It is essential that workers know the possible health effects of working in the heat and that heat-illness prevention and response programs are established in the workplace so that workers are kept safe from the health effects of extreme heat.

There is a need to investigate the baseline information regarding how people perceive the heat risk to develop a heat stress effective management system. Workers' awareness of the possible effects of heat stress and perceptions of its risk also constitute an essential part of policy decisions and improving climate change risk information and communication [19–21].

In Italy, the WORKLIMATE project ("Impact of environmental thermal stress on workers' health and productivity: intervention strategies and development of an integrated heat and epidemiological warning system for various occupational sectors", https://www.worklimate.it) (accessed on 30 June 2022), which started in June of 2020, has the aim to improve the knowledge base and awareness among workers on the health effects of environmental thermal stress conditions. As part of the project activities, a web-based questionnaire survey was conducted at the national level to investigate workers' perceptions and knowledge regarding the negative consequences of occupational heat stress, especially during COVID-19, and to identify potential barriers to prevent heat-related illnesses in the workplace, including education and training. The ultimate goal of our study is to identify workers' needs and gaps in knowledge, suggesting the adaptation measures that best comply to the needs of both workers and employers.

2. Materials and Methods

A cross-sectional questionnaire survey was conducted in Italy among workers in the hottest months of 2020, from the 1st of June to the 31st of October, through different multimedia channels, in order to reach a wide and varied target at the national level, specifically the following platforms were used: Physical Agents Portal (https://www.portaleagentifisici.it/) (accessed on 30 June 2022), Facebook, Twitter, LinkedIn, and WhatsApp, based on a communication plan daily updated. Direct mailing was used as well. The questionnaire was distributed through the Google Form online platform (https://docs.google.com/forms/d/19R5EGY5nH6k5vsjEAtx5Hx__SiV1l4Iv5BieHsV2m1U/edit?ts=5f0c33c5, last accessed on 11 January 2022), complemented by an informed consent form. Participation was voluntary and anonymous. The estimated completion time was around 20 min. Data were collected, stored, and analyzed according to the Regulation on the protection of natural persons with regard to the processing of personal data (EU Regulation 2016/679-General Data Protection Regulation-GDPR-application from 25 May 2018). This activity received the ethical clearance from the Commission for Ethics and Integrity of Research of the National Research Council (CNR) (N. 0009389/2020, 2 June 2020).

2.1. Questionnaire Design

The questionnaire of this pilot study (Supplementary Materials) was constructed ad hoc, taking into consideration the main literature review on the subject [22–31]. A pretesting on a random sample allowed the optimization of the instrument and to determine the time needed to complete the questionnaire.

The survey is composed by four sections:

1. SECTION A—DEMOGRAPHIC AND SOCIO-OCCUPATIONAL DATA—gender, age, school degree qualification, nationality, fasting for personal reasons, geographical area of work, work environment, marital status, number of children, job sector, job performed, company size, physical activity, presence of heat sources, use of chemicals, use of protective clothing, use of COVID-19 masks, warm months of the year worked, experience in Occupational Safety and Health (OSH), diagnosis of infection with the SARS-CoV-2 virus, development of COVID-19 disease in symptomatic form, and the presence of chronic diseases (questions from 1 to 25);
2. SECTION B—RISK PERCEPTION—questions on the qualitative dimensions of the risk [29–31] associated with heat stress, i.e., general risk perceived, voluntary nature, immediacy of effects, personal knowledge, scientific knowledge, novelty, chronic/catastrophic, common/terrifying, future generations, control of severity, visibility, personal exposure, collective exposure, severity of consequences (questions 26 to 43 on a 5-point Likert scale from 1 = “strongly disagree” to 5 = “strongly agree”);
3. SECTION C—RISK KNOWLEDGE—questions on the evidence relating to the most important effects of heat waves and heat stress, the categories of workers involved, and the main factors of vulnerability (questions 44 to 57 on a 5-point Likert scale from 1 = “strongly disagree” to 5 = “strongly agree”);
4. SECTION D—ACCIDENTS, PREVENTION MEASURES AND WORK POLICIES—questions about the frequency of heat-related diseases and injuries, opinions about work factors/hazards, and organizational aspects that contribute to the occurrence of such injuries, types of workers involved, heat injury prevention training, main sources of information on the prevention of heat-related diseases and injuries, warnings or alerts about the possibility of a heat wave, perception of loss of productivity, perceived obstacles to prevent heat-related workplace injuries (questions 58 to 81).

2.2. Study AREA and Climatic Characteristicsg

In the period of the questionnaire administration (from June to October 2020), during the complex management of the COVID-19 pandemic, climatic conditions in Italy were characterized by air temperatures generally above the average compared to the reference period 1981–2010. In particular, the most important thermal anomalies occurred in central Italy (Figure 1A), with positive anomalies close to 1.5 °C compared to 1981–2010. Concerning to the two hottest summer months (July and August), July (Figure 1B) revealed the highest thermal anomalies, greater than 1.0 °C compared to the climatological average in central and southern Italy, with peaks of 1.2 °C in Lazio and Campania regions. In August (Figure 1C), the thermal anomaly decreased, however, maintaining temperatures between 0.6 and 1.0 °C above the average compared to 1981–2010.

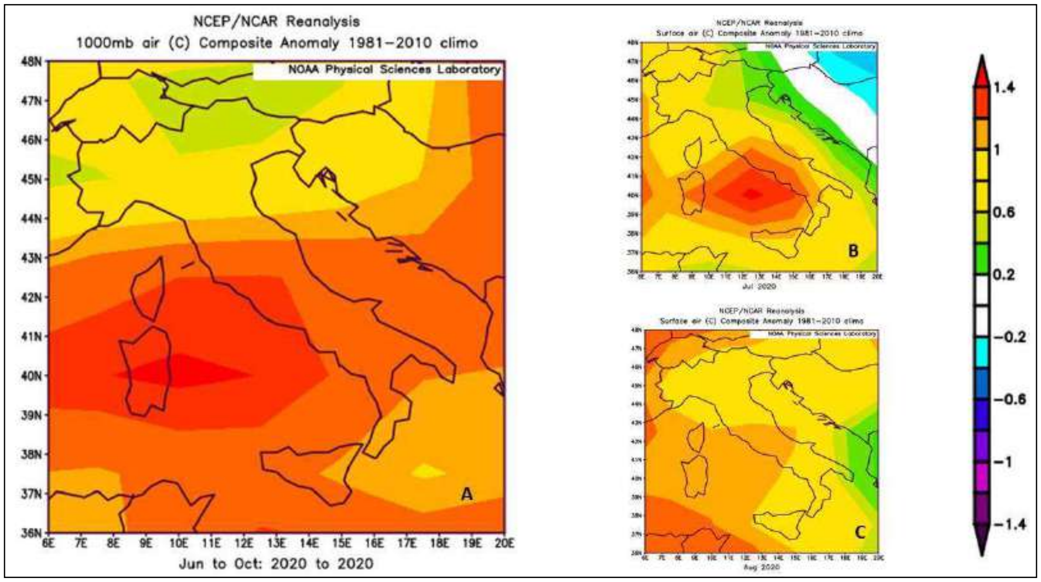

Figure 1. Air temperatures anomalies in Italy during the period June–October 2020 (**A**), July (**B**), and August 2020 (**C**) compared to the reference period 1981–2010. Data obtained from https://psl.noaa.gov/cgi-bin/data/composites/printpage.pl, accessed on 27 January 2022.

2.3. Data Analysis

The data collected were analyzed using descriptive statistics (i.e., frequency, mean, standard deviation) and analytical tests. The analysis of variance (ANOVA) and chi-square analysis (χ^2) were used to evaluate differences between groups. The chosen groups (for example, age, school degree qualification, workplace environment, use of wearing protecting clothing, use of COVID 19 mask, chronic diseases, etc.) were further grouped into three macro-groups (a. Demographic and professional characteristics, b. Characteristics of the work, c. Factors aggravating heat stress) in order to evaluate the fundamental aspects in the assessment of risk perception. The homogeneity of variance was verified with Levene's test. The Brown–Forsythe and Welch tests were used when the homogeneity of variance assumption did not hold for the data. A Principal Component Analysis (PCA) with Varimax rotation was carried out and Cronbach's Alpha calculation allowed an empirical assessment of the reliability to assess the dimensionality of sections "RISK PERCEPTION" and "RISK KNOWLEDGE". The results were considered significant at a *p*-value less than 0.05. All analyses were performed using SPSS v.25.0 for Windows (IBM, Armonk, NY, USA).

3. Results

3.1. Descriptive Analysis

In total, 345 workers participated in the self-administered web survey, most of whom (67.5%) carried out their work activities in central Italy. The sex distribution was coherent with that of the employed population in Italy with 57.7% men. The average age of participants was 45.4 years (SD ± 10.7): 59.7% of the sample in their professional life are or have been involved in OSH and 66.7% of the sample suffer from chronic diseases. The level of education (school degree qualification) of the respondents was high, with 61.2% of them having a bachelor/specialist/postgraduate degree and 30.4% of them having a high school diploma. As regards to the working environment, 64.9% of workers were mainly indoors in an air-conditioned environment, 21.2% were mainly indoors in a non-air-conditioned environment, and 13.9% of them were mainly outdoors. The most represented occupational sectors were professional, scientific, and technical activities (25.2%); construction (15.7%); public administration and Armed forces/military (11.9%); manufacturing (8.1%); and health and social works (8.1%). One in four (25.5%) received training on the prevention of heat-related injuries in the workplace, and 17.1% received warnings or alerts (Table 1).

Table 1. Sample description.

		N	%
Participants		345	
Gender	Male	199	57.7
	Female	146	42.3
Nationality	Italian	331	95.9
	EU	11	3.2
	Non-EU	3	0.9
Geographical area of working	North	94	27.2
	Centre-South	251	72.8
Marital status	Married-Accompanied	201	58.3
	Other	144	41.7
Age group	0–34	62	18
	35–44	101	29.3
	45–54	113	32.8
	55+	69	20
School degree qualification	Primary school certificate	3	0.9
	Junior high school certificate	26	7.5
	High school diploma	105	30.4
	Bachelor's degree	29	8.4
	Master's degree/specialist degree	89	25.8
	Postgraduate training	93	27.0
Workplace environment	Mainly indoors in air-conditioning environment	224	64.9
	Mainly indoors in non-air-conditioned environment	73	21.2
	Mainly Outdoors	48	13.9
Economic activity sector	Agriculture, forestry, and fishing	5	1.4
	Extraction of minerals from quarries and mines	1	0.3
	Manufacturing	28	8.1
	Electricity, gas, steam, and air conditioning supply	3	0.9
	Water supply; sewerage, waste management, and remediation activities	3	0.9
	Construction-Building	54	15.7
	Trade	17	4.9
	Transport and storage	9	2.6
	Accommodation and food service activities	2	0.6
	Information and communication services	16	4.6
	Financial and insurance activities	13	3.8
	Real estate activities	1	0.3
	Professional, scientific, and technical activities	87	25.2
	Rental, travel agencies, business support services	1	0.3
	Public administration and defense	41	11.9
	Education	27	7.8
	Health and social work	28	8.1
	Artistic, sporting, entertainment, and recreational activities	9	2.6
Number of employees in the company	From 1 to 9 employees	79	22.9
	From 10 to 49 employees	63	18.3
	From 50 to 249 employees	89	25.8
	250 and more employees	114	33

Intensity of physical activity in the workplace (on average)	Very light-light	232	67.2
	Intense-very intense	113	32.8
Heat sources	Yes/sometimes	62	18
	No	283	82
Use of chemicals	Yes/sometimes	86	24.9
	No	259	75.1
Wearing protective clothing	Yes/sometimes	175	50.7
	No	170	49.3
Use of COVID-19 face masks	0 h	71	20.6
	From 1 to 5 h	160	46.4
	6 h and more	114	33
Dealing with Occupational Safety and Health (OSH)	Yes	206	59.7
	No	139	40.3
Chronic diseases	Yes	230	66.7
	No	115	33.3
Injuries or accidents occurred during work experience due to hot/high humidity conditions	Don't know	32	9.3
	Never	90	26.1
	Rarely	100	29.0
	Few times	97	28.1
	Often	26	7.5
Training on the prevention of heat-related injuries carried out in the workplaces	Yes	53	15.4
	In some companies	35	10.1
	No	221	64.1
	Don't know	36	10.4
Warnings or alerts about the possibility of a heat wave received from employer	No	286	82.9
	Yes, with messages	21	6.1
	Yes, verbally	24	7.0
	Yes, by notices placed at information points	4	1.2
	Yes, by company-specific training	10	2.9

The main sources of information on the prevention of heat-related illness in the workplace were internet (16%), specific training in the workplace (13.8%), occupational physician (11.2%), TV and radio (8.4%) (Figure 2).

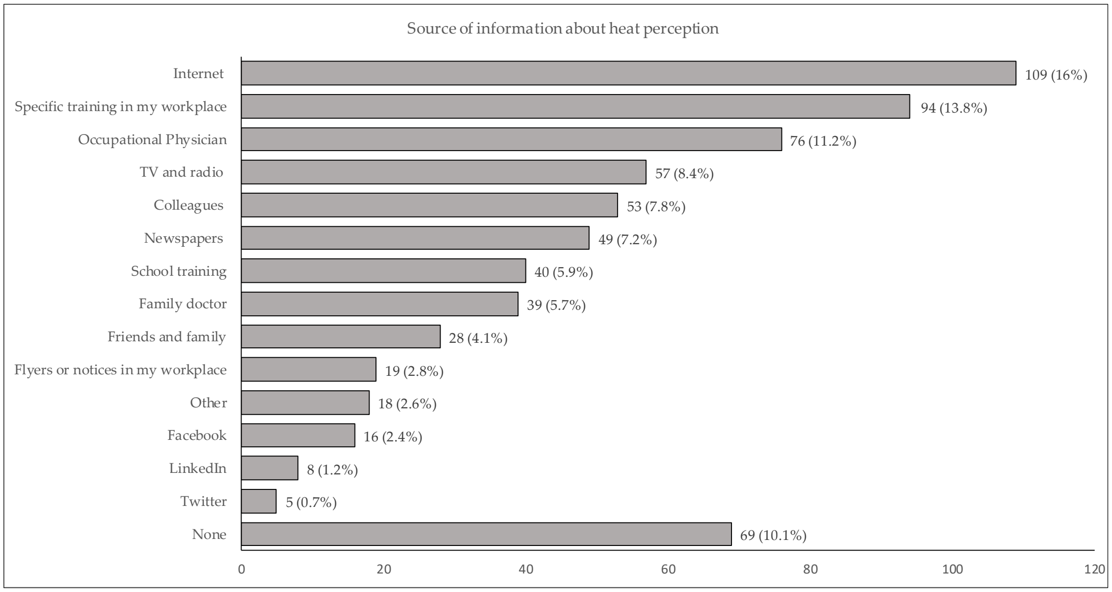

Figure 2. Frequencies and percentages of answers to the question 77—What are your main sources of information on the prevention of heat-related diseases in the workplace? (Multiple choice).

The whole sample perceived that heat is an important contributor to productivity loss (m = 3.93 on a scale of 1 to 5) (Figure 3).

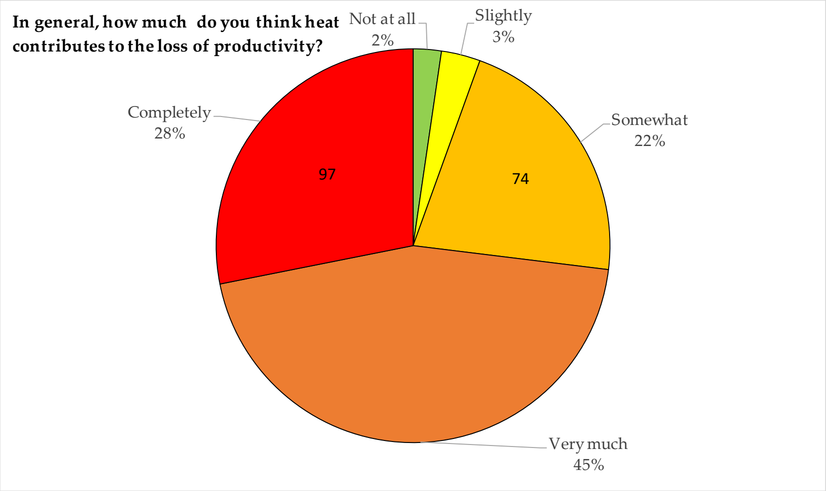

Figure 3. Frequencies and percentages of answers to the question 80—In general, how much do you think heat contributes to the loss of productivity?

In total, 64.6% of the respondents stated that rarely or sometimes or often injuries occur (at least partly) due to hot/high humidity conditions (Table 1). According to this group of workers, the factors/risks that contributed most to the occurrence of these heat-related injuries/illnesses were working in the sun without access to shade (solar radiation) (m = 3.97, sd = 1.04 on Likert scale from 1 = not at all to 5 = fully); working indoors without air conditioner, fan, or adequate ventilation (m = 3.74, sd = 1.08); and fire, steam, hot surfaces (m = 3.69, sd = 1.15). Again, for the same respondents, the organizational aspect mostly contributing to the occurrence of these heat-related injuries/illnesses was the lack of specific health and safety training on heat stress (m = 3.58, sd = 1.17 on Likert scale from 1 = not at all to 5 = fully). The workers who had mostly suffered these heat injuries were those between the ages of 56 and 65 (30.1%) and those over 65 (24.9%).

3.2. Principal Component Analysis of Section Risk Perception

A Principal Components analysis (PCA) was carried out on "Risk perception" to verify the existence of common dimensions. Four factors that explain 64.1% of the variance emerged from the analysis (Table 2).

The first factor (α = 0.83), which explains the 30.3% of the variance, was called "Personal exposure and fear of risk", because it brings together all the items concerning personal exposure to heat risk and related fear.

The second factor (α = 0.69), which explains the 14.3% of the variance, was called "Collective exposure and risk quality", because it brings together all the items concerning collective exposure to hot risk and the general qualities of this risk such as immediate effect, chronic or catastrophic nature, and voluntariness.

The third factor (α = 0.52), which explains the 10.5% of the variance, was called "Impact on health and prevention", because it brings together all the items concerning how much prevention measures in the workplace can reduce risk severity and the existence of observable symptoms.

The fourth factor (α = 0.40), which explains the 9.0% of the variance, was called "Knowledge risk perception", because it brings together all the items concerning opinions on the degree of knowledge of heat risk by workers and the scientific world.

In the factorial solution, the items 26, 27, 32, 34, 35, 43 were excluded.

Table 2. Principal Component Analysis of section "Risk perception". Extraction method: Principal Component Analysis. Rotation method: Varimax with Kaiser normalization.

N-Item	Component			
	1 "Personal Exposure and Fear of Risk"	2 "Collective Exposure and Risk Quality"	3 "Impact on Health and Prevention"	4 "Knowledge Risk Perception"
38—In summer, during my work, I feel exposed to heat (Personal exposure)	0.805			
41—I am afraid that heat waves will cause me to have an accident at work (Fear of risk)	0.781			
39—During a heat wave I feel very much at risk (Personal exposure)	0.780			
42—I am afraid that I will get sick because of heat waves (Fear of risk)	0.732			
29—Heat causes an immediate fatal effect for exposed persons (Immediacy effect)		0.754		
40—During a heat wave there are many workers at risk in Italy (Collective exposure)		0.709		
33—Heat is a potentially lethal risk (Chronic/Catastrophic)		0.693		
28—Workers are involuntarily exposed to heat (Voluntary risk)		0.538		
37—Heat risk damage is observable (Observability)			0.794	
36—Preventive measures in the workplace can reduce the severity of the heat risk (Controlling severity)			0.754	
31—The scientific world has a complete understanding of the heat risk (Knowledge of the risk)				0.819
30—Workers exposed to heat have precise knowledge of the risk (Knowledge of the risk)				0.731

3.3. Principal Component Analysis of Section Risk Knowledge

Principal Component Analysis (PCA) was carried out on items of "Risk knowledge" to verify the existence of common dimensions. One factor (α = 0.83), which explains the 54.4% of the variance, emerged from the analysis (Table 3).

In the factorial solution the items 46, 47, 51, 52, 53, 55, 56, 57 were excluded.

Table 3. Principal Component Analysis of section "Risk knowledge". Extraction method: Principal Component Analysis.

N-Item	Component
	1 "Risk Knowledge"
48—People with heart disease are at risk of worsening their health during a heat wave	0.793
44—Heat can be the cause of accidents for outdoor workers	0.775
49. Heat-related illnesses can lead to death	0.772
45—Heat can cause injuries for those working in a non-air-conditioned indoor environment	0.747
50—Dehydration in hot weather predisposes to the development of serious kidney disease	0.692
54—Heat waves can be a risk factor for depression and anxiety	0.631

3.4. Risk Perception: Differences between Groups

Table 4 shows the results reported by the respondents for the section "Risk perception".

Table 4. Means and standard deviations of the items in the section "Risk perception" on a 5-point Likert scale from 1 = "strongly disagree" to 5 = "strongly agree".

Risk Perception (Items)	Mean	SD
26—I feel that my health is threatened by climate change	3.22	1.01
27—I think that heat waves endanger my health	3.26	0.96
28—Workers are involuntarily exposed to heat	3.33	1.03
29—Heat causes an immediate fatal effect for those exposed	2.27	1.04
30—Workers exposed to heat have precise knowledge of the risk	2.20	0.84
31—The scientific world has a complete understanding of the heat risk	2.74	0.94
32—The heat risk is a new risk for Italian companies	2.98	1.07
33—Heat is a potentially lethal risk	3.32	0.99
34—Heat is a risk that workers have learned to live with	2.57	0.85
35—Heat poses a very low threat to future generations	1.77	0.95
36—Preventive measures in the workplace can reduce the severity of the heat risk	3.74	0.94
37—Heat risk damage is observable	3.36	0.93
38—In summer, during my work, I feel exposed to heat	2.96	1.10
39—During a heat wave I feel very much at risk	2.91	1.01
40—During a heat wave there are many workers at risk in Italy	3.66	0.85
41—I am afraid that heat waves will cause me to have an accident at work	2.65	1.15
42—I am afraid that I will get sick because of heat waves	2.43	1.05
43—During a heat wave I am afraid that the risk of transmission of the virus responsible for COVID-19 will increase	1.97	0.97

Regarding the factor "Personal exposure and fear of risk", and in particular, the macro groups "Demographic and professional characteristics" (a), "Characteristics of the work" (b), and "Factors aggravating heat stress" (c) (Table 5), the respondents considered themselves to be exposed to heat on average (item 38).

Table 5. Personal exposure and fear of risk for three macro-groups (a demographic and professional characteristics, b characteristics of the work, c Factors aggravating heat stress) for the items 38, 39, 41, 42, 40 36, 31, 30. SD, Standard Deviation.

Demographic and Professional Characteristics Age Groups (Years)	**N**	**%**	**Personal Exposure and Fear of Risk (N-Item)**								**Collective Exposure and Risk Quality (N-Item)**		**Impact on Health and Prevention (N-Item)**		**Knowledge of Risk Perception (N-Item)**			
			38		**39**		**41**		**42**		**40**		**36**		**31**		**30**	
			Mean (SD)	**F**	**Mean (SD)**	**F**	**Mean (SD)**	**F**	**Mean (SD)**	**F**	**Mean (SD)**	**F**	**Mean (SD)**	**F**	**Mean (SD)**	**F**	**Mean (SD)**	**F**
≤40	103	29.9													2.57 (0.99)	4.64		
41–54	173	50.1													2.74 (0.86)			
≥55	69	20													3.01 (1.02)			
School Degree																		
Primary-high school diploma	134		3.29 (1.19)	19.65	3.15 (1.04)	13.01			2.26 (0.92)				3.52 (1.05)				2.38 (0.92)	
Bachelor's degree-postgraduate training	211		2.74 (1.00)		2.75 (0.96)				2.48 (1.14)				3.88 (0.84)	11.11			2.08 (0.77)	9.82
Job Years																		
<5	84	24.3					2.49 (1.15)											
6–10	57	16.5					2.42 (1.08)											
11–20	104	30.1					2.56 (1.11)											
>21	100	29					3.00 (1.11)	4.75										
Dealing with Occupational Safety and Health (OSH)																		
Yes	206	59.7													2.86 (0.95)			
No	139	40.3													2.58 (0.91)	7.66		
Characteristics of the Work Workplace Environment	**N**	**%**	**Personal exposure and fear of risk (N-item)**								**Collective exposure and risk quality (N-item)**		**Impact on Health and Prevention (N-Item)**		**Knowledge of Risk Perception (N-Item)**			
			38		**39**		**41**		**42**		**40**		**36**		**31**		**30**	
			Mean (SD)	**F**	**Mean (SD)**	**F**	**Mean (SD)**	**F**	**Mean (SD)**	**F**	**Mean (SD)**	**F**	**Mean (SD)**	**F**	**Mean (SD)**	**F**	**Mean (SD)**	**F**
Mainly indoors in air-conditioning environment	224	64.9	2.58 (0.94)		2.77 (0.93)		2.45 (1.06)		3.10 (1.22)	10.77			3.83 (0.86)	6.31			2.08 (0.73)	10.08
Mainly indoors in non-air-conditioned environment	73	21.2	3.51 (1.06)		2.93 (1.06)		2.77 (1.22)						3.86 (0.89)	6.32			2.19 (0.84)	
Mainly Outdoors	48	13.9	3.85 (1.05)	47.74	3.50 (1.11)	10.87	3.38 (1.16)	14.23					3.15 (1.17)				2.75 (1.08)	
Kind of Physical Activity in the Workplace (on Average)																		

Very light-light	232	67.2	2.69 (0.99)				2.42 (1.05)						3.91 (0.81)	20.62			2.10 (0.78)	7.85
Intense-very intense	113	32.8	3.50 (1.13)	46.78			3.11 (1.22)	28.92					3.39 (1.09)				2.39 (0.94)	
Training Heat-Related Injuries																		
Yes/In some companies	88														3.08 (0.97)		2.42 (0.94)	
No/Don't know	257														2.63 (0.91)	15.52	2.12 (0.79)	15.52
Warnings Heat Wave Received																		
No	286														2.67 (0.93)	10.48	2.14 (0.81)	7.13
Yes	59														3.10 (0.90)		2.49 (0.95)	

Factors Aggravating Heat Stress	**N**	**%**	**Personal Exposure and Fear of Risk (N-Item)**								**Collective Exposure and Risk Quality (N-Item)**		**Impact on health and prevention (N-item)**		**Knowledge of Risk Perception (N-Item)**			
Heat Sources			**38**		**39**		**41**		**42**		**40**		**36**		**31**		**30**	
			Mean (SD)	**F**	**Mean (SD)**	**F**	**Mean (SD)**	**F**	**Mean (SD)**	**F**	**Mean (SD)**	**F**	**Mean (SD)**	**F**	**Mean (SD)**	**F**	**Mean (SD)**	**F**
Yes/sometimes	62	18	3.63 (1.16)	30.37			3.24 (1.21)	21.38					3.39 (1.19)				2.48 (1.04)	
No	283	82	2.8 (1.04)				2.52 (1.10)						3.82 (0.86)	7.33			2.13 (0.78)	6.27
Use of Chemicals																		
Yes/sometimes	86	24.9	3.53 (1.19)	28.94			3.17 (1.16)	25.78										
No	259	75.1	2.76 (1.01)				2.47 (1.10)											
Wearing Protective Clothing																		
Yes/sometimes	175	50.7	3.30 (1.13)	38.87			3.01 (1.14)	39.64					3.57 (1.04)					
No	170	49.3	2.60 (0.96)				2.27 (1.04)						3.92 (0.79)	12.08				
Use of COVID-19 masks																		
0 h	71	20.6	2.72 (1.06)	5.15														
From 1 to 5 h	160	46.4	2.88 (1.10)															
6 h and more	114	33	3.21 (1.11)															
Chronic Diseases																		
Yes	230	66.7			3.15 (1.07)	10.04					3.83 (0.76)	8.09						
No	115	33.3			2.79 (0.96)						3.57 (0.88)							

The feeling of being particularly exposed to heat risk was associated with: a lower level of education (school degree qualification); working outdoors or indoors in a non-air-conditioned environment; a high or very high work intensity; working near heat sources or use chemicals; wearing protective clothing; wearing a COVID mask for more than 5 h. During a heat wave, the sample felt on average at risk (item 39), in particular, those with a lower education, those suffering from chronic diseases, those working mainly outdoors. The entire sample had little fear of personally being the victim of an accident at work caused by heat waves (item 41). The most afraid were those who have been doing the same job for more than 20 years, those who work mainly outdoors, those who have a high or very high work intensity, those who work near heat sources or use chemicals, and those who wear protective clothing. The responding workers also had little fear of getting sick from heat waves (item 42), more fear was felt by those who work mainly outdoors.

Regarding the factor "Collective exposure and risk quality", respondents thought that during a heat wave in Italy, there are many workers at risk (item 40), in particular, those suffering from chronic diseases. The sample agreed on average, that heat risk is involuntary (item 28) and that it represents a potentially lethal risk (item 33). There was little agreement among the sample with the statement "Heat causes an immediate fatal effect for those exposed" (item 29).

Regarding the factor "Impact on health and prevention", the respondents believed that preventive measures in the workplace can reduce the severity of heat risk (item 36), in particular, it was stated by those with a higher education, those who work mainly indoors in air-conditioned and non-air-conditioned environments, those with a light or very light work intensity, those who do not work near heat sources, those who do not use protective clothing. The sample considered the average observable thermal damage, i.e., that the symptoms of injuries or illnesses due to exposure to heat are on average recognizable (item 37).

Regarding the factor "Knowledge risk perception", according to the whole sample, the scientific community has quite little knowledge about heat risk (item 31), especially younger people (up to 40 years old), those who do not work or have worked on OSH, those who do not receive heat risk warnings, those who have not received training on heat injury prevention. The entire sample agreed that workers exposed to heat have little knowledge of the risk (item 30), in particular, those who have a higher education, those who work mainly indoors in an air-conditioned environment, those who have a light or very light work intensity, those who do not receive heat risk warnings, those who have not received training on the prevention of heat-related injuries, those who do not work near heat sources.

3.5. Risk Knowledge: Differences between Groups

The responses related to risk knowledge were re-coded in 'correct' and 'incorrect' knowledge.

The entire sample shows little knowledge of hot-weather risk. The only questions answered correctly by more than 40% were: "Due to the shade of the buildings, heat waves are less common in cities than in rural areas" (51.9%), "Heat stress during the night is of no importance" (59.4%), "Heat waves can be a risk factor for depression and anxiety" (44.9%). As for the first statement, the opposite is true. The second question was answered more correctly by women (68.5%, $p = 0.002$), those who do not work near heat sources (62.9%, $p = 0.004$), those who have not received training on the prevention of heat injuries (62.6%, $p = 0.025$).

Questions answered less than 20% correctly were: "Heat can cause injuries for those working in an unconditioned indoor environment" (16.2%), "Younger workers are particularly vulnerable during a heat wave" (6.1%), "Excessive sweating during a heat wave can be a sign of heat stress" (19.4%), 'Heat waves promote the growth of harmful bacteria in water and food' (18.6%).

3.6. Perceived Obstacles to Preventing Heat-Related Workplace Injuries: Differences between Groups

Respondents believed that the top five obstacles to preventing heat-related occupational accidents (Figure 4) were:

1. Lack of commitment by employers to protect health and safety (m = 3.92, sd = 1.14 on a scale of 1 to 5); particularly for those with chronic illnesses (m = 4.15, sd = 1.06, F = 7.28, *p* = 0.007) and those who have not received training on preventing heat-related injuries (m = 4.02, sd = 1.10, F = 9.17, *p* = 0.003).
2. Lack of training by company health and safety managers (m = 3.91, sd = 1.13); especially of those who have not received training on preventing heat-related injuries (m = 4.04, sd = 1.04, F = 10.19, *p* = 0.002) and those working in large companies (m=4.12, sd = 1.06, F = 3.26, *p* = 0.022).
3. Lack of training of workers (m = 3.81, sd = 1.12); especially of those with higher education (m = 3.96, sd = 1.04, F = 8.85, *p* = 0.003), those not trained in heat injury prevention (m = 3.94, sd = 1.06, F = 13.26, *p* = 0.000), and those working in large companies (m = 4.02, sd = 1.08, F = 3.23, *p* = 0.023).
4. Lack of compliance with regulations (m = 3.79, sd = 1.07); especially for those working in medium-sized (m = 3.98, sd = 1.02, F = 5.12, *p* = 0.002) and large companies (m = 3.92, sd = 1.08, F = 5.12, *p* = 0.002), those suffering from chronic illnesses (m = 3.97, sd = 1.00, F = 5.44, *p* = 0.020).
5. Lack of awareness among company health and safety managers of the risks from heat (m = 3.77, sd = 1.18); especially for women (m = 3.98, sd = 1.05, F = 8.25, *p* = 0.004) and those who have not received training on preventing heat-related injuries (m = 3.94, sd = 1.06, F = 16.79, *p* = 0.000).

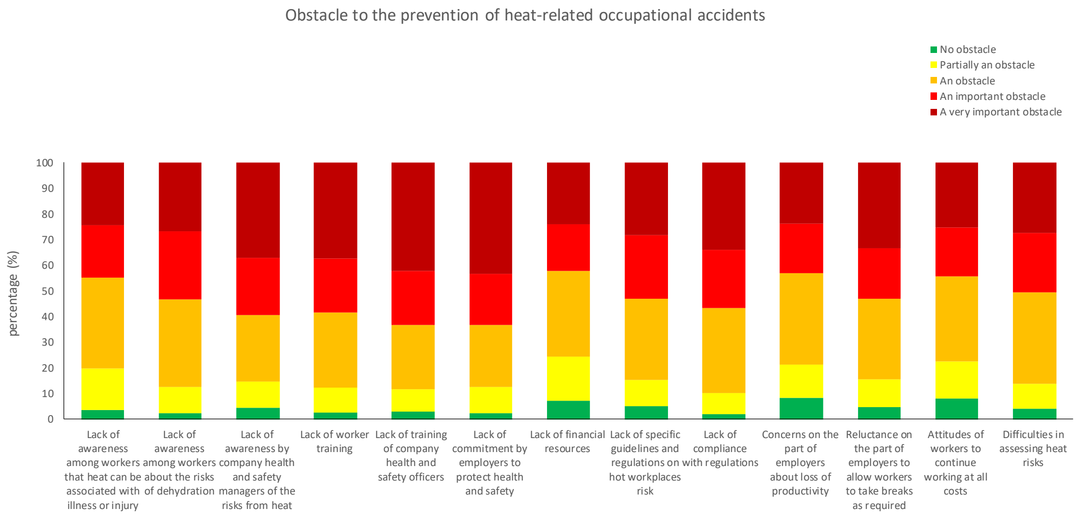

Figure 4. Percentages of answers to question 81—To what extent do you think that each of the following conditions can hinder prevention of heat-related occupational injuries? (A 5-point Likert scale from 1 = no obstacle at all to 5 = a very important obstacle).

4. Discussion

The year 2020 was the second hottest year on Earth in a record 140 years (just behind 2016) and the hottest year on record in Europe [32]. An increasing number of epidemiological studies have provided evidence of the association between heat exposure and the risk of accidents at work [5,6,14,23,33–35] and this phenomenon can be explained by a decrease in cognitive performance in people who work in hot and humid environments in Europe [36]. Confirming this aspect, a recent review demonstrated that a raised core temperature is associated with a reduction in vigilance and more complex dual-task performance [37]. In addition, also dehydration associated with hot conditions causes a severe reduction in physical and cognitive performance [37–40]. In general, according to Varghese et al. [35], work-related injuries/accidents in hot conditions can be caused by physical discomfort and altered behavior, fatigue, declining psycho-motor performance, loss of concentration, and reduced alertness.

Prolonged exposure to heat can also have a major impact on productivity [34,41–43]. A better understanding of how workers perceive the risks of exposure to heat in the workplace is necessary for the development of heat prevention strategies [35] and to minimize the impact of extremely high temperatures on the health and safety of workers [44]. However, only a few studies have investigated perceptions of heat risk among workers [9,19,21,22,24–27,45,46].

The main strength of this study is that the increase of knowledge of the heat risk workers' perception can be particularly useful for the development of the risk awareness process by all safety actors. The results of this study showed that the categories most exposed to heat risk are those who feel most at risk, even during a heat wave, and who are most afraid of being personally the victim of an accident at work caused by heat waves or getting sick from it. This result confirms the evidence of the Australian survey [19,27,46] and more generally of the more developed countries.

The whole sample considered that during a heat wave in Italy, there are many workers at risk, and that on average heat risk is involuntary and potentially lethal. However, it emerged that the risk perception was low in younger workers (less than 40 years old), in contrast to what emerged in the recent study on the general population in Urban Citizen in Germany [24], where highest heat risk perception was among people aged 18–29 years. Our result is in line with what emerged in Marinaccio et al. [6] where a higher risk of injury on hot days was found among males and young (age 15–34) workers.

All the interviewees considered the average observable thermal damage, that is, they considered that the symptoms of injuries or illnesses due to heat exposure are on average recognizable. Meanwhile, the categories most at risk have little awareness of how preventive measures in the workplace can reduce the severity. The five main obstacles perceived by respondents to preventing heat-related injuries at work were lack of commitment by employers to protect health and safety, lack of training of company health and safety managers, lack of training of workers, lack of compliance with regulations, and lack of awareness among company health and safety managers on the risks deriving from heat stress.

As for the perception of risk knowledge, according to the entire sample, the scientific community has a fairly poor knowledge of heat risk, as do workers exposed to heat.

Consistently with the result of the perception of risk knowledge, the degree of knowledge of the heat risk resulting from this survey is low. Only one in four of the respondents received training on the prevention of heat-related injuries at work and an even lower proportion, 17.1%, received warnings or alarms.

The whole sample believed that heat is an important contributor to loss of productivity and this result is common in other surveys on the heat risk in the workplace. For example, Singh et al. [46], in a telephone survey carried out in Australia in the summer of 2010, focused on occupational heat risk, and showed that five dominant themes emerged on the effects of heat on the health and productivity of workers, one of them being the reduction in productivity due to heat.

To the best of our knowledge, this is the first study conducted at the national level in Italy to explore workers' perception on the impact of heat stress on health, as well as to assess preventive practices and identify potential barriers to heat-related illnesses and injuries prevention in the workplace. While the COVID-19 pandemic hampered the conduction of case studies in the field in 2020, we were able to carry out a pilot study in preparation for the larger-scale surveys planned for the two subsequent summer seasons within the WORKLIMATE project.

Heat stress is an issue particularly for outdoor workers, and the latter represented the minority of participants in the 2020 survey. Unfortunately, the questionnaire submission during the COVID-19 pandemic, when many restrictions were in place in Italy also limiting outdoor activities, led to a prevalence of workers engaged in indoor activities among the respondents to the questionnaire. In the recruitment process, in the next survey iterations, it is crucial to increase the channels through which the questionnaire is distributed, to minimize selection bias and ensure outdoor workers who are most exposed are included. Nonetheless, information on awareness and perception of the problem of (mainly) indoor workers, allowed us to obtain useful information. The perception of indoors workers on heat stress is a seldom explored topic that needed to be evaluated.

Secondly, although the questionnaire had been built after taking into account functionally equivalent international and national questionnaires [19,22–26,28–31] and a pretesting had been conducted on a random workers' sample for optimization prior to the web-based survey launch, the pilot study allowed us to identify several questions that were too complicated and needed to be simplified and some others that were ambiguous or unnecessary and that needed to be discarded.

5. Conclusions

The survey highlighted that the sample of workers interviewed perceived a risk during a heat wave and that on average the heat risk does not depend on their wishes but can be potentially lethal. Unfortunately, however, some categories of workers, especially the youngest, still have a low perception of risk and this suggests the need to adopt policies to increase the risk perception related to heat. In addition, there is little awareness of how preventive measures in the workplace can reduce the severity of the heat risk and therefore the number of heat-related injuries were attributed by the majority of workers to the lack of training or in any case inadequate training; less than one in five workers received heat alarms. Although this survey represents only a sample of workers, with obvious limitations, especially regarding the low representation of outdoor workers, also because the COVID-19 restrictions during the pandemic period, highlights that Italian workers are not well prepared for the likelihood of increasing incidence of heat stress due to climate change. There is therefore a need to improve the heat risk prevention strategies in the occupational field by increasing training at multiple levels and developing appropriate heat health warning systems addressed to occupational sectors.

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A potential wearable solution for preventing heat strain in workplaces: The cooling effect and the total evaporative resistance of a ventilation jacket

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ABSTRACT

The increase in average seasonal temperatures has an impact in the occupational field, especially for those sectors whose work activities are performed outdoors (agricultural, road and construction sectors). Among the adaptation measures and solutions developed to counteract occupational heat strain, personal cooling garments represent a wearable technology designed to remove heat from the human body, enhancing human performance. This study aims to investigate the effectiveness and the cooling power of a specific cooling garment, i.e. a ventilation jacket, by quantifying the evaporative heat losses and the total evaporative resistance both when worn alone and in combination with a work ensemble, at three adjustments of air ventilation speed.

Standardised “wet” tests in a climatic chamber were performed on a sweating manikin in isothermal conditions considering three clothing ensembles (single jacket, work ensemble and a combination of both) and three adjustments of fan velocity.

Results showed a significant increase ($p < 0.001$) in evaporative heat loss values when the fan velocity increased, particularly within the trunk zones for all the considered clothing ensembles, showing that fans enhanced the dissipation by evaporation. The cooling power, quantified in terms of percent changes of evaporative heat loss, showed values exceeding 100% when fans were on, in respect to the condition of fans-off, for the trunk zones except for the Chest. A significant ($p < 0.01$) decrease (up to 42.3%) in the total evaporative resistance values of the jacket, coupled with the work ensemble, was found compared to the fans-off condition.

Results confirmed and quantified the cooling effect of the ventilation jacket which enhanced the evaporative heat losses of the trunk zones, helping the body to dissipate heat and showing the potential for a heat adaptation measure to be developed.

1. Introduction

Global warming appears more evident year by year registering the 2020 as Earth’s second warmest year in the 140-year record (just behind 2016) and Europe’s warmest year on record (NOAA, 2021). The situation has been aggravated by a significant increase in the frequency, the intensity and the duration of heatwave events (WHO, 2018), as well as a “deseasonalisation” of heatwaves, occurring outside of the typically

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considered hot period and above all with an increased earliness of heatwave (Morabito et al., 2017). These facts have had an impact in the occupational field particularly for those sectors where work activities are performed outdoors, especially in the agricultural, road and building construction sectors. In these cases, outdoor environmental parameters can represent a constraint because they cannot be regulated or adjusted.

Epidemiological studies provided evidences of the association between heat exposure and the risk of occupational injuries (Fatima et al., 2021; Marinaccio et al., 2019; Binazzi et al., 2019; Bonafede et al., 2016). Prolonged exposure to heat may, in fact, produce important impact on the health of workers (dehydration, heat cramps, heat exhaustion and heat stroke) as well as on their productivity (Flouris et al., 2018). From a physiological point of view, heat exposure can result in the need of the human body to dissipate both the heat stored when the air temperature is higher than the skin temperature and that internally produced by the performed activity. In these conditions, the human thermoregulatory system activates the appropriate mechanisms (vasodilatation and sweating) to try to keep the core temperature (CT) within a safe range. When these mechanisms are insufficient, the CT begins to increase progressively, heat strain can occur increasing the probability of occupational injuries. Therefore, there is a need to suggest mitigation and adaptation solutions to counteract occupational heat strain.

In the era of Industry 4.0 (Ajoudani et al., 2020), wearable solutions are being developed to improve work conditions and reduce risks within the workplaces (Del Ferraro et al., 2020b). Within the field of the Ergonomics of Thermal Environments, technological innovations are geared towards the development of wearable solutions with the scope of preventing heat strain (global warming is accelerating this process), creating innovative and smart systems for continuously monitoring worker's physiological parameters during heat exposure (Sergi et al., 2021; Falcone et al., 2021) or personal cooling garments (PCGs). PCGs were conceived with the intention of removing heat from the human body in order to cool it and alleviate physiological strain caused by heat exposure, enhancing human performance (Morris et al., 2020; Golbabaei et al., 2020; Chan et al., 2015). Nowadays, different types of PCGs exist, designed using different principles such as air-cooled garments (ACG), subdivided into natural air-cooled garments (ACG-Ns) which use evaporative cooling and cold air-cooled garments (ACG-Cs) that use conductive, convective and evaporative cooling; liquid cooling garments (LCGs) based on conductive cooling of a circulating liquid and phase change materials (PCMs) mainly based on conductive cooling by using the latent heat storage of phase change materials. In practice, the selection of the most appropriate PCG to counteract the effects of heat should take into account different factors: the technical characteristics, the effectiveness also in relation to thermal environment where the PCG should be used (for example, in general, PCGs based on evaporative cooling are less effective in very humid environments while those using conductive cooling can be effective regardless the environmental conditions) and the duration of the cooling power; any interferences with the working activity or with possible personal protective equipment and the acceptance by the worker. Innovations are continuously being developed in cooling garments such as the use of fans embedded in the clothing creating an air ventilation garment (AVG), as well as hybrid cooling garments (HCGs), which combine two of the above-mentioned cooling systems, for example PCMs and fans.

AVGs have attracted interest in the last years and also encouraged investigations by researchers due to their high portability, requiring no external connection to a compressor or a coolant supplier, guaranteeing a user's autonomy and mobility and being feasible for applications in occupational field. Studies were focused on the evaluation of the AVG cooling power and of their thermal properties (Zhao et al., 2013; Yi et al., 2017a; Yang et al., 2020; Del Ferraro et al., 2021), on the effects of AVGs on the human thermal response (Zhao et al., 2015a, 2015b, 2021) and on the cooling effect, when AVGs were combined with other cooling systems (HCGs) (Zhao et al., 2015a; Zhao et al., 2015b; Wang et al., 2020; Xu et al., 2020; Wan et al., 2018; Zhao et al., 2017; Yi et al., 2017b; Chan et al., 2017; Song et al., 2016). This type of investigation is generally performed by carrying out simulations in a climatic chamber on a sweating manikin (Del Ferraro et al., 2017, 2018, 2020a; Wang et al., 2012, 2014). In fact, Zhao et al. (2013) studied the effect of fans and openings placed at different parts of the torso and results suggested that the ventilation fans should be located along the spine area and in the lower back zone where the most evaporative cooling is required. Yi et al. (2017) compared the airflow rate and the work duration of two ventilation units powered by different types of batteries, finding that the unit powered by the rechargeable lithium-polymer battery not only reached a higher flow rate but had a longer work duration than the alkaline battery. Yang et al. (2020) investigated the effect of air ventilation, clothing size and air ventilation rate on the upper body heat loss and of the clothing size on thermophysiological responses by carrying out tests on a sweating manikin. They found that the effects of clothing size on the upper body heat loss varied with the ventilation rate and that this can reduce the upper body heat loss and the apparent evaporative resistance. Del Ferraro et al. (2021) investigated the effectiveness of a ventilation jacket focused on the dry heat exchanges, by quantifying the dry heat loss and the total thermal insulation of the single jacket also combined with a work ensemble at three different adjustments of the air ventilation speed and finding significant increase in the dry heat loss of the trunk zones and significant decreases in total thermal insulation as the air ventilation speed increased.

This study, as a part of the Italian project WORKLIMATE (project details available at https://www.worklimate.it), focused on the evaporative properties of a ventilation jacket, which are crucial to ensure heat dissipation from the human body through evaporation during heat exposure, by investigating and quantifying the evaporative heat loss (H_E) and the total evaporative resistance ($R_{e,T}$), both when worn alone and in combination with a work ensemble, at three different adjustments of air ventilation speed. Standardised tests ("wet" tests) in a climatic chamber on a sweating manikin were performed to investigate the effectiveness of the tested ventilation jacket on the evaporative heat exchanges.

2. Materials and methods

The cooling effect of a ventilation jacket was investigated by performing standardised "wet" tests in a climatic chamber (INAIL, Monte Porzio Catone, Italy) using a sweating thermal manikin. During this type of test, heat exchanges between the manikin and the environment only occurred through evaporation. H_E values were quantified and their values were used in the calculation of the total evaporative resistance $R_{e,T}$ values, as shown in paragraph 2.4.

2.1. The tested cooling garment

The ventilation garment tested was represented by a short-sleeve cotton jacket with two embedded fans located at the lateral lower back sites with a total weight of 0,75 Kg (Fig. 1).

The jacket was composed of two layers: an outer layer made of cotton and an inner layer of polyester with a net lining placed only at the trunk back side. Ventilation was assured by two fans, with a diameter of 8 cm, powered by a rechargeable Li-ION battery pack with an autonomy of 8 h, a voltage of 7.4 V and an energy capacity of 4400 mAh, embedded in a pocket placed inside the jacket. Air velocity could be adjusted at four different levels, reaching the maximum value of the flow rate of about 12 l/s for each fan. The jacket had six additional circular air – openings, placed vertically in the middle - upper part of the back, each of them with a diameter of 1 cm. The distance between two consecutive openings varied between 4.5 cm and 5 cm with a total of about 23.5 cm between the first and the last openings (from centre to centre). The bottom of the jacket fitted the buttocks tightly due to an elastic strap being sewn into the bottom hem of the jacket. Two external pockets in the upper front

Fig. 1. The ventilation jacket tested with six circular openings and two fans placed in the back site.

part and a long central zipper with a button at the beginning and at the end of the zipper completed the design of the tested ventilation jacket.

The pathway of the airflow is schematically illustrated in Fig. 1 where the natural air, entered from the fans, is channeled towards the upper part of the trunk (shoulders) coming out from six circular openings, as well as from the collar and sleeves.

2.2. The sweating thermal manikin

The evaluation of H_E and $R_{e,T}$ values derived from “wet” tests performed on a sweating manikin, i.e. on a manikin able to simulate the human sweating and the evaporative heat exchange. A twenty-six zone “Newton” sweating manikin (Thermetrics LLC, Seattle, WA) meeting the requirements of ASTM F2370 (2016) was used in this study, with surface discretization shown in Fig. 2.

The manikin was constructed using a thermally conductive carbon-epoxy composite shell with embedded heaters and wire sensors. It corresponded to the 50th percentile of Western Males and had a body surface area of 1.8 m^2 and a height of 1.78 m. A total of 139 pores were distributed on the manikin’s surface through which the system delivered the water punctually to the surface. The fabric skin, worn by the manikin during the tests, distributed the water uniformly, allowing the simulation of the human sweating.

The manikin was controlled by the Software ThermDac v8.4.4.0 (Thermetrics LLC, Seattle, WA).

2.3. The experimental protocol

Tests were carried out on a standing manikin placed in the central part of the climatic chamber where the air entered by flowing through a mesh wall in front of the manikin and exited through the back wall.

Standardised tests were performed in isothermal conditions (IC), with the manikin’s surface temperature (T_s) and the air temperature (t_a) set at 35 °C ($T_s = t_a = 35$ °C) according to ASTM F2370 (2016), which also required that:

- the air velocity (v_a) value should be set at 0.4 ± 0.1 m/s;
- the relative humidity (RH) value should be set at 40 ± 5 %;

With these requirements, the mean value ± standard deviation (SD) of the environmental parameters obtained in the climatic chamber by the performed tests were: $t_a = 35.0 \pm 0.3$ °C; $v_a = 0.37 \pm 0.01$ m/s; $RH = 40.0 \pm 0.65$ %.

Tests were exclusively run in a “wet test” mode which implied also a constant skin temperature mode. The manikin was firstly dressed with a pre-wetted fabric “skin” (as shown in Fig. 2) and then with the garments

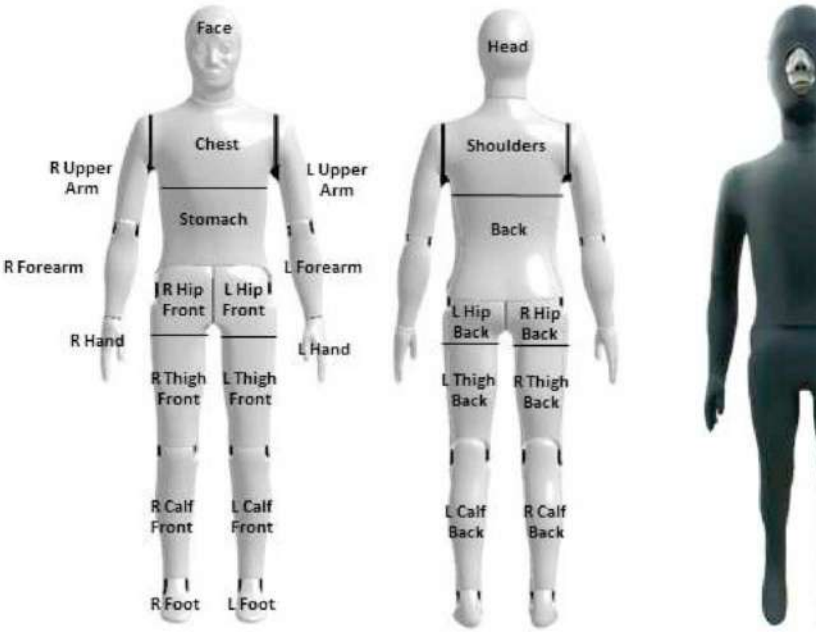

Fig. 2. The twenty-six thermal zones of Newton manikin and the fabric skin used in the "wet" tests.

to be tested. All the manikin's zones were heated at 35 °C ($T_s = t_a$) and maintained at this temperature by the system. At the same time, the system started to deliver water to the manikin's surface, through the pores distributed on the surface, in order to maintain the fabric skin saturation. Once the steady-state was reached (which was needed to be maintained for 30 min), the surface temperatures of the twenty-six thermal zones and the power to the manikin's body segments ($H_{E,i}$, with $i = 1\ldots26$) were recorded every minute and averaged to calculate the $R_{e,T}$ value of the tested ensemble, as explained in paragraph 2.4.

Three clothing ensembles were tested:

1. The single ventilation jacket (JACK) with three different adjustments of the fan velocity (v_f): $v_f = 0$ (fans-off), $v_f = 2$ (fans-on at an intermediate value, with a flow rate of about 6 l/s for each fan) and $v_f = 4$ (fans-on at the maximum value, with a flow rate of about 12 l/s for each fan);
2. The work ensemble (ENS) consisting of a cotton short-sleeve T-shirt, a pair of cotton work pants (long straight pants), cotton briefs, ankle-length athletic socks and athletic shoes;
3. The ventilation jacket (zipper closed) worn over the work ensemble (ENS + JACK) with three adjustments of the fan velocity: $v_f = 0$, $v_f = 2$ and $v_f = 4$.

"Wet" tests on the nude sweating manikin were performed as a general reference condition before starting the tests on the garments.

For each clothing ensemble and fan adjustment, three independent replications were performed on the same day. For each garment, three identical sets were available and were tested randomly.

A total of twenty-four tests were run in IC (comprising of the "wet" tests on the nude sweating manikin).

2.4. The calculation of $R_{e,T}$ value

The parallel method formula (1) reported in ASTM F2370 (2016) and in Annex D of ISO 9920 (2007) allows the calculation of $R_{e,T}$ values from tests performed on a sweating manikin:

$$R_{e,T} = \frac{(P_s - P_a)A}{H_E - \frac{(T_s - t_a)A}{I_T}} \tag{1}$$

where:

P_s is the water vapour pressure at the manikin's sweating surface (kPa);

P_a is water vapour pressure of the air (kPa);

A is the manikin's surface area (m^2);

H_E is the power required to heat the manikin (W).

T_s is the manikin's surface temperature (°C);

t_a is the air temperature (°C);

I_T is the total insulation of the clothing ensemble, including the surface air layer (m^2K/W) derived from the dry test on the thermal manikin.

In IC ($T_s = t_a$), the general formulation (1) is simplified into equation (2), as follows:

$$R_{e,T} = \frac{(P_s - P_a)A}{H_E} \tag{2}$$

For each investigated clothing ensemble, three values of $R_{e,T}$ were calculated (one for each replication performed) and averaged to determine the mean total evaporative resistance value ($\overline{R}_{e,T}$).ASTM F2370 (2016) required that any of the three replications did not vary more than ± 10 % from $\overline{R}_{e,T}$.

2.5. Statistical analysis

Descriptive data and statistical analyses were performed using the IBM SPSS Statistics version 26.0.

The observed H_E values calculated for different combinations of garments (JACK and ENS + JACK with three different adjustments of the fan velocity) and for each considered thermal zone of the manikin and $\overline{R}_{e,T}$ values were analysed by one-way analysis of variance (ANOVA). The Bonferroni test was applied to evaluate the paired differences (the significance level was set at $p < 0.05$).

3. Results

Results reported in this study are refer to the sixteen thermal zones selected among those assumed to be the most influenced by the effect of the fans, covered by the ventilation jacket or proximal to it, such as: Face, Head, Right Upper Arm (R Upper Arm), Left Upper Arm (L Upper

Arm), Right Forearm (R Forearm), Left Forearm (L Forearm), Right Hand (R Hand), Left Hand (L Hand), Chest, Shoulders, Stomach, Back, Right Hip Front (R Hip Front), Right Hip Back (R Hip Back), Left Hip Front (L Hip Front), Left Hip Back (L Hip Back). Among them, the four thermal zones belonging to the trunk are: Chest, Shoulders, Stomach and Back.

For all the considered ensembles and for each adjustment of the fan velocity, H_E mean values of each thermal zones and $\overline{R}_{e,T}$ values were quantified.

3.1. Evaluation of the evaporative heat loss H_E

H_E mean values of the selected sixteen thermal zones and their percent change in values both for JACK and JACK + ENS, at the three

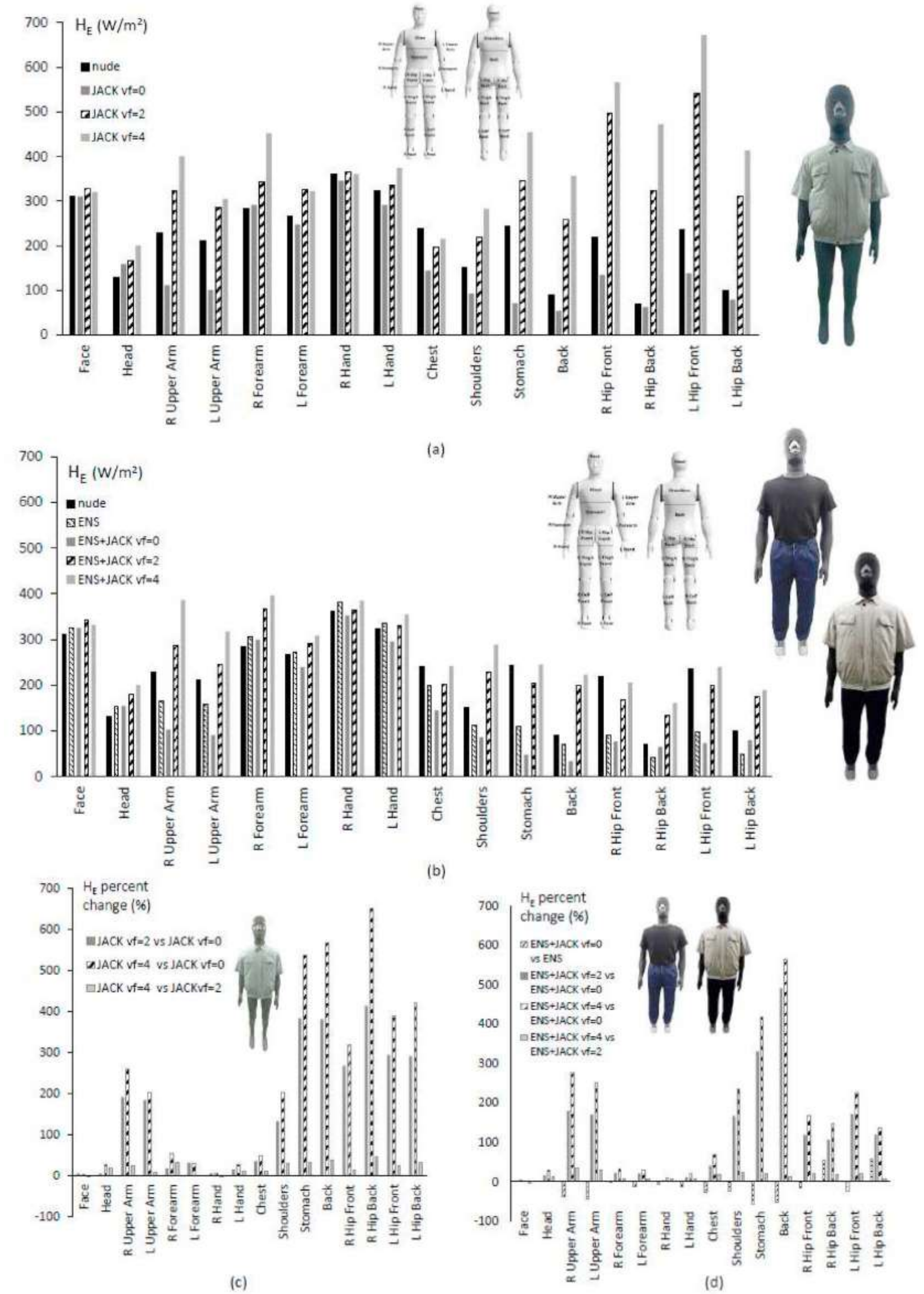

Fig. 3. H_E values of the selected thermal zones: (a) manikin dressed with only JACK; (b) manikin dressed with ENS and ENS + JACK. H_E percent changes:(c) manikin dressed with only JACK; (d) manikin dressed with ENS and ENS + JACK.

different adjustments of v_f, were reported in Fig. 3.

In the investigated conditions related to JACK, results revealed that, at $v_f = 0$ and among the sixteen thermal zones, the Back is the zone showing the lowest H_E value ($H_E = 53.48\ W/m^2$), the R Hand the highest H_E value ($H_E = 360.64\ W/m^2$) and, looking at only the zones of the trunk, the highest value was reached by the Chest ($H_E = 144.72\ W/\ m^2$). Considering the other two adjustments of v_f, the lowest H_E values at $v_f = 2$ and $v_f = 4$ were achieved by the Head (respectively $H_E = 167.32\ W/\ m^2$ and $H_E = 200.53\ W/m^2$) while the highest values by the L Hip Front (respectively $H_E = 541.69\ W/m^2$ and $H_E = 672.25\ W/\ m^2$). Among the trunk zones, the Chest showed the lowest H_E values ($H_E = 196.07\ W/\ m^2$at $v_f = 2$, $H_E = 215.56\ W/m^2$ at $v_f = 4$) while the Stomach the highest ($H_E = 345.57\ W/m^2$at $v_f = 2$, $H_E = 454.73\ W/m^2$ at $v_f = 4$).

In case of ENS and ENS + JACK conditions (panel (b) of Fig. 3), the lowest H_E values were reached in three conditions out of four by the R Hip Back ($H_E = 41.76\ W/m^2$ in ENS, $H_E = 134.82\ W/\ m^2$ in ENS + JACK at $v_f = 2$, $H_E = 160.78\ W/m^2$ in ENS + JACK at $v_f = 4$) while in ENS + JACK at $v_f = 0$ by the Back ($H_E = 33.53\ W/m^2$). The highest values were achieved by the R Hand for the two fans-off conditions ($H_E = 380.81\ W/\ m^2$ for ENS and $H_E = 352.26\ W/m^2$ for ENS + JACK at $v_f = 0$) and by the R Forearm for the other two fans-on conditions ($H_E = 367.03\ W/\ m^2$ for ENS + JACK at $v_f = 2$ and $H_E = 396.35\ W/m^2$ for ENS + JACK at $v_f = 4$). Among the four thermal zones of the trunk, results revealed that the Back reached the lowest H_E values for all the four conditions of ENS and ENS + JACK ($H_E = 71.77\ W/m^2$ in ENS, $H_E = 33.53\ W/\ m^2$ in ENS + JACKt at $v_f = 0$, $H_E = 198.47\ W/m^2$ in ENS + JACK at $v_f = 2$, $H_E = 222.33\ W/m^2$ in ENS + JACK at $v_f = 4$). Highest values were reached by the Chest in the two fans-off conditions ($H_E = 198.48\ W/\ m^2$ for ENS and $H_E = 144.03\ W/m^2$ for ENS + JACK at $v_f = 0$) and by the Shoulders in the two fans-on conditions ($H_E = 229.51\ W/m^2$ for ENS + JACK at $v_f = 2$ and $H_E = 288.12\ W/m^2$ for ENS + JACK at $v_f = 4$).

The cooling performance of the ventilation jacket was assessed in terms of H_E percent changes, as shown in Fig. 3, where the highest values were found when fans were turned on. In particular, panels (c) and (d) of Fig. 3 revealed that, among the zones of the trunk, the Back showed the highest H_E percent change values when the conditions of fans-on were compared with the condition of fans-off: in JACK, in fact, it reached the value of 381.8 % for $v_f = 2$ vs $v_f = 0$ (even if formally the Stomach reached the 384.1 %) and the value of 567.4 % for $v_f = 4$ vs $v_f = 0$; in ENS + JACK, it achieved the value of 491.9 % for $v_f = 2$ vs $v_f = 0$ and of 563.1 % for $v_f = 4$ vs $v_f = 0$. The Chest showed the lowest H_E percent change values in comparisons with the condition fans-on vs fans-off: in JACK, with a value of about 35.5 % for $v_f = 2$ vs $v_f = 0$ and about 48.9 % for $v_f = 4$ vs $v_f = 0$; in ENS + JACK about 40.2 % for $v_f = 2$ vs $v_f = 0$ and about 67.5 % for $v_f = 4$ vs $v_f = 0$.

The comparison between ENS and ENS + JACK at $v_f = 0$ revealed negative H_E percent change values for most of the selected thermal zones (twelve out of sixteen). The highest decrease was found in the Stomach (−56.5 %).

Tables 1 and 2 report results of the statistical analysis applied to H_E values with the indication of H_E mean values, their confidence intervals (CIs) and the significance of the tests.

In the case of JACK, results of the ANOVA revealed statistically significant differences for the most part of the selected zones except for the Head (v_f =0 vs $v_f = 2$) and for the L Forearm (v_f =2 vs $v_f = 4$) while for ENS + JACK, the differences are statistically significant for all the sixteen thermal zones considered.

3.2. Evaluation of the total evaporative resistance

Calculations of $\overline{R}_{e,T}$ values were performed according to Eq. (2) at the three adjustments of the fan velocity. $\overline{R}_{e,T}$ values and their percent changes were shown in Fig. 4, respectively in panels (a) and (b).

Table 1

Mean values and confidence intervals (CIs) of H_E for the sixteen thermal zones, for JACK with the three adjustments of v_f.

Manikin zone	Mean (CI) for v_f = 0 (W/m^2)	Mean (CI) for v_f = 2 (W/m^2)	Mean (CI) for v_f = 4 (W/m^2)	Sign.
Face	311 (308–313) [a]	329 (328–331) [b]	320 (316–325) [c]	***
Head	159 (157–161) [a]	167 (162–172) [a]	201 (195–206) [b]	***
R Upper Arm	111 (110–112) [a]	324 (322–326) [b]	401 (399–403) [c]	***
L Upper Arm	100 (100–101) [a]	285 (284–287) [b]	305 (303–306) [c]	***
R Forearm	291 (289–294) [a]	343 (340–346) [b]	452 (449–455) [c]	***
L Forearm	248 (246–250) [a]	326 (324–328) [b]	322 (320–324) [b]	***
R Hand	346 (344–348) [a]	367 (364–369) [b]	361 (359–363) [c]	***
L Hand	292 (290–294) [a]	335 (333–337) [b]	375 (372–378) [c]	***
Chest	145 (144–146) [a]	196 (195–197) [b]	216 (214–217) [c]	***
Shoulders	93 (91–96) [a]	218 (216–219) [b]	283 (281–285) [c]	***
Stomach	71 (70–72) [a]	345 (342–347) [b]	455 (453–457) [c]	***
Back	53 (53–54) [a]	258 (255–260) [b]	357 (355–359) [c]	***
R Hip Front	135 (134–136) [a]	497 (495–500) [b]	567 (564–569) [c]	***
R Hip Back	63 (61–64) [a]	323 (321–325) [b]	472 (470–474) [c]	***
L Hip Front	137 (136–138) [a]	542 (539–544) [b]	672 (670–675) [c]	***
L Hip Back	79 (78–80) [a]	310 (308–313) [b]	414 (411–416) [c]	***

***p<0.001 according to ANOVA; different letters in [] indicate statistically significant differences between different adjustments of v_f (p-value<0.05) according to the Bonferroni test.

The highest $\overline{R}_{e,T}$ values were obtained in the fans-off condition ($v_f = 0$), both for JACK and for ENS + JACK. The fans produced a decrease in the $\overline{R}_{e,T}$ values which is highest when $v_f = 4$ is compared to $v_f = 0$ ($\overline{R}_{e,T}$ percent change = - 47.1 % for JACK and $\overline{R}_{e,T}$ percent change = - 42.3 % for ENS + JACK). A reduction in $\overline{R}_{e,T}$ values, even if slightly lower than that obtained for $v_f = 4$, was registered also for $v_f = 2$ with respect to the condition of fans-off ($\overline{R}_{e,T}$ percent change = - 35.3 % for JACK and $\overline{R}_{e,T}$ percent change = - 34.6 % for ENS + JACK).

The $\overline{R}_{e,T}$ percent change revealed a positive value only for ENS + JACK at $v_f = 0$ vs ENS (+13 %).

The statistical analysis applied to $\overline{R_{eT}}$ values and reported in Table 3 with the indication of $\overline{R_{eT}}$ mean values, their CIs and the significance of the tests for the conditions tested, showed statistically significant differences obtained by ANOVA test both for JACK and for JACK + ENS.

4. Discussion

PCGs are hypothesized to be a promising wearable solution against heat stress, conceived with the scope to remove heat from the human body in order to cool it and to enhance human performance. Technological innovations are continuously introduced in this field, for example, through the use of fans embedded in a garment, creating an AVG. In this study, the effectiveness of a specific AVG is investigated, i.e. a ventilation jacket, focusing and quantifying its evaporative properties in terms of H_E and $\overline{R}_{e,T}$ values at three different adjustments of the fan velocity, through standardised “wet” tests in a climatic chamber on a sweating manikin. The choice of considering a scenario with the

Table 2

Mean values and confidence intervals (CIs) of H_E for the sixteen thermal zones, for ENS + JACK with the three adjustments of v_f.

Manikin zone	Mean (CI) for $v_f = 0$ (W/m^2)	Mean (CI) for $v_f = 2$ (W/m^2)	Mean (CI) for $v_f = 4$ (W/m^2)	Sign.
Face	325 (324–327) [a]	342 (340–344) [b]	332 (331–333) [c]	***
Head	155 (153–156) [a]	180 (177–183) [b]	200 (199–202) [c]	***
R Upper Arm	102 (102–103) [a]	286 (285–288) [b]	387 (386–388) [c]	***
L Upper Arm	90 (90–91) [a]	244 (243–246) [b]	317 (317–318) [c]	***
R Forearm	299 (296–302) [a]	367 (364–370) [b]	396 (394–398) [c]	***
L Forearm	239 (237–241) [a]	291 (288–293) [b]	308 (307–309) [c]	***
R Hand	352 (350–354) [a]	365 (362–367) [b]	385 (383–387) [c]	***
L Hand	295 (292–298) [a]	330 (327–334) [b]	355 (352–357) [c]	***
Chest	144 (143–145) [a]	202 (201–203) [b]	241 (240–242) [c]	***
Shoulders	86 (84–87) [a]	230 (227–232) [b]	288 (287–289) [c]	***
Stomach	47 (47–48) [a]	204 (203–206) [b]	245 (245–246) [c]	***
Back	34 (33–34) [a]	198 (197–200) [b]	222 (222–223) [c]	***
R Hip Front	77 (76–77) [a]	168 (167–169) [b]	205 (204–206) [c]	***
R Hip Back	65 (65-65) [a]	135 (134–135) [b]	161 (160–161) [c]	***
L Hip Front	73 (73–74) [a]	200 (198–201) [b]	239 (239–240) [c]	***
L Hip Back	80 (79–80) [a]	175 (174–176) [b]	189 (189-189) [c]	***

***p<0.001 according to ANOVA; different letters in [] indicate statistically significant differences between different adjustments of v_f (p-value<0.05) according to the Bonferroni test.

ventilation jacket coupled with a work ensemble allowed the cooling effects of the jacket to be observed with the presence of other clothes, simulating a condition of "real" use of the jacket and quantifying the cooling performance for the possible use of the jacket in specific occupational fields.

Results presented in this study derived from "wet" tests, where the heat exchanges between the manikin and the environment occurred only by evaporation. "Wet" tests were performed according to ASTM F 2370 (2016) which represents the only standard detailed requirements of the sweating manikin and the test procedures in order to measure the Re_T value of a clothing ensemble using a sweating manikin. While there are ASTM F 1291 (2016) and ISO 15831 (2004) for evaluating I_T value, the latter being the ISO specific reference for performing dry tests on a thermal manikin, there is no ISO standard for evaluating Re_T value (Lei, 2019). The European Standard EN 17528 was not published and it was a draft when the study was carried out.

There are some open issues relating to the measurement of the evaporative resistance of clothing raised from the literature. One refers to the isothermal condition required to perform the "wet" tests. Wang (2017) observed that there is a difference in temperature between the surface of the fabric skin ($T_{sk,f}$) used in the "wet" tests and the manikin surface and that the evaporation occurs from the fabric skin surface. According to study of Wang (2017), the isothermal condition should be established between the fabric skin surface temperature and the air temperature ($T_{sk,f} = t_a$) and not between the manikin surface temperature and the air temperature ($T_s = t_a$). He suggested a correction that should be made when "wet tests" are performed in the "so-called" isothermal condition ($T_s = t_a$) and the heat loss method (Eqs. (1) and (2)) is applied to calculate the total evaporative resistance. In this study, values of the total evaporative resistance are shown without the correction.

The local behaviour of the selected sixteen thermal zones showed that generally the zones with a direct contact with the air (R Hand, L Hand, R Forearm) showed the highest H_E values, while the zones more covered (such Back or Hip Back) showed the lowest values. The action of the fans showed an increase in H_E values, with respect to the condition of fans-off, for most of the considered thermal zones. The H_E increases, passing from the condition of fans-off to the condition of fans-on, appeared significant and more evident for the ten zones covered by the ventilation jacket (R Upper Arm, L Upper Arm, Chest, Shoulders, Stomach, Back, R Hip Front, R Hip Back, L Hip Front, L Hip Back), both for JACK and for ENS + JACK as expected and they increased with the increase of the fan velocity. This represented the first positive result which revealed that the fans enhanced the dissipation of the heat by evaporation compared to the condition of fans-off. Evaporation, in fact, represents the main way of dissipating the heat during exposure to a hot environment, especially when the "dry" heat losses are reduced due to the small temperature gradient between the skin and the environment ($t_a < T_s$) or when the body tends to "gain" heat because $t_a > T_s$. In these cases, enhancing evaporative heat losses from the body can be an effective way to help the body to dissipate heat and to try to keep the core temperature in a safe range.

The trend observed for H_E values is in line with the results found by Del Ferraro et al. (2021) who observed significant increases in the dry heat losses and decreases in the thermal insulation values due to fans for the same ventilation jacket and in combination with a work ensemble and by Yang et al. (2020) who found an increase in the total heat loss of the upper body region with the increase in the ventilation rate, for a long-sleeve ventilation jacket in non – isothermal conditions, for different sizes and levels of air ventilation rate.

The cooling power quantified in this study in terms of H_E percent change ((panels c) and d) of Fig. 3) showed values exceeding 100 % when fans were on (both in JACK and ENS + JACK) with respect to the fans-off condition, for all the ten thermal zones except for the Chest and, among the zones of the trunk, the Back is the one which revealed the highest H_E percent change values. This is an important finding because the upper back is one of the areas with the highest sweating rate.

An increase higher than 100 % was found also by Yang et al. (2020) in their study where an increase of 168 % in the upper body heat loss, for the clothing size L in the presence of high ventilation, was observed and by Zhao et al. (2013) who detected percent increases in heat losses of the whole torso ranging from 137 to 251 % compared to the fans-off conditions.

The second result that emerged from this study and that was strictly connected to the first one, was the significant reduction found in the $\overline{R}_{e,T}$ values when the fans were on (both for JACK and ENS + JACK) compared to the condition of fans-off. Calculations performed to quantify the percent change of $\overline{R}_{e,T}$ showed that the reduction in $\overline{R}_{e,T}$ values increases with the increase in the fan velocity and the cooling effect of the ventilation jacket (i.e. reduction in $\overline{R}_{e,T}$ values) was found not only when the manikin worn the single ventilation jacket but also when the jacket was worn over a work ensemble. A reduction in the thermal properties was also detected by Yang et al. (2020) who found a decrease in the apparent evaporative resistance in the upper body part due to the effect of a long-sleeve ventilation jacket in their test performed in non - isothermal conditions and by Yi et al. (2017b) who quantified the thermal insulation and the evaporative resistance of the torso in their study on the effectiveness of a newly designed hybrid cooling vest. The value of $\overline{R}_{e,T} = 0.017\ KPa{\cdot}m^2/W$ calculated in this study for JACK at $v_f = 0$ is very similar to the value of $0.0173\ KPa{\cdot}m^2/W$ reported by Zhao et al. (2013) in their study for the total evaporative resistance of their ventilation jacket.

Future human subject studies investigating the cooling effect of the

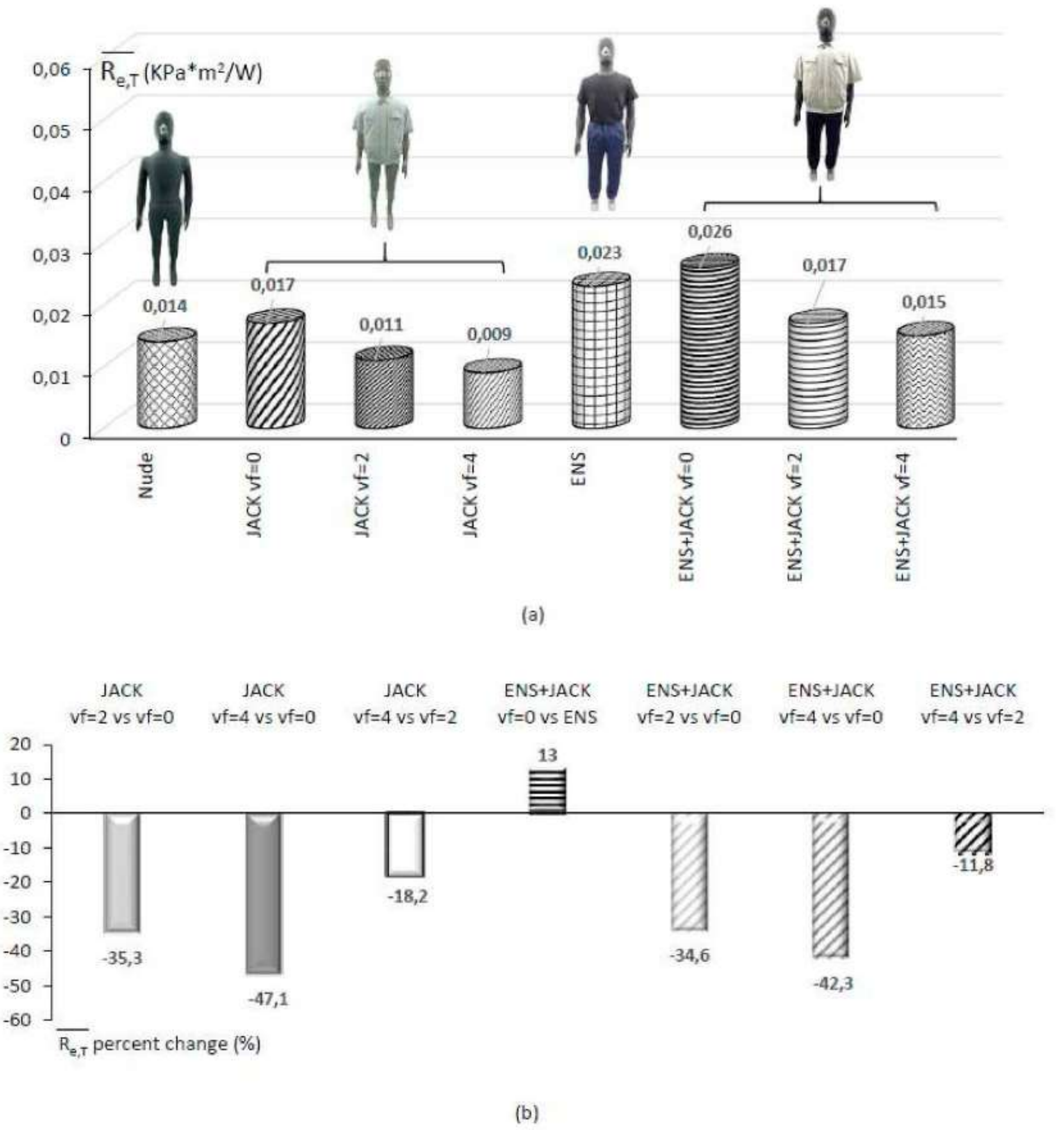

Fig. 4. (a) $\overline{R}_{e,T}$ values for the nude manikin and all the considered ensembles. (b) $\overline{R}_{e,T}$ percent change values.

Table 3
Mean values and confidence intervals (CIs) of $\overline{R_{eT}}$.

Condition	Mean (CI) for v_f = 0 ($KPa\cdot m^2/W$)	Mean (CI) for v_f = 2 ($KPa\cdot m^2/W$)	Mean (CI) for v_f = 4 ($KPa\cdot m^2/W$)	Sign.
JACK	0.017 (0.015–0.018) [a]	0.011 (0.009–0.012) [b]	0.009 (0.009–0.009) [c]	***
ENS + JACK	0.026 (0.025–0.028) [a]	0.017 (0.016–0.019) [b]	0.015 (0.015–0.015) [c]	***

***$p<0.001$ according to ANOVA; different letters in [] indicate statistically significant differences between different adjustments of v_f (p value < 0.01) according to the Bonferroni test.

tested ventilation jacket on the human thermophysiological response could be useful to complete the thermal analysis and to validate the effectiveness of this technology as a sustainable solution to reduce the impact of heat stress on health.

Results obtained in this paper should be interpreted with caution and need to be confirmed by human trials in order to verify the real effectiveness of the tested ventilation jacket and to better understand how (how often, for how long, etc.) it should be used. Furthermore, the impact of this technology on the user's acceptability should be evaluated, accounting for potential discomfort related to the use of the ventilation jacket during the execution of work activity in the heat.

5. Conclusions

This study investigated the cooling effect of a ventilation jacket performing "wet" tests in a climatic chamber on a sweating manikin in isothermal condition ($T_s = t_a = 35\ ^\circ C$) considering three clothing ensembles (the single jacket, a work ensemble and a combination of both) and three different adjustments of the fan velocity ($v_f = 0$, $v_f = 2$, $v_f = 4$). Results obtained showed:

1. Significant increases in evaporative heat loss, i.e. cooling effect with the increase of the fan velocity for all the thermal zones of the trunk and for all the considered ensembles;

2. Significant decreases of the total evaporative resistance values with the increase of the fan velocity (up to 42.3 % when the jacket is coupled with the work ensemble).

Results revealed that the action of the fans enhanced the evaporative heat losses of the trunk zones helping the body to dissipate heat.

Future investigations on the human thermal response will be useful to complete the analysis of this cooling garment and to understand if the ventilation jacket can represent an effective solution to be used as an adaptation strategy to counteract the heat stress for workers exposed to warm and hot environments. According to future climate projections, concrete actions are needed to prevent the potential impact of heat-waves and occupational heat exposure and to reduce the risk of injuries and productivity losses.

Credit author statement

Simona Del Ferraro: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Tiziana Falcone:** Methodology, Validation, Investigation, Writing - Review & Editing, Visualization. **Marco Morabito:** Conceptualization, Formal Analysis, Resources, Data Curation, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. **Alessandro Messeri:** Conceptualization, Resources, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. **Michela Bonafede:** Writing - Review & Editing, Supervision, Project administration, Funding acquisition. **Alessandro Marinaccio:** Writing - Review & Editing, Supervision, Project administration, Funding acquisition. **Chuansi Gao**: Resources, Writing - Review & Editing**. Vincenzo Molinaro:** Conceptualization, Methodology, Resources, Writing - Review & Editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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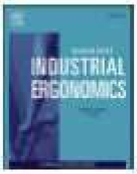

Cooling garments against environmental heat conditions in occupational fields: measurements of the effect of a ventilation jacket on the total thermal insulation

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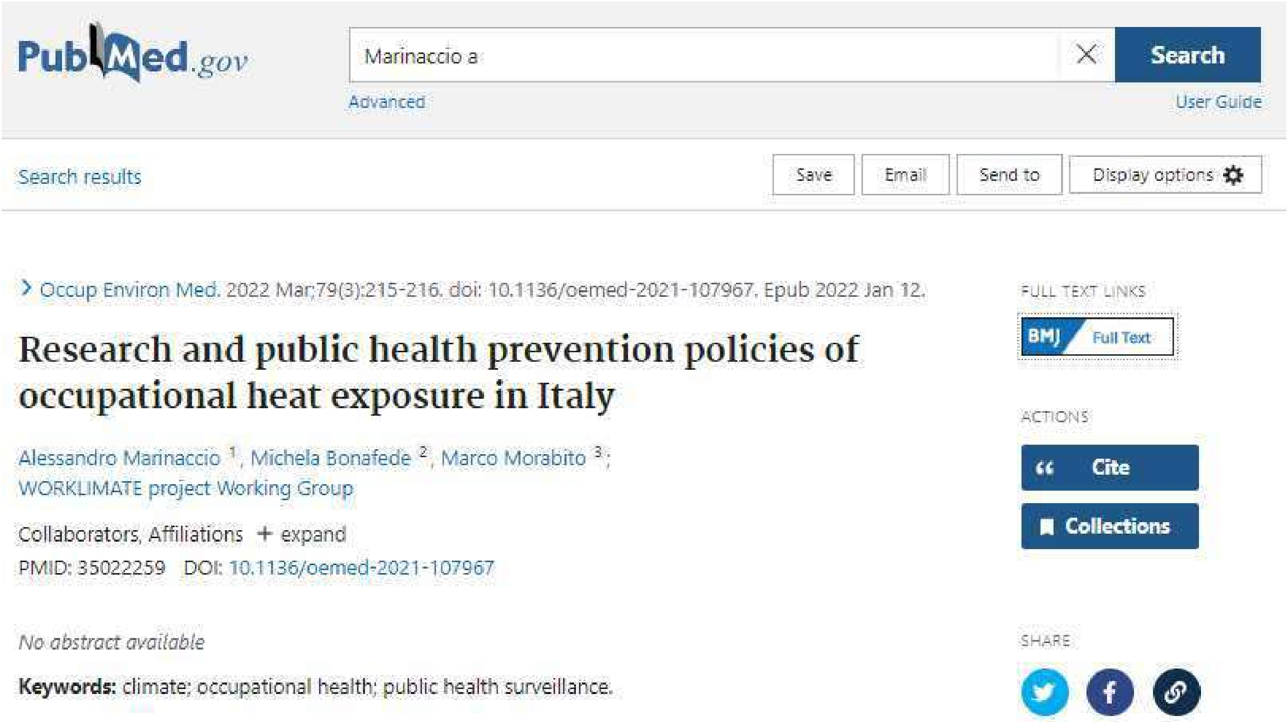
ABSTRACT

Personal cooling garments (PCGs) can represent an adaptation solution to counteract heat strain and to improve worker's health and productivity (especially for some outdoor work activities as in agriculture and in the construction industry). The cooling effect of a ventilation jacket was preliminarily investigated carrying out "dry" tests in a climatic chamber on a thermal manikin. A standardized condition with air temperature, ta = 22.4 °C, three different adjustments of the fan velocity ($v_f= 0$, $v_f = 2$ and $v_f = 4$), and three different ensembles (the single jacket, a work ensemble and a combination of both) were considered. Results showed significant increases in dry heat losses (through convection) for the trunk thermal zones, higher when the fans were on, for all the ensembles considered. Percent changes greatly exceeded 100 % for the thermal zones close to the fans. The air ventilation determined significant decreases of the total thermal insulation (I_T) values (up to 35 %) compared to the fans-off condition, confirming and quantifying the cooling effect of the ventilation jacket.



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Research and public health prevention policies of occupational heat exposure in Italy

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Collaborators, Affiliations + expand

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Keywords: climate; occupational health; public health surveillance.

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Article

Performances of Limited Area Models for the WORKLIMATE Heat–Health Warning System to Protect Worker's Health and Productivity in Italy

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Abstract: Outdoor workers are particularly exposed to climate conditions, and in particular, the increase of environmental temperature directly affects their health and productivity. For these reasons, in recent years, heat-health warning systems have been developed for workers generally using heat stress indicators obtained by the combination of meteorological parameters to describe the thermal stress induced by the outdoor environment on the human body. There are several studies on the verification of the parameters predicted by meteorological models, but very few relating to the validation of heat stress indicators. This study aims to verify the performance of two limited area models, with different spatial resolution, potentially applicable in the occupational heat health warning system developed within the WORKLIMATE project for the Italian territory. A comparison between the Wet Bulb Globe Temperature predicted by the models and that obtained by data from 28 weather stations was carried out over about three summer seasons in different daily time slots, using the most common skill of performance. The two meteorological models were overall comparable for much of the Italian explored territory, while major limits have emerged in areas with complex topography. This study demonstrated the applicability of limited area models in occupational heat health warning systems.

Keywords: occupational health and safety; wet-bulb globe temperature (WBGT); climate change; high-resolution forecasts; personalized forecasts for workers; limited area model (LAM); meteorological model performance

1. Introduction

Climate change projections indicate that most people who inhabit our planet will experience more recurrent natural hazards [1], and particularly, intense and longer-lasting heatwave periods over the coming decades [2]. The world of work, especially that carried out outdoors, is intimately connected with the natural environment and climate conditions. The increase of environmental temperature directly affects the occupational sector in a generally negative way [3,4]. Looking ahead, the heat stress phenomenon, that the National Institute for Occupational Safety and Health (OSHA) defines as the sum of the heat generated in the body (metabolic heat) plus the heat gained from the environment minus the heat lost from the body to the environment [5], will become an even more important issue, impacting on the health of workers and reducing the total number of working hours. In particular, during heatwaves, outdoor workers are those who present the greatest sun exposition, dehydration, and heat stress that can lead directly to heat-related illnesses [6,7] as well as an increased risk of accidents happening because of the tiredness and lack of concentration due to working in the heat [8,9]. These effects are expected to increase over the next few years not only because of climate change, but also because of demographic changes in the working population. The increasing average age of the working population affects various components of the physical work capacity, including aerobic power and capacity, muscular strength, and tolerance of thermal stress [10]. In addition, the increasing number of immigrant workers represents an additional critical factor due to cultural aspects (religious, linguistic, adaptation to local conditions). Immigrants reveal a different perception of the heat risk and consequently a greater vulnerability [11,12]. It is also important to note that workers involved in outdoor activities, especially in agriculture and construction sectors, often wear personal protective clothing and equipment that significantly increases the heat stress by limiting the body heat loss. The heat stress vulnerability of a worker is strictly individual and therefore depends on a multiplicity interconnected factors: work environment, work effort, physical characteristics, state of health, hydration status, age, and type of clothing worn. In light of this situation, it is fundamental to increase adaptation strategies with the aim to mitigate the effects heat conditions at different temporal scales (few days to decades), also including local microclimatic monitoring and developing warning systems that are also representing the priorities of both World Meteorological Organization (WMO) and World Health Organization (WHO). For these reasons, in recent years, a great number of heat-health warning systems (HHWSs) have been developed for the general population [13], and in particular for vulnerable groups including workers [14,15].

HHWSs generally do not use single standard parameters, e.g., air temperature and humidity, wind speed, or solar radiation, but a combination of them expressed as an index, to describe in detail the thermal stress induced by the outdoor environment on the human body. For these reasons, a great number of biometeorological indices have been developed and find application in various fields. The empirical Wet Bulb Globe Temperature (WBGT) according to UNI EN ISO 7243 [16] and the rational Predicted Heat Strain (PHS) according to UNI EN ISO 7933 [17] are currently the only systems developed at an international level for an objective assessment of heat stress referring to groups of workers. In particular, the WBGT, being an empirical index and easier to apply, is used precisely for a first screening of heat stress on workers and is therefore suitable for applications in the forecasting meteorological field. The Wet-Bulb Globe Temperature (WBGT) index [18,19] represents the international reference among heat stress indices for work activity assessments [5,15,16,20] because it responds to the needs of the occupational sector that are different compared to the general population and other vulnerable groups. Recently, the WBGT, was also chosen and used as the heat stress indicator in the “HEAT-SHIELD occupational warning system” platform [15] within the frame of the European HEAT-SHIELD Project (HORIZON 2020, research and innovation program under the grant agreement 668786). In particular, it was the first operational website platform providing personalized short- and long-term heat warning (up to 46 days) with also hydration and work/break schedule recommendations (up to five days) to safeguard workers’ health and productivity. The HEAT-SHIELD HHWS is currently the only warning system addressed to workers that provides forecasts up to medium–long term range, using a probabilistic meteorological model calibrated with observations on specific locations. However, this system has some limitations: provides information with a low temporal resolution (daily forecast without any sub-daily detail) because it is based on a monthly ensemble forecasts model (ECMWF) without detailed intra-daily forecast. It is location-specific because the forecasts are available only for 1800 European locations where downscaling and bias-correction procedures are applied using observed data. It is available as a web service and not as APP.

These HHWSs systems are based on the outputs of different weather forecast systems from high-resolution models to probabilistic ensembles or to a combination of them [15]. In the case of Europe, the national agencies run their own simulations or use those from the European Center for Medium-Range Weather Forecasts (ECMWF) or a combination of both. There are also ready-to-use products from the ECMWF such as the EFI (extreme forecast index) of temperature, indicating how extreme predicted temperatures are [13]. There are several studies on the verification of the parameters predicted by meteorological models [21–26], but very few relating to the validation of heat stress indicators [15,27].

To try to fill the gaps in the HEAT-SHIELD HHWS, an Italian Project (WORKLIMATE) approved under the BRIC-INAL 2019 funding is under development. It is focused on the estimation of social costs of accidents at work and on the development of heat-related adaptation strategies for workers also accounting for qualitative approaches. One of the main objectives of the project will be to develop a first experimental version of an occupational HHWS for Italy, taking into account also epidemiological aspects. The HHWS will be represented by a first high resolution experimental version of Web Forecasting Platform (https://www.worklimate.it/en/maps-choice/shade-intense-physical-activity/; accessed on 18 September 2021) and a mobile web app with personalized heat-stress-risk based on the worker's characteristics and on the work environment (i.e., workers exposed to the sun or in shaded areas). In particular, WORKLIMATE will try to respond to several occupational needs providing a specific and detailed personalized HHWS useful for worker and various stakeholders with detailed intra-daily information (per time slots) in the short term (forecast up to five days) concerning the heat risk level and behavioral suggestions (hydration and breaks recommended) to reduce the impact of the heat on different occupational sectors. Furthermore, the recommendations provided will also take into account the presence of some individual vulnerability/susceptibility factors.

To be able to meet these requirements, the goal is to use, in the WORKLIMATE operational chain, a limited area meteorological model to achieve a high scale of analysis (less than 10 km) and temporality (sub-daily detail of the forecasts).

In particular, the performances of two limited area models operational at the "Environmental Modelling and Monitoring Laboratory for Sustainable Development (LaMMA Consortium)" were tested on several locations along Italy over a period of about three summer seasons and their possible use in the operational chain will be discussed highlighting strengths and weaknesses.

2. Materials and Methods

2.1. Methodology

The comparison between model outputs and weather stations data was carried out over the period May–September and for 4 time slots: 0–6, 6–12, 12–18, 18–24 (daylight saving time). Each time slot was analyzed both considering all its hourly data and its maximum value. In the paper only the results of hottest period of the day, time slot 12–18, were showed. The analyses were performed for each weather station and for both Day2 (tomorrow forecast) and Day3 (after tomorrow forecast). Day1 (today) data are not shown because it is not fully suitable for an alert system that must provide information at least 24 h in advance. Results are presented both per station and as an average value for homogeneous geographical areas.

2.2. Meteorological Observation Dataset

Hourly meteorological data (air temperature, air humidity, and wind speed) of about 40 Italian weather stations were collected and archived in order to verify the performances of different meteorological models. The meteorological stations have been chosen in order to represent most of the climatological characteristics of the most populated Italian areas compatibly with data availability.

The main sources of data were the Regional Hydrologic Services of Tuscany and Umbria (SIR) and National Weather Service (AM). These services are responsible for the maintenance and data validation and each weather station was installed in accordance with the rules of the World Meteorological Organization [28,29]. Concerning solar radiation, the METEOSAT satellite estimation from LSA SAF products belonging to EUMETSAT (https://www.eumetsat.int/lsa-saf; accessed on 21 September 2021) was used due to the difficulties in obtaining reliable ground data. Meteorological hourly data were collected for the period 1 July 2018–7 August 2020.

After a first check on the collected dataset, only 28 stations showed continuity and good quality of data during the period 2018–2020 and in particular during the hottest months of the year (from May to September) and in the daytime slots (06:00–12:00 and 12:00–18:00 in daylight saving time). The distribution of the stations is not homogeneous, however sufficient to highlight possible critical issues. The distribution of the weather stations over Italy is shown in Figure 1.

Figure 1. Distribution of the Italian weather stations analysed for the creation of the observation dataset. The chosen stations were identified by the name of the location.

The 28 weather stations are also listed in Table 1 where they have been classified by three geographical macro-areas: North inland plain areas (A), Coastal areas (B); Central-south inland areas (C). For each location, latitude, longitude, and altitude are shown.

Concerning the macroarea A, Bolzano was not included during the calculations of the average skill scores by area, because contrary to the others locations it was in a very narrow valley surrounded by very high mountains (very complex topography), and for this reason the model reconstructs a very higher elevation (about 1050 a.s.l) than the real one (262 m a.s.l). However, it was used to compare its skill scores with those of the other location of the area.

Table 1. Distribution of the Italian weather stations used in the study. For each location, latitude (Lat.), longitude (Lon.) and altitude (Alt. a.s.l) are showed. A, North inland plain areas; B, Coastal areas; C, Central-south inland areas.

A				**B**				**C**			
Location	Lat	Lon	Alt	Localion	Lat	Lon	Alt	Localion	Lat	Lon	Alt
Bolzano	46.46	11.32	262	Venice	45.47	12.34	5	Florence	43.80	11.2	50
Bergamo	45.66	9.7	237	Rimini	44.02	12.61	13	Montopoli	43.66	10.74	29
Milan	45.63	8.72	212	Pescara	42.43	14.18	11	Legoli	43.56	10.8	180
Brescia	45.42	10.28	97	Roma	41.80	12.23	5	Cesa	43.30	11.82	246
Verona	45.38	10.87	68	Olbia	40.89	9.51	13	Foligno	42.95	12.67	224
Turin	45.20	7.64	287	Naples	40.88	14.29	72	Braccagni	42.93	11.08	40
Bologna	44.53	11.29	37	Alghero	40.63	8.28	40	Grosseto	42.74	11.05	7
				Lecce	40.23	18.13	53	Decimomannu	39.34	8.86	24
				Capo Bellavista	39.93	9.71	150	Lamezia	38.90	16.24	16
				Cagliari	39.25	9.05	3				
				Palermo	38.18	13.09	44				
				Catania	37.46	15.06	17				

2.3. Meteorological Forecast Model Dataset

Between the limited area models available at the “Environmental Modelling and Monitoring Laboratory for Sustainable Development- LaMMA Consortium”, Bolam and Moloch models were chosen for the comparison. LaMMa (https://www.lamma.rete.toscana.it; accessed on 21 September 2021) is a public consortium between the Tuscany Region and the National Research Council which carries out activities related to observation systems and meteorological modeling at different spatial scales. Furthermore, the LaMMA provides meteorological forecasts to the Civil Protection and carries out research activities in various fields, including the climatological one. The Bolam model [30,31] is a hydrostatic meteorological model, continuously developed at CNR-ISAC (Bologna, Italy) in 1992. The main prognostic variables are the wind components, the absolute temperature, the surface pressure, the specific humidity, and the turbulent kinetic energy. The surface layer and the planetary boundary layer are modelled according to the similarity theory [32], with a mixing-length based turbulence closure model, to parameterize the turbulent vertical diffusion of momentum, heat and moisture. The turbulence closure is of order 1.5 [33], in which the turbulent kinetic energy is predicted. The Soil Model uses 4–6 layers and computes surface energy, momentum, water and snow balances, heat and water vertical transfer, and vegetation effects at the surface (evapo-transpiration, interception of precipitation, wilting effects etc.) and in the soil (extraction of water by roots). It takes into account the observed geographical distribution of different soil types and soil physical parameter. The atmospheric radiation is computed with a combined application of the global radiation [34] scheme and the ECMWF scheme [35,36]. The model was tested and favorably compared with many other limited area models, in the course of the Comparison of Mesoscale Prediction and Research Experiments [37,38] as well as the MAP (Mesoscale Alpine Programme) field phase [39]. Moloch, on the other hand, is a non-hydrostatic, fully compressible, convection resolving model recently developed at CNR-ISAC in 2000 [40]. The model was employed, among other studies, in the international forecasting demonstration project called MAP-DPHASE, in which many mesoscale high-resolution NWP models were compared in real time (during autumn 2007), especially in relation to QPF (Quantitative Precipitation Forecasting—[41]) and in the European project RISKMED [42]. The two models have surface schemes (Land Surface Model, Planetary Boundary Layer and Radiation) very similar, with the exception of specific differences introduced in Moloch to treat the complex processes characterizing convective systems, and hence behave in similar way in forecasting surface variables (e.g., 2 m temperature and dew point, 10 m winds and windgust, short and long wave radiation). Other differences between the two models present in the different horizontal resolution (7 km for Bolam vs. 2.5 km for Moloch), and in initial and boundary conditions. Davolio et al. [43] reported that Bolam and Moloch have been used for numerous scientific studies and applications, e.g., sensitivity and impact studies, and diagnostics of meteorological phenomena, including severe weather and storms. In addition, they also reported that these models were used in several operational applications.

The operational chain of Bolam is based on initial and boundary conditions provided by the Global Forecast Model (GFS) of the NCEP at 0.25 deg resolution (about 25 km), 2 runs a day (00 and 12 UTC) performed with a lead time of +120 h for 00 run and +132 h for 12 run. The operational chain for Moloch is based on initial and boundary conditions provided other than by GFS (as Bolam) also by the IFS Global Model of the ECMWF at 0.10 deg resolution (about 10 km), 4 runs a day (00, 06, 12 and 18 UTC) performed with a lead time of +84 h for 00 run, +42 h for 06 run, +84 h for 12 run and +54 h for 18 UTC run. In the present study, only the 00 UTC run and the first 72 h of prediction were considered. In this paper, the Bolam model will be called BOL, while Moloch will be called MOL-G and MOL-E, respectively, depending on whether it is initialized with the GFS or with IFS Global Model of the ECMWF.

Hourly model outputs were available from 1 July 2018 to 7 August 2020. Figure 2 shows, for each location, the elevation of the meteorological stations and that of the closest meteorological model grid points (BOL and MOL). The model grid point extraction was performed using the only criterion of the minimum distance from the location without any type of correction.

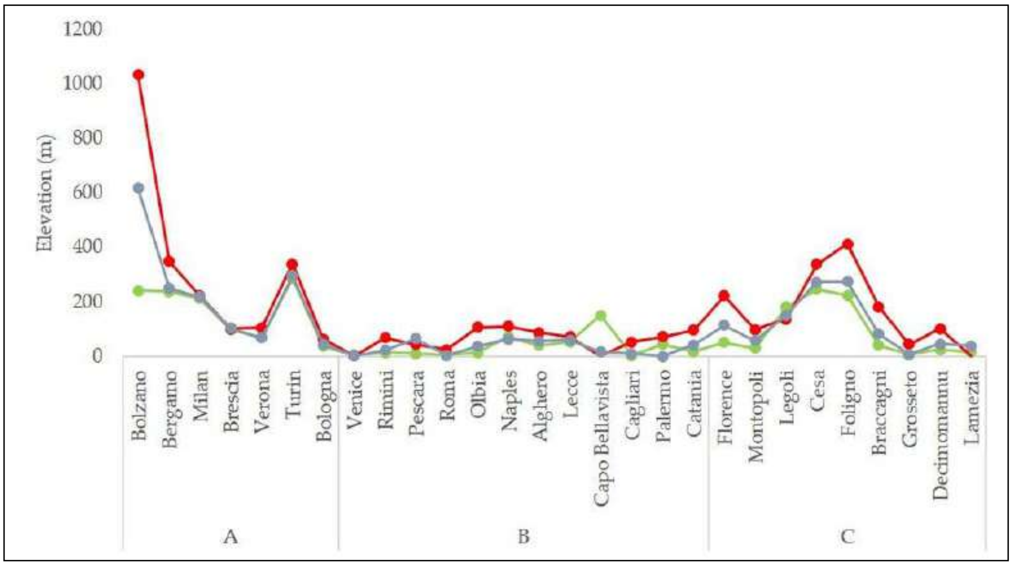

Figure 2. Elevation of the weather stations and the closest meteorological model grid points. Green line, weather station; Red line, BOL model; blue line, MOL model.

Figure 3 shows the areas of Italian peninsula where the models grid points have an elevation higher than at least 200 m with respect to that of a digital terrain model (DTM) with a spatial resolution of 90 m (overestimation of the elevation).

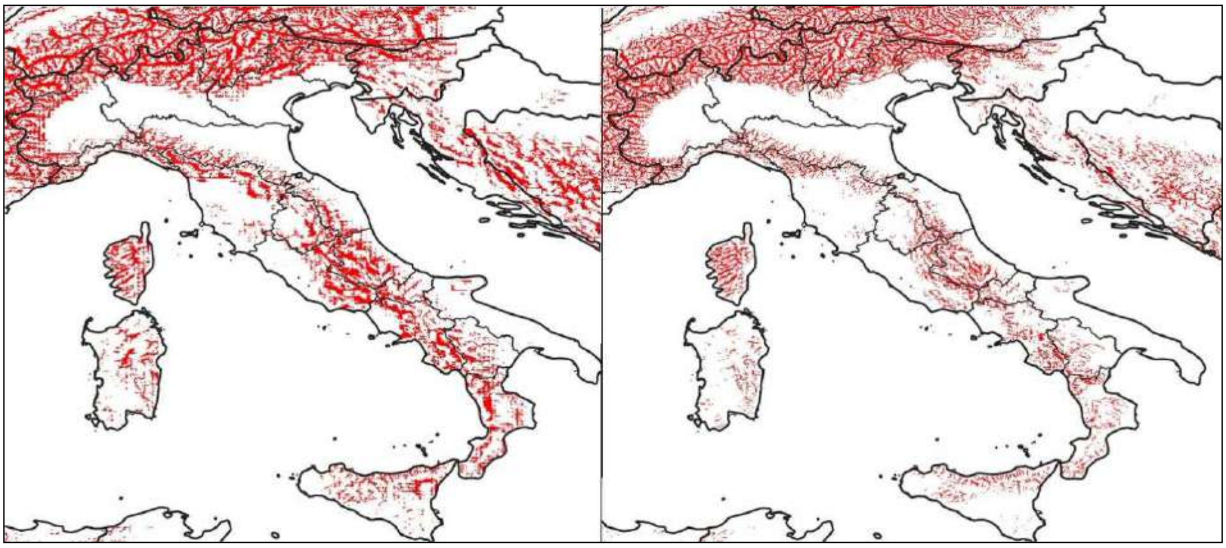

Figure 3. In red the areas of Italian peninsula where the models grid points (BOL on the left, MOL on the right) have an elevation higher than at least 200 m respect to that of a digital terrain model (DTM) with a spatial resolution of 90 m.

2.4. Heat Stress Indicator

The Wet Bulb Globe Temperature (WBGT) index was selected as the heat strain indicator for the WORKLIMATE high-resolution heat–health warning system. WBGT was developed in the 1950s as a basis for environmental heat stress monitoring to control heat casualties at military training camps in the USA [5,18] and in particular in a study on heat-related injuries during military training [44]. Today, it represents the most commonly used heat stress index for a first screening of heat stress conditions in workplaces, with recommended rest/work cycles at different metabolic rates clearly specified in the international standard to ensure that the average core body temperature of a worker does not exceed 38°C [16]. The WBGT represents a good compromise between the data forecasted by the meteorological model and the quality/usefulness of the forecast information of the heat risk taking into account the various exposure scenarios to which workers are exposed. WBGT is considered to fulfill the purpose for individualized heat warnings, with customized limits for different workers potentially useful for managing policies against the heat effects. For this reason, it was also chosen and used as the heat stress indicator in the "HEAT-SHIELD occupational warning system" [16] realized within the frame of the European HEAT-SHIELD Project (grant agreement 668786). WBGT is a combination of the following meteorological parameters:

- Dry-bulb temperature (Ta), measured with a thermometer shaded from direct heat radiation.
- Natural wet-bulb temperature (Tnwb), measured with a wetted thermometer exposed to the actual wind and heat radiation.
- Black Globe Temperature (Tg), measured inside a 150mm diameter black globe.

This indicator therefore allows to estimate the thermal stress conditions both of a subject exposed to the direct short-wave radiation (WBGT-sun) and of a subject not directly exposed to direct short-wave radiation (WBGT-shade). For WBGT workplace calculation starting from meteorological data, Lemke and Kjellstrom's [45] procedure was used and the approach of Bernard and Pourmoghani [46] was also applied [47] for computing WBGT in the shade and in the sun, respectively. These implementations allow the calculation of both the natural wet bulb temperature, that is the largest component (70%) of WBGT, and the black globe temperature (it contributes 20–30% of WBGT) as required by the WBGT formulas starting from air temperature, humidity, wind speed, and solar radiation provided by the weather forecast model [16]. WBGT-sun and WBGT-shade hourly values were also calculated using the limited area models' meteorological data provided by the LaMMA

Consortium. Using the procedure already used in the Heat-Shield forecast system [15], the predicted WBGT value was corrected in WBGTeff to take into consideration the clothing information and then compared with the customized risk threshold (WBGT RAL and WBGT REL for acclimatized and unacclimatized worker, respectively), obtaining the risk level (RL) [16]:

$$\text{WBGT}\mathit{eff} = \text{WBGT predicted} + \text{Clothing Adjustment Value (CAV) as described in ISO 7243} \quad (1)$$

$$\text{WBGT RAL}(^\circ\text{C}) = 59.9 - 14.1 \text{ log10 MR} \quad (2)$$

$$\text{WBGT REL}(^\circ\text{C}) = 56.7 - 11.5 \text{ log10 MR} \quad (3)$$

$$\text{RL (\%)} = (\text{WBGT}\mathit{eff} / \text{WBGT RAL (o WBGT REL)}) \times 100 \quad (4)$$

$$\text{RL0 (green)} = \text{RL(\%)} \leq 80 \quad (5)$$

$$\text{RL1 (yellow)} = 80 < \text{RL(\%)} < 100 \quad (6)$$

$$\text{RL2 (orange)} = 100 < \text{RL(\%)} < 120 \quad (7)$$

$$\text{RL3 (red)} = \text{RL(\%)} \geq 120 \quad (8)$$

The 5-day threshold with critical heat stress conditions (in our case with at least a moderate risk level) was used to define when a worker can be considered acclimatized to heat within a warm season.

The RL (0 not significant; 1 low risk, 2 moderate risk, 3 high risk) were calculated for a standard worker (weight 75 kg, height 175 cm), acclimatized to heat, engaged in intense physical activity, and wearing normal working overalls. The RL predicted (RLP) by the limited area model were then compared with the RL obtained using meteorological parameters (RLO) recorded by weather stations (following in the paper observed data). Obviously, the RL skill scores obtained considering this typology of worker are to be considered purely indicative as they may vary with the characteristics of the worker.

2.5. Data Analysis and Forecast Evaluation Metrics

The hourly RLPs and RLOs (both for WBGT-sun and WBGT-shade) were compared using contingency tables (Table 2). For each of the 28 location, contingency tables were created, taking into account the day of forecast and the daily time slot. Each table was then populated with the hourly RLP and RLO pair values. In this way, the table diagonal represents the number of hours with correct forecast, i.e., the hours in which the RLP exactly matches the RLO.

Table 2. Contingency table between the observed (RLO) versus predicted (RLP) values risk classes.

		RLO			
		0	1	2	3
RLP	0	C00	C10	C20	C30
	1	C01	C11	C21	C31
	2	C02	C12	C22	C32
	3	C03	C13	C23	C33

Then, the following skill scores were calculated [48]:

- Hit rate (HR): Correct predictions probability (%) on the total of events (including class 0).

$$\text{HR} = \frac{\text{C00} + \text{C11} + \text{C22} + \text{C33}}{\text{C00} + \text{C10} + \text{C20} + \text{C30} + \text{C01} + \text{C11} + \text{C21} + \text{C31} + \text{C03} + \text{C13} + \text{C23} + \text{C33}} \times 100$$

- Critical success index (CSI): Correct predictions probability (%) considering only $\text{RL} \geq 1$.

$$\mathrm{CSI} = \frac{\mathrm{C11} + \mathrm{C22} + \mathrm{C33}}{\mathrm{C10} + \mathrm{C20} + \mathrm{C30} + \mathrm{C01} + \mathrm{C11} + \mathrm{C21} + \mathrm{C31} + \mathrm{C02} + \mathrm{C12} + \mathrm{C22} + \mathrm{C32} + \mathrm{C02} + \mathrm{C13} + \mathrm{C23} + \mathrm{C33}} \times 100$$

- Probability of detection (POD): Correct predictions probability (%) of any class. This skill was calculated for RL1 (POD1), RL2 (POD2), and RL3 (POD3). POD was also calculated, also considering the forecast of a higher class than the observed as correct. This was carried out for both RL1 (POD1x) and RL2 (POD2x).

$$\mathrm{POD1} = \frac{\mathrm{C11}}{\mathrm{C10} + \mathrm{C11} + \mathrm{C12} + \mathrm{C13}} \times 100$$

$$\mathrm{POD2} = \frac{\mathrm{C22}}{\mathrm{C20} + \mathrm{C21} + \mathrm{C22} + \mathrm{C23}} \times 100$$

$$\mathrm{POD3} = \frac{\mathrm{C33}}{\mathrm{C30} + \mathrm{C31} + \mathrm{C32} + \mathrm{C33}} \times 100$$

$$\mathrm{POD1x} = \frac{\mathrm{C11} + \mathrm{C12}}{\mathrm{C10} + \mathrm{C11} + \mathrm{C12} + \mathrm{C13}} \times 100$$

$$\mathrm{POD2x} = \frac{\mathrm{C22} + \mathrm{C23}}{\mathrm{C20} + \mathrm{C21} + \mathrm{C22} + \mathrm{C23}} \times 100$$

- Lack alarm ratio (NA): The probability (%) that if RL0 was predicted, a higher class has been observed instead.

$$\mathrm{NA} = \frac{\mathrm{C10} + \mathrm{C20} + \mathrm{C30}}{\mathrm{C00} + \mathrm{C10} + \mathrm{C20} + \mathrm{C30}} \times 100$$

- False alarm ratio (FA): The probability (%) that if RL0 is observed, a higher class has been predicted instead.

$$\mathrm{FA} = \frac{\mathrm{C01} + \mathrm{C02} + \mathrm{C03}}{\mathrm{C00} + \mathrm{C01} + \mathrm{C02} + \mathrm{C03}} \times 100$$

- Normalized lack alarm ratio (NA*): Lack alarm probability (%) normalized on the total number of hours analyzed.

$$\mathrm{NA}* = \frac{\mathrm{C10} + \mathrm{C20} + \mathrm{C30}}{\mathrm{C00} + \mathrm{C10} + \mathrm{C20} + \mathrm{C30} + \mathrm{C01} + \mathrm{C11} + \mathrm{C21} + \mathrm{C31} + \mathrm{C02} + \mathrm{C12} + \mathrm{C22} + \mathrm{C32} + \mathrm{C03} + \mathrm{C13} + \mathrm{C23} + \mathrm{C33}} \times 100$$

- Normalized false alarm ratio (FA*): False alarm probability (%) normalized on the total number of hours analyzed.

$$\mathrm{FA}* = \frac{\mathrm{C01} + \mathrm{C02} + \mathrm{C03}}{\mathrm{C00} + \mathrm{C10} + \mathrm{C20} + \mathrm{C30} + \mathrm{C01} + \mathrm{C11} + \mathrm{C21} + \mathrm{C31} + \mathrm{C02} + \mathrm{C12} + \mathrm{C22} + \mathrm{C32} + \mathrm{C03} + \mathrm{C13} + \mathrm{C23} + \mathrm{C33}} \times 100$$

In addition to the skill scores on WBGT expressed in terms of categorical RLs, mean error (ME), mean absolute error (MAE), and root mean square error (RMSE) have been calculated for continuous variables (included WBGT expressed as temperature). The ME is the average of the deviations between predicted (Y) and observed (O) values:

$$\mathrm{ME} = \frac{1}{\mathrm{M}} \sum_{\mathrm{m}=1}^{\mathrm{M}} (\mathrm{Ym} - \mathrm{Om})$$

When ME is 0, it means that the positive and negative deviations between the predicted and observed values balance out. For this reason, a ME equal to zero can be the result of either deviation close to 0, but also the result of positive and negative deviations that balance each other. To evaluate the gap average size in absolute value, the MAE was used:

$$\mathrm{MAE} = \frac{1}{\mathrm{M}}\sum_{\mathrm{m}=1}^{\mathrm{M}} |\,(\mathrm{Ym} - \mathrm{Om})\,|$$

ME equal to 0 associated with an MAE close to zero is the desirable situation. Finally, the RMSE was also calculated, which attributes a greater weight to the largest gaps:

$$\mathrm{RMSE} = \sqrt{\frac{1}{\mathrm{M}}\sum_{\mathrm{m}=1}^{\mathrm{M}} (\mathrm{Ym} - \mathrm{Om})}$$

3. Results

Day2-WBGT Forecast Validation (Period May-September, Time Slot 12–18 All the Hour)

BOL, MOL-E, and MOL-G showed a similar probability of detection of the RL1 (POD1) that represents the most frequent risk level observed and predicted (RLO1 and RLP1) (values close to 50%) during the hottest time slot of the warm period (Table 3).

Table 3. Day2-WBGT-shade average categorical skill scores for the 12–18 time slot for each geographical macro-areas. In the "northern inland plain areas", Bolzano values were not included in the average.

	A			**B**			**C**		
Model	**BOL**	**MOL_E**	**MOL_G**	**BOL**	**MOL_E**	**MOL_G**	**BOL**	**MOL_E**	**MOL_G**
Data	1908	1968	1920	1902	1962	1914	1896	1956	1908
HR	82.9	79.6	80.2	80.0	79.1	78.3	74.5	78.9	79.7
CSI	78.3	75.0	75.4	75.7	74.9	73.6	69.2	75.2	75.9
POD1	81.2	78.0	79.1	84.2	82.2	84.0	79.9	80.2	81.9
POD2	89.2	92.1	90.9	73.6	74.6	67.8	61.9	79.9	79.1
POD3									
POD1x	96.2	98.1	97.2	94.9	95.4	95.0	87.8	93.8	94.4
POD2x	89.5	92.4	91.6	73.6	74.6	67.8	61.9	80.1	79.1
NA	8.5	5.3	7.0	12.0	11.0	11.5	24.3	16.9	15.0
FA	19.7	28.2	26.1	16.8	19.8	19.1	11.1	19.9	18.9
NA*	2.0	1.0	1.5	2.4	2.1	2.3	5.6	2.8	2.6
FA*	5.0	7.2	7.0	3.7	4.2	4.2	2.2	3.9	3.8
RLO 1	53.1	53.0	52.7	47.3	47.4	47.2	48.2	47.7	48.1
RLO 2	20.8	21.5	20.6	30.8	31.3	30.7	32.2	33.1	32.0
RLO 3	0.0	0.0	0.0	0.3	0.2	0.3	0.3	0.3	0.3
RLP 1	50.2	50.1	50.2	52.1	51.2	53.7	54.0	49.3	50.4
RLP 2	26.6	30.4	28.4	27.6	29.8	26.3	23.4	32.9	31.2
RLP 3	0.1	0.1	0.2	0.0	0.0	0.0	0.0	0.1	0.0

Model: BOL, BOLAM initialized on the GFS; MOL-E, MOLOCH initialized on the ECMWF; MOL-G, MOLOCH initialized on the GFS; Data, sample size; HR, hit Rate (%); CSI, critical success index (%); POD1, probability of risk level 1 detection (%); POD2, probability of risk level class 2 detection (%); POD3, probability of risk level 3 detection (%); POD1x, probability of risk level 1 or higher class detection (%); POD2x, probability of risk level 2 or higher class detection (%); NA, lack alarm (%); FA, false alarm (%); NA*, normalized lack alarm (%); FA*, normalized false alarm (%); RLO1, risk level 1 observed (%); RLO2, risk level 2 observed (%); RLO3, risk level 3 observed (%); RLP1, risk level1 predicted (%); RLP2, risk level2 predicted (%); RLP3, risk level 3 predicted (%); empty cell, it was not possible to calculate the indicator due to the lack of data observed or predicted by the model for at least one location.

The average POD1 showed values close to 80% and with the highest values in "coastal areas" (BOL = 84.2% and MOL-G = 84%). If the forecast in a higher class than the observed one is also considered correct (POD1x), the score rises above 90% for almost all models and for all macro-geographical areas. The highest values in this case were in "northern inland plain areas" (MOL-E = 98.1%, MOL-G = 97.2%, and BOL = 96%).

The variability of the skill scores between the different locations of each macro-geographical areas was minimal (data not shown), and for Bolzano despite in an area with a complex orography the skill scores were relatively high and not too different from that of the other north inland locations where POD1 was between 57 and 80% and POD1X between 85 and 90%. Considering the average probability of detection of the RL2 (POD2) the highest values, around 90%, were observed in "northern inland plain areas", while values in a range of 68–75% and 62–80% were on "coastal areas" and "other central-south inland areas", respectively. The lowest value of 62% was for BOL. No significant increases were observed in POD2x versus POD2, because almost never a RL3 was predicted considering the worker characteristics previously described. In almost all cases in which RL2 has been observed, there was at least one risk class (RL1 or RL2), and rare exceptions temporarily occurred in areas with particularly complex topography (such as for example in Alpine and Apennine valleys or some coastal areas). Figure 4 shows the probability of detection (POD2) of the Day2-WBGT-shade for the 12:00–18:00 time slot for each location of the three macro-geographical areas.

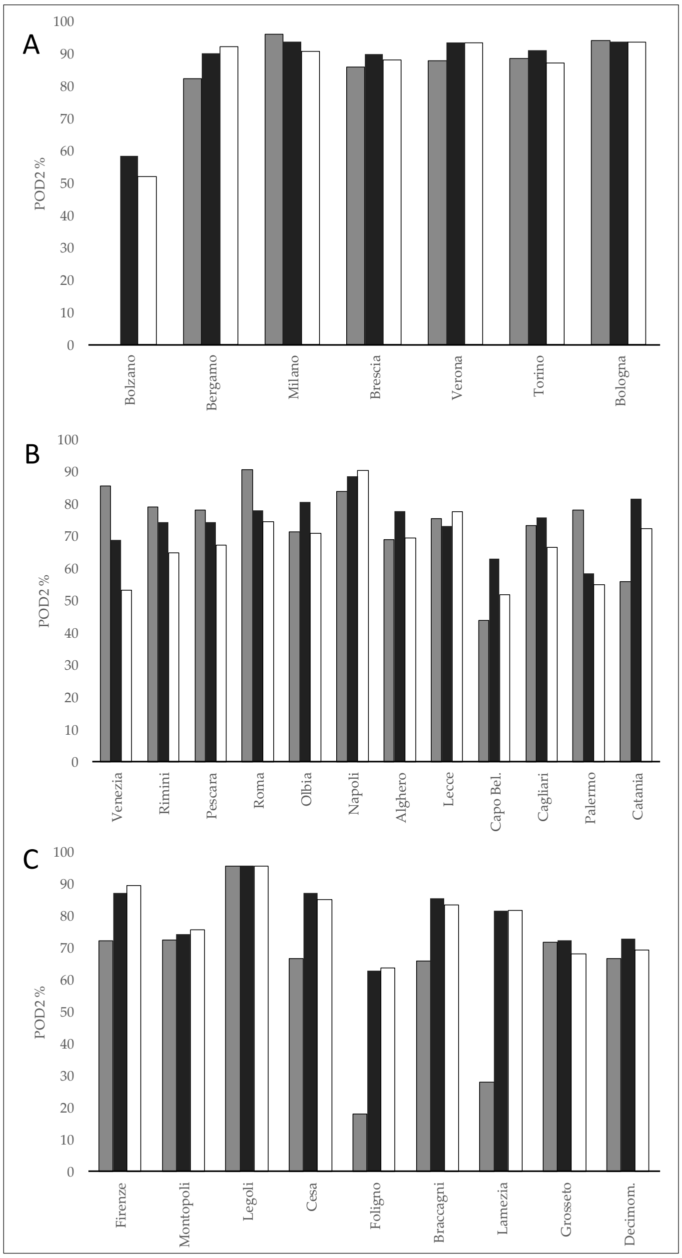

Figure 4. Probability of detection (POD2) of the Day2-WBGT-shade for the 12–18 time slot for each location of the three macro-geographical areas. (**A**), Northern inland plain areas; (**B**) Coastal areas; (**C**), Other central-southern inland areas; white, MOL-G; black, MOL-E; gray, BOL.

In “northern inland plain areas” the POD2 values in several locations were around 90% for all models with the exception of Bolzano where BOL was not able to predict RL2, whereas MOL-G and MOL-E in a percentage around 50–60%. In the “coastal areas”, POD2 was generally higher than 60% for several locations and for all models except for Capo Bellavista with POD2 ranging between 63% (MOL-E) and 44% (BOL). In the “other central-southern inland plain areas”, BOL showed rather low POD2 values (<30%) in Foligno and Lamezia, while for MOL-E and MOL-G it was close to 60%. For the other locations in the area, there were no significant differences between the models with POD2 above 60%. Concerning the lack alarm (NA), the lowest number was observed in “northern inland plain areas” (NA = 5.3–8.5%) while a progressive increase was observed moving from “coastal areas” (NA = 11–12%) to “other internal central-southern areas” (NA = 15–24.3%). The highest values were reached for BOL especially in the “other central-southern internal areas (NA = 24.3) (Table 3). A similar pattern was shown by the normalized lack alarms (NA*), but with significantly lower values. Figure 5 shows the normalized lack alarms (NA*) for the forecast of the Day2-WBGT-shade for the 12–18 time slot for each location of the three macro-geographical areas. The highest levels of NA* were found for BOL in areas with greater topographic complexity, well represented by Bolzano and secondarily by Foligno and Lamezia (NA* 38%, 14% and 9% respectively), while elsewhere the scores for different models were similar.

Concerning false alarms (FA and FA*) were greater in the “northern inland plain areas” for MOL-E (FA = 28.2 and FA* = 7.2) and MOL-G (FA = 26.1 and FA* = 7). It is interesting to observe how RL3 for WBGT-shade was almost never predicted or observed in all areas during the analyzed period, making it impossible to calculate the corresponding average POD3 (some had no data). At least for the time slot 12–18, the results obtained considering all its hourly values were not different to those obtained with its maximum value (data not shown).

Mean error (ME), mean absolute error (MAE), and root mean square error (RMSE) calculated on the numerical value of WBGT-shade confirmed a very similar performance of models in predicting WBGT-shade for all macro-geographical areas (Table 4). ME values were positive in “northern inland plain areas” for BOL (0.4), MOL-E (0.7), and MOL-G (0.7). On the contrary, they were slightly negative in the coastal areas and in the “other central-southern inland areas” ($-0.8 < \mathrm{ME} < 0$), highlighting a slight underestimation of the WBGT-shade values in these areas. Moreover, considering these skill scores, Bolzano showed the highest error especially for BOL (ME = −3.5 for BOL and −0.6 for MOL-E). The average mean absolute error for different models and areas was between 1 and 1.4 °C. The skill scores were very similar also considering the maximum time slot value with an underestimation of about 1 °C for BOL in other inland areas.

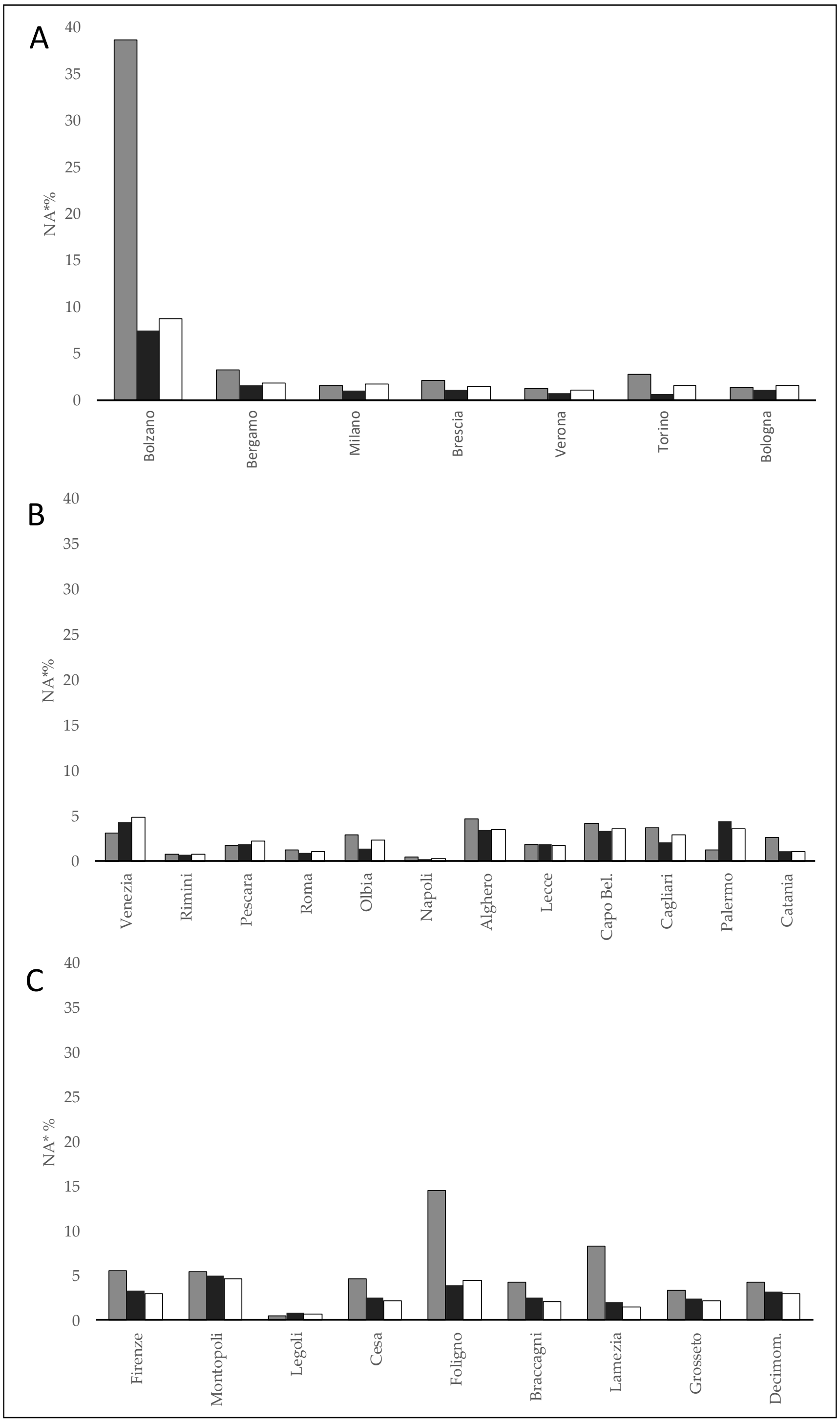

Figure 5. Normalized lack alarm (NA*) of the WBGT-shade for the 12–18 time band for each locality of the three macro-geographical areas. (**A**), Northern inland plain areas; (**B**), Coastal areas; (**C**), other central-southern inland areas; white, MOL-G; black, MOL-E; gray, BOL.

Table 4. Average values of Mean error, mean absolute error and root mean square error of the Day2-WBGT-shade predicted for the 12:00–18:00 time slot for the three geographical macro-areas. The scores were calculated both considering all its hourly data and the its maximum value. In the "northern inland plain areas" (A), Bolzano values were not included in the average.

		A			**B**			**B**	
Model	**BOL**	**MOL_E**	**MOL_G**	**BOL_G**	**MOL_E**	**MOL_G**	**BOL_G**	**MOL_E**	**MOL_G**
MAE	1.1	1.2	1.1	1.0	1.1	1.1	1.4	1.1	1.1
RMSE	1.4	1.5	1.5	1.3	1.4	1.4	1.7	1.5	1.4
ME	0.4	0.7	0.7	−0.2	−0.1	−0.1	−0.8	0.0	−0.1
Data	1908	1968	1920	1902	1962	1914	1897	1957	1909
MAEmax	1.0	1.1	1.1	1.0	1.1	1.1	1.4	1.1	1.0
RMSEmax	1.3	1.4	1.4	1.3	1.4	1.4	1.7	1.4	1.3
MEmax	0.3	0.8	0.8	−0.3	−0.1	−0.2	−0.9	0.0	0.0
Datamax	318	328	320	318	328	320	316	326	318

Model: BOL, BOLAM initialized on the GFS; MOL-E, MOLOCH initialized on the ECMWF; MOL-G, MOLOCH initialized on the GFS; MAE, mean absolute error; RMSE, root mean square error; ME, mean error; Data, sample size; MAEmax, mean absolute error of the maximum time slot value; RMSEmax, root mean square error of the maximum time slot value; MEmax, mean error of the maximum time slot value; Datamax, maximum value sample size.

The results relative to the prediction of WBGT-sun (Table 5), and therefore of the RL for a worker who carries out his activities directly exposed to solar radiation, are very similar to those observed for the WBGT-shade, even with an improvement in performance of the models for the forecast of the RL2.

Table 5. Day2-WBGT-sun average categorical skill scores for the 12–18 time slot for each geographical macro-areas. In the "northern inland plain areas" (A), Bolzano values were not included in the average.

		A			**B**			**C**	
Model	**BOL**	**MOL_E**	**MOL_G**	**BOL**	**MOL_E**	**MOL_G**	**BOL**	**MOL_E**	**MOL_G**
Data	1902	1962	1914	1898	1958	1910	1892	1952	1904
HR	77.5	75.8	76.1	80.7	79.6	80.2	75.0	79.7	79.7
CSI	74.3	72.6	72.8	78.5	77.3	77.9	71.8	77.5	77.5
POD1	71.8	67.2	68.5	76.7	74.7	78.2	74.3	75.3	76.2
POD2	87.6	89.3	89.3	88.0	86.3	85.4	78.4	88.3	88.1
POD3									
POD1x	95.0	96.4	96.2	94.5	94.4	94.8	86.9	92.5	93.3
POD2x	91.2	94.1	93.1	88.5	87.6	86.3	78.9	89.9	89.6
NA	12.3	7.7	9.7	15.7	14.5	13.7	26.9	17.9	17.5
FA	31.4	33.4	34.3	24.6	25.4	26.2	20.1	26.4	27.0
NA*	1.8	1.0	1.3	1.8	1.7	1.6	4.3	2.0	1.9
FA*	5.7	5.9	6.4	3.5	3.4	3.7	2.9	3.7	3.8
RLO 1	41.4	41.2	41.4	35.5	34.9	35.5	36.5	35.8	36.8
RLO 2	39.8	40.2	39.4	49.2	50.2	49.0	47.9	48.7	47.4
RLO 3	0.6	0.9	0.6	1.7	1.7	1.7	2.2	2.4	2.2
RLP 1	38.7	35.8	37.3	36.4	35.6	37.9	40.3	35.3	36.8
RLP 2	45.2	48.9	47.3	51.3	52.0	49.6	44.4	51.8	50.4
RLP 3	1.8	2.5	1.9	0.4	1.0	0.7	0.5	1.5	1.1

Model: BOL, BOLAM initialized on the GFS; MOL-E, MOLOCH initialized on the ECMWF; MOL-G, MOLOCH initialized on the GFS; Data, sample size; HR, hit Rate (%); CSI, critical success index (%); POD1, probability of risk level 1 detection (%); POD2, probability of risk level class 2 detection (%); POD3, probability of risk level 3 detection (%); POD1x, probability of risk level 1 or higher class detection (%); POD2x, probability of risk level 2 or higher class detection (%); NA, lack alarm (%); FA, false alarm (%); NA*, normalized lack alarm (%); FA*, normalized false alarm (%); RLO1, risk level 1 observed (%); RLO2, risk level 2 observed (%); RLO3, risk level 3 observed (%); RLP1, risk level1 predicted (%); RLP2, risk level2 predicted (%); RLP3, risk level 3 predicted (%); empty cell, it was not possible to calculate the indicator due to the lack of data observed or predicted by the model for at least one location.

In particular, POD2 and POD2x showed the highest values in "northern inland plain areas" with percentages close to 90% in all models and the highest value with MOL-E (94.1%). The lowest probability of detection for RL2 was for BOL in "other central-southern inland areas" (78.4%). POD1 and POD1x instead have slightly lower values than the WBGT-shade for all models. Moreover, for the WBGT-sun, although the observed RL3 increased, it was not possible to calculate the average POD3 (some locations had not data). The lack of alarm (NA and NA*) was similar to that observed for WBGT-shade, while the false alarms (FA) were greater (with the highest values in the "northern inland plain areas). However, considering the normalized value (FA*) the differences were significantly reduced. Moreover, for the WBGT-sun, mean error (ME), mean absolute error (MAE), and root mean square error (RMSE) confirmed a very similar performance of the models for all macro-geographical areas (Table 6).

Table 6. Average values of Mean error, mean absolute error and root mean square error of the Day2-WBGT-sun predicted for the 12–18 time slot for the three geographical macro-areas. The scores were calculated both considering all its hourly data and the its maximum value. In the "northern inland plain areas" (A), Bolzano values were not included in the average.

	A			**B**			**C**		
Model	**BOL**	**MOL_E**	**MOL_G**	**BOL**	**MOL_E**	**MOL_G**	**BOL_G**	**MOL_E**	**MOL_G**
MAE	1.3	1.4	1.4	1.2	1.2	1.2	1.4	1.4	1.4
RMSE	1.8	1.9	1.8	1.6	1.6	1.6	1.8	1.8	1.7
ME	0.7	1.0	0.9	0.0	0.1	0.0	0.1	0.5	0.5
Data	1902	1962	1914	1898	1958	1910	1905	1965	1917
MAEmax	1.1	1.2	1.2	1.1	1.2	1.2	1.4	1.3	1.3
RMSEmax	1.5	1.6	1.6	1.4	1.5	1.5	1.7	1.6	1.6
MEmax	0.4	0.9	0.9	−0.2	0.0	−0.1	0.0	0.6	0.5
Datamax	318	328	320	318	328	320	318	328	320

Model: BOL, BOLAM initialized on the GFS; MOL-E, MOLOCH initialized on the ECMWF; MOL-G, MOLOCH initialized on the GFS; MAE, mean absolute error; RMSE, root mean square error; ME, mean error; Data, Sample size; MAEmax, mean absolute error of the maximum time slot value; RMSEmax, root mean square error of the maximum time slot value; MEmax, mean error of the maximum time slot value; Datamax, maximum value simple size.

The models showed the best average performances in the "coastal areas" (ME~0) while the highest values of ME (0.9) were for MOL-E in the "northern inland plain areas". Compared to the WBGT-shade, there were generally no model underestimations in any geographic area.

The forecast for the third day showed values substantially comparable to those that emerged in the evaluation of the performance of the models for the second day (Supplementary Materials).

In general, the WBGT forecast proved more skillful than that of the single meteorological parameters used for its calculation, in particular comparison to temperature which is more comparable being expressed in the same unit of measure (°C) (data not shown).

4. Discussion

Meteorological models' predictions are affected by uncertainty which can be linked not only to an imperfect representation of the initial conditions of the atmosphere (small errors in the initial conditions of a forecast grow rapidly and affect predictability), but also to the approximate simulation of atmospheric processes of the state of-the-art numerical models [49,50]. Initial conditions are known approximately, and consequently two initial states only slightly differing would distinguish one from the other very rapidly as time progresses [51]. Environmental surface characteristics, such as the topography (altitude, coastline, etc.) or other soil specific characteristics (land-use, water content, soil type, etc.), are also approximated according to the horizontal resolution of the model [52]. However, it should be borne in mind that, even in very high-resolution models, the atmosphere and surface characteristics will never be as accurate as in reality (also taking into consideration that some information, e.g., land use and many other soil characteristics, is often grossly not updated and in any case mediated on horizontal resolution).

In this research, the potential of a deterministic approach in a HHWS for short range prediction was investigated. Although the verification was carried out only on 28 locations and for a limited period, BOL and MOL showed promising results in predicting the WBGT, the index selected as the heat strain indicator for the WORKLIMATE high-resolution heat–health warning system. However, the forecast skill generally progressively decreased increasing the RL. Bolam and Moloch forecasts, even if characterized by a different vertical and horizontal resolution, were overall comparable for much of the Italian explored territory, while major limits have emerged in areas with complex topography. It is well known that the representation of the territory topographic features represents one of the main problems of meteorological models. Mesinger and Veljovic [53] defined topography as "the perennial vertical coordinate problem". While in vast plains it is rather simple to reconstruct the territory characteristics, in a more complex context (for example, mountainous areas with narrow valleys and high reliefs, areas with land-sea interface, etc.) this is much more complicated. The resolution of most meteorological models is not fine enough to represent in the required detail surface features, such as hills or mountains, and the disturbances they introduce into the airflow [54]. Our study confirmed what emerged in other model validation studies [52,55], highlighting how the best performances are generally obtained for the higher resolution with an error reduction, especially in complex topography areas. In particular, the WBGT for most of the analyzed locations was well forecasted for RL1, with an average areal value of POD1 and POD1x also far above 90%. The skill decreased for RL2 (POD2 and POD2x) to between 60% and 90%. However, the risk index was generally significantly underestimated in the bottom of the valley or near reliefs (for example Bolzano and Foligno), while it is expected to be overestimated on the highest reliefs. This problem was greater for BOLAM than for MOL_G and MOL_E, confirming the positive effect of a resolution increase. However, even assuming a further increase in resolution, it would not be possible to predict the occurrence of very local microclimates (e.g., a green lawn or an asphalted square), which people most certainly encounter in their workplace [56–59]. Some underestimation problems have also been highlighted in two coastal locations (Capo Bellavista and Palermo) where the nearest grid point model is likely located on the land-sea interface, and this problem is also well known. Lazinger [60] suggests that the issue could be solved, for example, through a linear interpolation of near grid points or using a nearest land grid point values to avoid large error.

As regards the WBGTsun, there was a general increase in the skill because the solar radiation included in the WBGT-sun calculation is much less sensitive than the other parameters to the difference in altitude between the local model and weather station.

Although forecast errors were evaluated by means of skill score, such as mean and root-mean-square error, the identification of their sources in complex models remains one of the dominating challenges [61]. With the aim to reduce the error, a comparison of the daily WBGT forecasts against the corresponding observed values, a downscaling, and a bias correction procedure were carried out by Casanueva et al. [13] in Heat Shield HHWS for 1798 locations. It is extremely difficult to hypothesize post processing correction in WORKLIMATE that have to provide forecasts for a much large number of grid points.

Another positive result of the work was that the deterioration of the forecast skill was overall low in the first three days. This aspect is very important in a HHWS addressed to vulnerable groups and in particular to the occupational sector where the activities and general actions aimed at reducing the impact of heat on workers must be planned in advance [62–65].

Despite the results highlighted, as the higher resolution models performed better in specific situations, the BOL model was used for this first version of the Worklimate operational. Since the goal of Worklimate is a five-day forecast, the use of MOL-E or MOL-G would have required the use of BOL for the fourth and fifth day, and consequently the test of different phases of the operational chain would be more complex. Furthermore, Bolam also allows simpler data management (calculation times, forecast availability time for the user, data flow management) compatible with the available resources.

The main limitation of this study was represented by the limited and unbalanced number of weather stations used in the validation (only about 28 Italian weather station were collected). Furthermore, the validation was carried out only for the May– September period between 1 July 2018 and 7 August 2020 (11 months). The validation was carried out considering the risk level according to the WBGT index thresholds calculated for a standard worker (height 175 cm, weight 75 kg), dressed without personal protective equipment, and carrying out intense activities in the sun or in the shade. Considering workers involved in different physical activities, who wear PPE and perform different duties, the results could be different in terms of categorical verification.

In the future, the model validation could be extended to other weather stations, summer seasons, and other types of workers, also increasing the spatial resolution and possibly improving the forecast by relevant end-user requirements.

5. Conclusions

Climate change is increasing the frequency of extreme heat wave events, necessitating the further implementation of adaptation strategies and specific interventions to safeguard worker health and productivity. At the international level, there are very few examples of personalized occupational heat health warning systems, and this study lays the foundations for the creation of a web forecasting platform and a mobile web app with customized high-resolution heat-stress-risk forecasts on the basis of worker's characteristics, work effort, and work environment. These products are developed as part of the Worklimate project and are based on a heat stress indicator (WBGT) widely used internationally for the assessment of severe hot environments. This work assessed the performance of selected limited area models with a spatial resolution varying from 7 to 2.5 km. The results showed relatively good skills for forecasts up to three days for much of the analyzed meteorological weather locations on the Italian territory. The verification revealed promising results for the use of these models in specific warning systems for the occupational sector capable of providing information on the level of intra-daily risk. For this reason, a first experimental prototype of the system is already available on https://www.worklimate.it/en/maps-choice/shade-intense-physical-activity/ (accessed on 21 September 2021). Despite the results highlighted, with better performances of the high-resolution model, the BOL model was used for this first experimental version of the Worklimate operational system. This choice represents a good compromise between good forecast information (risk level for five daily time bands and a spatial resolution of 7 km) and a relatively easier operational chain (linked to the management of the data flow). The high temporal resolution of the selected model permits to obtain expected risk conditions on an intra-daily basis useful to better support the planning of work activity during the day based on the heat stress forecast.

In the future, further improvements in meteorological modeling, including the increase of the spatial resolution, could significantly improve the forecast, especially in complex topography areas.

Based on the results of this study, the WORKLIMATE HHWS can support the management of the occupational heat stress. It must be only considered as a system to support decisions in collaboration with existing tools that cannot in any case be separated from the direct observation of the environmental conditions of the workplace and from the individual vulnerability factors.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/ijerph18189940/s1, Table S1: Day 3-WBGT-shade average categorical skill scores, Table S2: Day 3-WBGT-sun average categorical skill scores, Table S3: Average values of Mean error, mean absolute error and root mean square error of the Day 3-WBGT-sun, Table S4: Average values of Mean error, mean absolute error and root mean square error of the Day 3-WBGT-shade.

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Article

A Web Survey to Evaluate the Thermal Stress Associated with Personal Protective Equipment among Healthcare Workers during the COVID-19 Pandemic in Italy †

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Abstract: The pandemic has been afflicting the planet for over a year and from the occupational point of view, healthcare workers have recorded a substantial increase in working hours. The use of personal protective equipment (PPE), necessary to keep safe from COVID-19 increases the chances of overheating, especially during the summer seasons which, due to climate change, are becoming increasingly warm and prolonged. A web survey was carried out in Italy within the WORKLIMATE project during the summer and early autumn 2020. Analysis of variance (ANOVA) was used to evaluate differences between groups. 191 questionnaires were collected (hospital doctor 38.2%, nurses 33.5%, other healthcare professionals 28.3%). The impact of PPE on the thermal stress perception declared by the interviewees was very high on the body areas directly covered by these devices (78% of workers). Workers who used masks for more than 4 h per day perceived PPE as more uncomfortable ($p < 0.001$) compared to the others and reported a greater productivity loss ($p < 0.001$). Furthermore, the study highlighted a high perception of thermal stress among healthcare workers that worn COVID-19-PPE and this enhances the need for appropriate heat health warning systems and response measures addressed to the occupational sector.

Keywords: occupational safety and health; adaptation strategy; PPE; global warming; heat stress

1. Introduction

In 2020, humanity faced, and is still facing, the most severe pandemic the world has been confronted with since the pandemic of "Spanish flu" back in 1918. Between the 1 January 2020 to the 8 February 2021, 105.805.951 confirmed cases of COVID-19 and 2.312.278 deaths worldwide have been reported by the World Health Organization (https://covid19.who.int/, accessed on 5 March 2021). The most affected continent were the Americas [1] with 47,122,757 confirmed cases, followed by Europe with 35,620,266 confirmed cases up to the 8 February 2021. The Covid-19 pandemic presents a massive unplanned experiment [2] and with regards to the occupational setting, in particular healthcare workers (HCW), have experienced a substantial increase in working hours (increase in shifts). This category of workers has been exposed to an increased risk of SARS-CoV-2 infection due to their frequent exposure to infected individuals, but at the same time also to psychological distress, fatigue, occupational stigma, depression and anxiety [3,4]. In addition, during the warm season, these symptoms can be exacerbated by heat stress imposed on the body for the enhanced use of Personal Protective Equipment (PPE), which is necessary to reduce the risk of disease transmission [5,6]. As also stated by the WHO [7], PPE wear by HCW varies a lot according to the work environment, the type of job activity and the type of patient (patients with confirmed coronavirus disease or not). Considering these aspects, PPE wear by HCW habitually includes face masks with filters (N95 respirator), face shields, goggles and closed work shoes [8].

However, the use of PPE, while necessary to keep workers safe from COVID-19, also increases the chances of overheating [9] and consequently amplify the risk of heat stress for these workers, [10,11]. The human body produces heat that increases according to the physical effort and therefore significantly increases in case of intense work activities [12]. The body must dissipate this excess of heat to the environment through sweat evaporation, convection and conduction [6]. The outgoing removal of metabolic body heat is limited by COVID-19′s PPE which, compared with standard medical scrubs, has approximately double the evaporative resistance [13]. Furthermore, this resistance can increase over 10-fold with added layers and with full encapsulation of the head and neck [14]. Consequently, limited heat loss combined with potentially high sweat rates, thermal discomfort, and fatigue can occur rapidly [15] leading to critical health conditions such as dehydration and hyperthermia. In addition, COVID-19′s PPE worn for long shifts and associated with environmental heat may further aggravates effects such as skin reactions [16], respiratory difficulties, nausea, digestive discomfort, headaches [17] and mental health impacts [18,19]. Furthermore, as the COVID emergency has made necessary to call back retired medical staff to work, these are at greater risk of COVID-19 health complications as well as heat stress due to their age [20–22].

In this situation, it is crucial to have a better understanding of the environmental working conditions and thermal stress perceived by HCW. In a context where the priority is the prevention of SARS-CoV-2 infection, it seems to be very important, to develop strategies to mitigate the effects of heat conditions, including for example monitoring of local thermal stress in the work place and the development of a specific heat-health warning system for occupational sectors [9,23–25]. These potential adverse physical and mental effects, experienced by frontline HCW, may further impact the already struggling healthcare system during the pandemic [6]. A few studies have assessed heat stress due to PPE in the healthcare sector during the COVID-19 pandemic in international settings through surveys [3,26]. In the frame-work various ad hoc questionnaires have been developed to evaluate the perceived level of heat stress experienced by healthcare professionals and how this situation has influenced their physical, cognitive and emotional sphere in working life [6,27,28].

In Italy, the "WORKLIMATE" project ("Impact of environmental thermal stress on workers' health and productivity: intervention strategies and development of an integrated heat and epidemiological warning system for various occupational sectors") started in June of 2020 (project details are available at https://www.worklimate.it, accessed on 6

April 2021). The aim of the project is to improve the knowledge basis and awareness on health effects of environmental thermal stress conditions (in particular heat) on workers. As part of the project activities, a web survey was carried out to investigate the impact of COVID-19′s PPE among healthcare workers. The e-research is, in fact, a new investigative tool, widely used in Countries with high internet usage. According to the literature [29,30], the advantages of e-research over a traditional study (telephone, post or personal interview) are: (a) speed of detection (the online survey times are certainly lower than research carried out in a traditional way); (b) monitoring and real-time analysis of the data (following the insertion/recording of the data, a summary and immediate analysis of the trend is possible); (c) cost- effectiveness (internet interviews are cheaper than similar surveys conducted using traditional methods); (d) reduction of intrusiveness of detection (an online questionnaire is a tool to which the user has decided to answer behind the prompt of very few external agents; this improves the fidelity and spontaneity of the answers); (e) achievement of specific targets favoring the communicative specificity of the survey; (f) use of multimedia (sound, pictures and movies).

The first aim of this study was to assess the impact of COVID-19′s PPE on the environmental thermal stress of HCW engaged in different activities. In addition, information regarding types of PPE, the potential productivity loss and adaptive behaviors carried out to reduce heat stress during the work shift, were also collected. This information could be particularly useful when defining prevention measures in response to heat stress among HCW and to improve their productivity during emergency situations like the COVID-19 pandemic, or other similar future-emergency measures, requiring the same approach as a priority.

2. Materials and Methods

A self-administered web-based questionnaire was developed (Supplementary Materials), complemented by an informed consent form, and the participation was voluntary and anonymous. The estimated time to complete the questionnaire was around 15/20 min. Data were collected, stored and analyzed according to the Regulation on the protection of natural persons with regard to the processing of personal data (EU Regulation 2016/679—General Data Protection Regulation—GDPR—application from 25 May 2018).

This activity received the ethical clearance from the Commission for Ethics and Integrity of Research of the National Research Council (CNR) (N. 0009389/2020, 2 June 2020).

2.1. Survey Development

The survey (Annex 1) was an adapted version of a tool developed by Lee et al. [6], used in a previous study to assess the knowledge, attitudes, and practices of HCWs in India and Singapore concerning PPE′ usage and heat stress during treatment and care activities. The WORKLIMATE questionnaire was created and administered entirely in Italian language (https://forms.gle/rBbJixexAaBD6m3h9) and consisted of different sections including:

- demographic data and characteristics of the worker (question from 1 to 8)
- relevant work information (9–13)
- heat-exposure-related questions and information about PPE′ usage at work (14–20)
- worker′s adaptation to heat stress and behavioral with PPE (21-27)
- worker′s knowledge about thermal stress and attitudes towards the PPE′s use (28–46)

A 5-point Likert scale (1 for strongly disagree and 5 for strongly agree) was used for questions from 28 to 46 concerning the worker′s knowledge about thermal stress and attitudes towards the PPE′s use.

2.2. Survey Administration

The questionnaire was prepared using the Google Form online platform (https://www.google.it/intl/it/forms/about/, accessed on 6 April 2021) and was disseminated through the official website and social accounts of the WORKLIMATE project (https://www.worklimate.it; https://www.facebook.com/Worklimate; https://twitter.com/worklimate) as well as through the involvement of Technicians for prevention in the environment and in the workplace. In addition, ad hoc emails were sent to professional associations and advertisements via personal networks and social media accounts of management committee members.

The questionnaire was administered only to HCW who work in Italian hospitals with a specific focus on Covid departments. The survey was accessible for 5 months, starting at the 1 June and ending at the 31 October 2020.

2.3. Study Area and Climatic Characteristics

The study analyzed data of 191 questionnaires collected during the summer and early autumn 2020, in months characterized by temperatures that were, in most of the Italian regions, slightly above the average compared to the climatology 1981–2010, especially in Central and Southern Italy (Figure 1). Between July and August, the thermal anomaly was close to 1.5 °C in some southern regions. We can therefore state that the questionnaire administration period coincided with a warmer summer than the reference climatology.

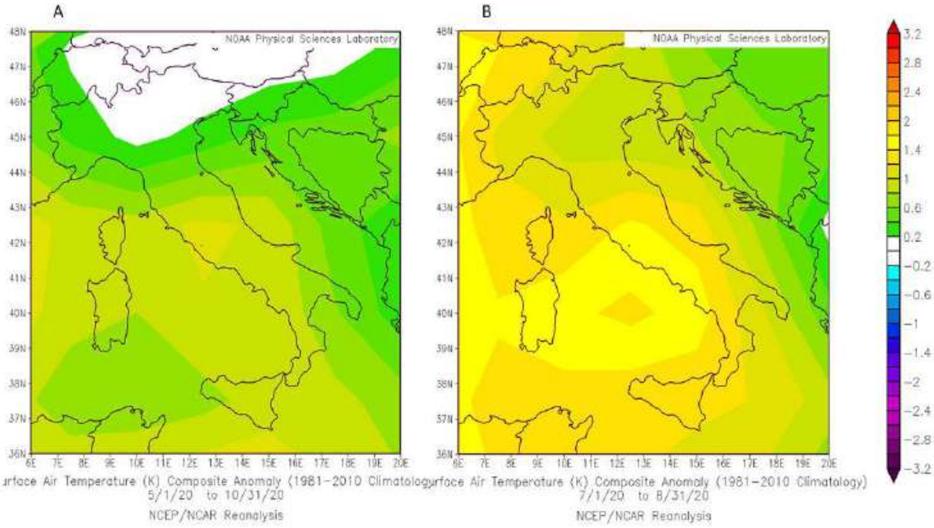

Figure 1. Air temperatures anomalies in Italy during the period May–October 2020 (**A**) and during the period July-August 2020 (**B**) compared to the climatology 1981–2010. Data obtained from https://psl.noaa.gov/cgi-bin/data/composites/printpage.pl, accessed on 6 April 2021.

2.4. Data Analysis

The data collected were analyzed using descriptive statistics (i.e., frequency, mean, standard deviation) and analytical tests. The analysis of variance (ANOVA) was used to evaluate differences between groups. The homogeneity of variance was verified with the Levene test. The Brown–Forsythe and Welch tests were used when the homogeneity of variance assumption did not hold for the data. A Principal Component analysis (PCA) with Varimax rotation was carried out and the Cronbach's Alpha calculation allowed an empirical assessment of the reliability to assess the dimensionality of section "worker's knowledge on thermal stress and attitudes towards the use of PPE. The results were considered significant at a p-value less than 0.05. All analyses were performed using SPSS v25.0 for Windows (IBM, Armonk, NY, USA).

3. Results

3.1. Descriptive Analysis

191 HCW participated in the self-administered web survey, most of whom (56%) carried out their work activities in South and Central Italy. The sex distribution was homogeneous for the health sector with 132 women (69.1%) and 59 men (30.9%). The

average age of participants was 43.7 years (SD ± 11.1), the average height and weight were respectively 169 cm (±8.4) and 69 kg (±14.5). As for body mass index (BMI), 65% of the interviewees fell into the normal weight (BMI < 25) category, while 35% were overweight (BMI > 25). The analyzed sample included many types of professions involved in the healthcare sector with the most HCW represented by hospital doctors (38.2%) and nurses (33.5%).

Less than 13% of HCW reported they avoid eating on fast days for personal reasons. More than half the responders (about 58%) declared they were involved in activities requiring a high or very high physical effort (Table 1).

Table 1. Results of the questionnaire submitted to healthcare workers.

Healthcare Workers		N [1]	% [2]
Do you avoid eating on fast days for personal reasons?	Never	167	87.4
	Sometimes	7	3.7
	Often	14	7.3
	Very often	1	0.5
	Ever	2	1.0
How do you judge your work effort on average?	At rest	2	1.0
	Lightweight	13	6.8
	Moderate	65	34.0
	High	82	42.9
	Very high	29	15.2
How do you judge the thermal environment in which you generally work?	Very cold	6	3.1
	Cold	11	5.8
	Slightly cold	20	10.5
	Neutral	40	20.9
	Slightly hot	33	17.3
	Hot	53	27.7
	Very hot	28	14.7
For how many hours do you usually wear N95 mask or equivalent (FFP2)?	0 h	39	20.4
	1 to 3 h	50	26.2
	4 to 6 h	65	34.0
	over 6 h	37	19.4
For how many hours do you usually wear FFP3 mask?	0 h	146	76.4
	1 to 3 h	28	14.7
	4 to 6 h	8	4.2
	over 6 h	9	4.7
How many hours do you usually wear a surgical mask?	0 h	17	8.9
	1 to 3 h	32	16.8
	4 to 6 h	69	36.1
	over 6 h	73	38.2
How many hours do you usually wear gloves (one pair)?	0 h	40	20.9
	1 to 3 h	66	34.6
	4 to 6 h	55	28.8
	over 6 h	30	15.7
How many hours do you usually wear gloves (two pairs)?	0 h	81	42.4
	1 to 3 h	62	32.5
	4 to 6 h	29	15.2
	over 6 h	19	9.9
How many hours do you usually wear a disposable gown?	0 h	48	25.1
	1 to 3 h	71	37.2
	4 to 6 h	50	26.2
	over 6 h	22	11.5

Table 1. *Cont.*

Healthcare Workers		**N** [1]	**%** [2]
How many hours do you usually wear a normal gown?	0 h	94	49.2
	1 to 3 h	27	14.1
	4 to 6 h	43	22.5
	over 6 h	27	14.1
How many hours do you usually wear a disposable apron?	0 h	155	81.2
	1 to 3 h	21	11.0
	4 to 6 h	11	5.8
	over 6 h	4	2.1
How many hours do you usually wear disposable glasses?	0 h	77	40.3
	1 to 3 h	41	21.5
	4 to 6 h	50	26.2
	over 6 h	23	12.0
How many hours do you usually wear a disposable visor?	0 h	78	40.8
	1 to 3 h	56	29.3
	4 to 6 h	38	19.9
	over 6 h	19	9.9
How many hours do you usually wear disposable headgear?	0 h	67	35.1
	1 to 3 h	34	17.8
	4 to 6 h	49	25.7
	over 6 h	41	21.5
How many hours do you usually wear disposable closed boots or work shoes?	0 h	119	62.3
	1 to 3 h	13	6.8
	4 to 6 h	21	11.0
	over 6 h	38	19.9
How many hours do you usually wear shoes covers?	0 h	102	53.4
	1 to 3 h	44	23.0
	4 to 6 h	32	16.8
	over 6 h	13	6.8
How many hours do you usually wear sanitary clogs?	0 h	73	38.2
	1 to 3 h	5	2.6
	4 to 6 h	42	22.0
	over 6 h	71	37.2
How many days per week do you use PPE at work?		5.2	SD 1.0
How long (minutes) does it take you to wear PPE at the start of the work shift?		7.1	SD 5.5
Do you work mainly in an air-conditioned environment?	Yes	151	79.1
	No	40	20.9
Is there a company procedure that allows you to remove PPE during work breaks?	Yes	106	55.5
	No	85	44.5
If yes, when? More than one answer is possible	In the middle of the day	39	20.4
	When i go to the toilet	31	16.2
	After each visit	31	16.2
	Whenever i need to	42	22.0
Is there a dedicated rest area in your workplace?	Yes	88	46.1
	No	103	53.9
How do you try and reduce heat stress when using PPE? It is possible to select more than one answer for this question.	I often drink water	108	56.5
	I drink ice cold drinks	1	0.5
	I take breaks whenever possible	81	42.4
	I try to dress in light clothing	90	47.1
	Breathing techniques	28	14.7
	I prefer ventilated and cool environments	64	33.5

Table 1. *Cont.*

Healthcare Workers		N[1]	%[2]
Heat stress in the areas covered by the PPE		150	78.5
Symptoms generally perceived when I wear PPE	Thirst	111	58.1
	Excessive sweating	135	70.7
	Fatigue	88	46.1
	Headache	82	42.9
	Difficulty concentrating	56	29.3
	Skin reaction	51	26.7
	General discomfort	99	51.8
What is your thermal sensation when you wear PPE during work activities?	Neutral	2	1.0
	Slightly hot	21	11.0
	Hot	68	35.6
	Very hot	100	52.4
Productivity loss perception caused by heat stress		155	81

[1] N, sample size; [2] % percentage of the sample.

About 60% of HCW declared they perceived heat discomfort (from slightly to very hot), despite the prevalent working environment being indoor and air-conditioned (79.1%). Less than 20% perceived slightly or very cold conditions. As expected among HCW, the number of days per week that PPE were used is very high (5.2; ±1) with a claimed average time to put on these garments about 7.1 min (±5.5) at the start of each work shift. Surgical mask were the most used PPE: it was worn for over 4 h a day by 74.3% of workers. N95 mask or FFP2 mask were also widely used and were worn for over 4 h per day by 53.4% of workers. The FFP3 mask was rarely used and it was worn at least 1 h a day by only 15% of the subjects. Gloves were also widely used, 34.6% said they used gloves from 1 to 3 h a day, 28.8% from 4 to 6 h and 15.6% over 6 h. About 32% of worker's stated that they used 2 pairs of gloves at the same time for 1 to 3 h a day and 25.1% after 4 h. 37.5% of workers wore disposable gowns from 1 to 3 h a day, 26.2% used them for a period between 4 and 6 h, 11% even more than 6 h. Normal gowns were slightly less used and overall only 47.8% said they used it for at least 1 h a day. Even less used were aprons: 9.0% of the participants used them for at least 1 h a day and only 2.1% used them over 6 h. As for eye protection, 59.7% of the participants used them and among workers and about 38.2% wore disposable glasses over 4 h a day (12% over 6 h). Disposable visors were also widely used by healthcare personnel: about 29% said they used them between 1 and 3 h a day, 20% between 4 and 6 h and about 10% over 6 h. Disposable headgear was widely used: 47.2% used it for at least 4 h a day and 64.9% for at least 1 h. As for the foot protection, the most used PPE were the sanitary clogs: over 37% of respondents said they used them for at least 6 h a day, 22% from 4 to 6 h. 46.6% of workers said they used shoe covers too, 16.8% between 4 and 6 h, 6.8% after 6 h. Finally only 55.5% of workers declared there was a company procedure that allowed them to dress and remove PPE during work breaks.

The impact of PPE on the thermal stress perception declared by the interviewees was very high on the body areas directly covered by the devices (78% of workers). In general, 99% of the participants declared a "hot" heat stress perception during work activity and slightly more than 50% even a "very hot" thermal sensation. The body parts affected by the HCW heat stress perception are depicted in Figure 2.

The lower face part was the body area for which the greatest number of HCW (35.6%) declared very hot sensation: 34% hot and 11% slightly hot; but 13.6% of participants perceived cold. Regard to the hands (27.2%), the armpits (30.4%) and the chest (28.8%), the HCW declared a very hot sensations too and respectively 24.1%, 26.7% and 22.5% hot sensations. According to the interviewees, the upper face part was also affected by hot conditions, in particular 27.2% of the respondents felt very hot, 32.5% hot and 12.6%

slightly hot conditions. Less heat stress was perceived on the neck and legs, in fact only 19% and 15.7% declared very hot conditions respectively.

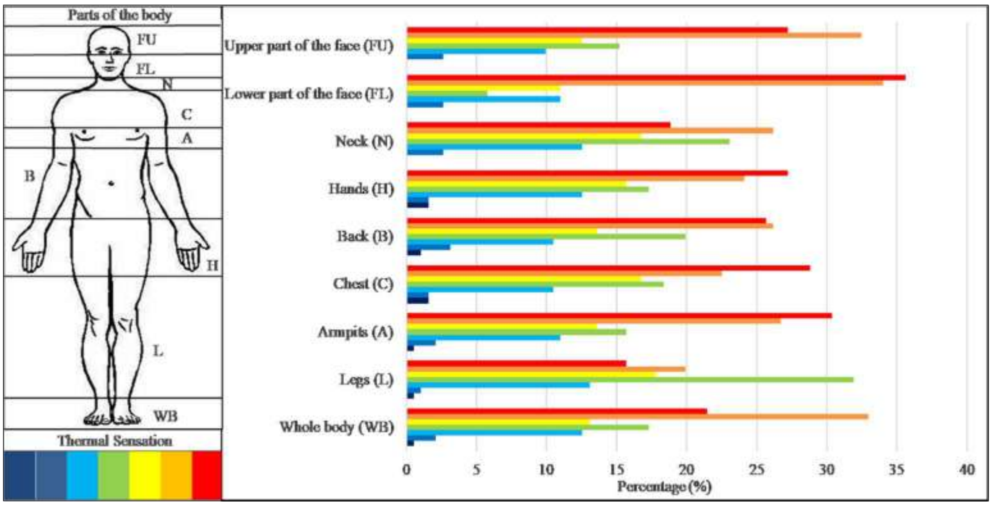

Figure 2. Thermal sensations declared by healthcare workers for each parts of the body covered by PPE during working time. Dark blue: Very cold; Blue: Cold; Light blue: Slightly cold; Green: Neutral; Yellow: Slightly hot; Orange: Hot; Red: Very hot.

The symptoms related to heat stress prevalently described were: thirst (58%), excessive sweating (70.7%), general discomfort (51.8%), fatigue (46.1%) and headache (42.9%). Skin reactions (26.7%) and difficulty concentrating (29.3%) were reported too. Many HCW reported adopting strategies to reduce the effects of heat, particularly by often drinking water (56.5%), taking breaks whenever possible (42.4%), wearing light clothing (47.1%), preferring ventilated and cool environments if present (33.5%). Less represented were breathing techniques and only 1 subject declared drinking ice cold drinks. A great number of HCW (81%) self-reported a productivity loss related to heat stress exposure.

3.2. Principal Component Analysis

From the Principal Components analysis (PCA) have carried out on "Worker's knowledge about thermal stress and attitudes towards PPE use" to verify the existence of common dimensions. Three factors that explain 67.1% of the variance emerged from the analysis (Table 2).

The first factor (α = 0.90), which explains the 34.9% of the variance, has been called "Perception of heat stress conditions in the workplace and productivity "because it brings together all the items concerning the subjective impacts of heat stress and the perception of loss of productivity of the worker.

The second factor (α = 0.82), which explains the 16.7% of the variance, has been called "HCW behavior during the working days "because it brings together all the items concerning actual behaviours during work days, what healthcare professionals avoid doing or what is uncomfortable for them to do.

The third factor (α = 0.75), which explains the 15.4% of the variance, has been called "Awareness of good practices" because it brings together all the items concerning some good practices for managing heat stress.

In the factorial solution the items 37, 38, 39, 40, 45, 46 have been excluded.

Table 2. Principal Component Analysis of section "Worker's knowledge about thermal stress and attitudes towards PPE use". Extraction method: Principal component analysis. Rotation method: Varimax with Kaiser normalization.

N-Item	Component		
	1 "Perception of Heat Stress Conditions in the Workplace and of Productivity Loss"	2 "HCW Behavior during the Working Days"	3 "Awareness of Good Practices"
29-Heat stress can impair my reasoning	0.873		
31-Heat Stress can affect my psychological state	0.829		
33-Heat stress can negatively affect my commitment at work	0.813		
28-Heat stress can affect my productivity	0.790		
32-Heat stress can negatively affect my emoticons	0.788		
30-Heat Stress can affect my physical health	0.765		
42-I avoid taking breaks to not remove and put on the PPE again		0.863	
43-I avoid drinking and eating to reduce breaks to use toilet		0.849	
41-It is uncomfortable to take breaks to rehydrate		0.763	
44-I avoid taking breaks to reduce the risk of getting infected		0.715	
35-A good hydration before the work shift will improve my heat tolerance			0.875
34-Keeping fit will improve my heat tolerance			0.824
36-Adequate rest between shifts will improve my tolerance			0.746

3.3. Differences between HCW Groups

The analysis of variance highlights significant differences between the average scores assigned to different items for different groups. The groups were chosen considering all the aspects that can play a key role in the different thermal perception in the occupational field: geographical area in which the workplace was located; thermal environment exposure; physical and personal characteristics of the worker (gender, age, BMI); kind of work, work effort, PPE characteristic and use (type of PPE, duration of use); worker behavior; company procedures and symptoms.

For most items, the analysis of variance did not show significant differences between workplaces in different geographical areas (North compared with Central-South Italy) and did not show any significant difference between working environments with or without air conditioning. We also carried out an ANOVA between workers who declared to work in a hot environment (about 60%) and those working in a cold or neutral environment (about 40%) but no significant differences emerged except for the item "My work productivity is reduced when I wear PPE" ($p < 0.05$). In this case, the subjects who worked in a warm environment declared to be more agreement with this item (M = 3.3, SD = 0.1) than who worked in a cold or neutral environment (M = 2.9, SD = 0.1).

The age and gender of the workers did not seem to influence significantly the answers provided by the interviewees too. On the other hand, several physical characteristics, and especially BMI, reveled a significant heat impact ($p < 0.01$) on the reasoning skills of workers. A difference ($p < 0.05$) emerged between the group of overweight or obese subjects (BMI > 25) (M = 4.5, SD = 0.7) compared to normal or underweight workers (BMI < 25) (M = 4.1, SD = 1.0) concerning the effect of heat stress on the impair reasoning.

Moreover, a difference ($p < 0.05$) emerged between hospital doctors and nurses concerning the role of a good hydration and adequate rest between shifts to improve tolerance to heat. In particular, doctors seemed to be more in agree with these two items and declared

PPE's more uncomfortable (M = 4.1, SD = 1.0) compared to what reported by the nurses too (M = 3.7, SD = 1.2).

The groups were chosen considering all the aspects that can play a key role in the different thermal perception in the occupational field. The results of the analysis between groups divided into 4 fundamental issues are shown below: perception of heat stress conditions in the workplace (items 28, 29, 31, 32, 33); perception of productivity loss and PPE use (items 37, 39, 46); behavior during the working days (items 38, 41, 42, 43, 44) and awareness of good practices should be adopted before and during the shift (items 34, 35, 36, 40, 45).

Concerning the first two issues aimed at assessing the perception of heat stress conditions in the workplace and the perception of productivity loss by the worker, a significance emerged from the interviews between different group, linked to the kind of work, the use of glasses, visor and headgear, as well as the thermal sensation related to the use of PPE (Tables 3 and 4).

Table 3. Difference between groups concerning issues related to the effects of the heat stress on workers and their productivity loss perception.

Item			Kind of Work		Thermal Sensation with PPE		Glasses and Visor		Headgear	
N°		G	M(SD)	F/Sig	M(SD)	F/Sig	M(SD)	F/Sig	M(SD)	F/Sig
29	Heat stress can impair my reasoning	1	4.2 (0.9)	ns	4.0 (1.1)	ns	4.0 (1.1)	ns	**3.9 (1.0)**	**4.2 ***
		2	4.2 (1.1)		4.0 (0.9)		4.2 (1.0)		**4.1 (1.0)**	
		3	4.2 (1.0)		4.3 (1.0)		4.3 (1.0)		**4.4 (1.0)**	
30	Heat Stress can affect my physical health	1	4.0 (1.0)	ns	**4.0 (1.2)**	**4.4 ****	3.9 (1.2)	ns	**3.9 (1.2)**	**6.1 ****
		2	4.3 (0,9)		**4.0 (1.1)**		4.2 (0.9)		**4.2 (0.9)**	
		3	4.2 (0.9)		**4.4 (0.8)**		4.3 (0,8)		**4.4 (0.8)**	
31	Heat Stress can affect my psychological state	1	4.2 (0.9)	ns	4.1 (1.0)	ns	4.3 (0.9)	ns	4.2 (1.0)	Ns
		2	4.3 (0.9)		4.2 (1.0)		3.3 (0.9)		4.1 (1.0)	
		3	4.2 (0.9)		4.4 (0.9)		4.3 (0.9)		4.4 (0.8)	
32	Heat stress can negatively affect my emoticons	1	4.1 (1.1)	ns	4.0 (1.3)	ns	4.1 (1.1)	ns	4.0 (1.2)	Ns
		2	4.2 (1.0)		4.0 (1.1)		4.2 (1.0)		4.2 (1.1)	
		3	4.0 (1.2)		4.2 (1.1)		4.0 (1.2)		4.2 (1.1)	
33	Heat stress can negatively affect my commitment at work	1	4.1 (1.1)	ns	3.9 (1.4)	ns	4.0 (1.1)	ns	3.9 (1.1)	Ns
		2	4.1 (1.2)		4.0 (1.1)		4.2 (1.2)		4.1 (1.3)	
		3	4.1 (1.1)		4.2 (1.1)		4.1 (1.2)		4.3 (1.1)	
46	The PPE I wear prevent the evaporation of sweat	1	4.2(1.0)	ns	**3.5 (1.1)**	**7.1 *****	**3.9 (1.0)**	**6.9 *****	3.8 (1.1)	Ns
		2	4.3 (1.0)		**4.1 (0.8)**		**3.9 (1.2)**		4.0 (1.0)	
		3	4.0(1.1)		**4.4 (1.1)**		**4.5 (0.9)**		4.5 (0.9)	
37	Wearing PPE is uncomfortable for me	1	**4.1 (1.0)**	**5.7 ****	**2.9 (1.4)**	**10.6 *****	**3.7 (1.2)**	ns	3.7 (1.2)	Ns
		2	**3.7 (1.2)**		**3.6 (1.1)**		**3.6 (1.4)**		3.6 (1.3)	
		3	**3.4 (1.3)**		**4.1 (1.1)**		**4.0 (1.1)**		3.9 (1.1)	
39	My work productivity is reduced when I wear PPE	1	3.2 (1.2)	ns	**2.6 (1.3)**	**7.7 *****	3.0 (1.0)	ns	3.1 (1.2)	Ns
		2	3.2 (1.2)		**2.9 (1.1)**		3.2 (1.4)		3.2 (1.2)	
		3	3.1 (1.2)		**3.5 (1.2)**		3.3 (1.3)		3.3 (1.2)	
28	Heat stress can affect my productivity	1	4.3 (0.8)	ns	**4.1 (1.1)**	**5.3 ****	4.4 (1.0)	ns	**4.0 (1.0)**	**4.6 ****
		2	4.4 (0.9)		**4.1 (0.9)**		4.3 (0.8)		**4.3 (0.8)**	
		3	4.2 (1.0)		**4.5 (0.8)**		4.4 (0.8)		**4.5 (0.9)**	

Group (G): Kind of work (1 general practitioner and hospital doctor, 2 nurse/pediatric nurse, 3 other); Thermal sensation with PPE (1 neutral or slightly hot, 2 hot, 3 very hot); Glasses and visor (1 not used, 2 from one to three hours, 3 more than four hours); Headgear (1 not used, 2 from 1 h to four hours, 3 more than four hours). A 5-point Likert scale (1 for strongly disagree and 5 for strongly agree) was used for questions. M is the Mean value; F is Fisher–Snedecor distribution; in brackets Standard deviation (SD). (Sig): *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$ and values in bold.

Table 4. Difference between groups concerning issues related to the effects of the heat stress on workers and their productivity loss perception.

	Item		**Work Effort**		**Company Procedure to Dress PPE**		**Rest Area**		**Parts of the Body**	
N°		**G**	**M(SD)**	**F/Sig**	**M(SD)**	**F/Sig**	**M(SD)**	**F/Sig**	**M(SD)**	**F/Sig**
29	Heat stress can impair my reasoning	1	4.1 (1.0)	ns	**4.0 (1.1)**	**4.8** *	4.2 (1.0)	ns	4.2 (1.0)	ns
		2	4.2 (1.0)		**4.4 (0.8)**		4.1 (1.0)		4.3 (1.0)	
30	Heat Stress can affect my physical health	1	4.0 (1.0)	ns	4.1 (1.0)	ns	4.2 (0.9)	ns	4.2 (0.9)	ns
		2	4.3 (0.9)		4.3 (0.9)		4.2 (1.0)		4.1 (1.1)	
31	Heat Stress can affect my psychological state	1	4.2 (1.0)	ns	**4.1 (1.0)**	**6.1** **	4.3 (0.9)	ns	4.2 (1.0)	ns
		2	4.3 (0.9)		**4.5 (0.8)**		4.2 (1.0)		4.4 (0.7)	
32	Heat stress can negatively affect my emoticons	1	4.0 (1.2)	ns	3.9 (1.2)	ns	4.0 (1.1)	ns	4.1 (1.1)	ns
		2	4.1 (1.1)		4.3 (0.9)		4.2 (1.1)		3.9 (1.2)	
33	Heat stress can negatively affect my commitment at work	1	4.2 (1.1)	ns	**3.9 (1.2)**	**4.4** *	4.1 (1.2)	ns	4.1 (1.2)	ns
		2	4.0 (1.2)		**4.3 (1.0)**		4.1 (1.1)		4.1 (1.2)	
46	The PPE I wear prevent the evaporation of sweat	1	4.1 (1.0)	ns	4.1 (1.1)	ns	4.2 (1.0)	ns	4.2 (1.1)	ns
		2	4.2 (1.0)		4.3 (0.9)		4.1 (1.1)		4.2 (0.9)	
37	Wearing PPE is unconfortable for me	1	**3.6 (1.3)**	**4.4** *	3.5 (1.3)	ns	3.7 (1.1)	ns	3.7 (1.2)	ns
		2	**3.9 (1.1)**		4.1 (1.0)		3.8 (1.3)		3.9 (1.2)	
39	My work productivity is reduced when I wear PPE	1	3.0 (1.2)	ns	**3.0 (1.2)**	**4.9** *	3.2 (1.3)	ns	**3.1 (1.2)**	**6.2** **
		2	3.3 (1.3)		**3.4 (1.2)**		3.2 (1.2)		**3.6 (1.2)**	
28	Heat stress can affect my productivity	1	4.2 (0.8)	ns	**4.1 (1.0)**	**7.9** ***	4.3 (0.9)	ns	4.3 (0.9)	ns
		2	4.3 (0.9)		**4.5 (0.7)**		4.3 (0.9)		4.3 (1.0)	

Group (G): Work effort (1 from moderate to rest, 2 from high to very high); Company procedure to dress PPE (1 yes, 2 no); Rest area (1 yes, 2 no); Different perception between parts of the body covered by PPE (1 yes, 2 no). A 5-point Likert scale (1 for strongly disagree and 5 for strongly agree) was used for questions. M is the Mean value; F is Fisher–Snedecor distribution; in brackets Standard deviation (SD). (Sig): *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$ and values in bold.

Workers who used the headgear for more than 4 h a day (Table 3) and who worked in the company without a specific procedure regarding use of PPE (Table 4), declared a significant ($p < 0.05$) reasoning impairment (items 29). Furthermore, a company procedure to dress PPE was significantly correlated ($p < 0.01$) with a psychological distress associated with heat stress (item 32) and with the awareness that this condition can also affect the commitment at work (item 33). In addition, subjects who reported a very hot thermal sensation and who used the headgear for more than 4 h a day declared a significant ($p < 0.01$) effect of heat stress on their physical health too (item 30).

General practitioners and hospital doctors (M = 4.1, SD = 1.0) considered PPE more uncomfortable ($p < 0.001$) than other healthcare workers (M = 3.4, SD = 1.3) (Table 4). Furthermore, the productivity loss (item 28) was found to be significantly correlated ($p <0.001$) to the perception of thermal sensation due to the use of PPE. Workers who reported a very hot thermal sensation were more aware of the role of PPE in hindering sweat evaporation (item 46) as well as those who used glasses or visors for more than 4 h a day (Table 3). As for the perception of productivity loss, it appeared significantly greater in subjects who declared a very hot thermal sensation ($p < 0.05$), in those who wore more headgear ($p < 0.05$) and highly correlated ($p < 0.001$) with the lack of company procedures to dress PPE (Table 4). Thermal perception and company procedures on the correct use of PPE also played a key role in attributing the productivity loss to the PPE use (item 39). This was confirmed by the fact that workers who declared a different thermal perception between different body parts covered by the PPE were more in agreement with this item.

On the other hand, as regards the items relating to the issue "HCW behavior during the working days" (items 38, 41, 42, 43, 44) and "awareness of good practices should be adopted before and during the shift" (items 34, 35, 36, 40, 45), the different kind of work, the use of glasses, visor and headgear as well as the thermal sensation related to the use of PPE, showed a significant difference between different groups. (Tables 5 and 6).

Workers who used glasses, visors and headgear more, also declared a greater difficulty in taking breaks to rehydrate (item 41). This behavior was confirmed by the fact that these workers were ($p < 0.01$ and $p < 0.001$ respectively) agree with the item 42 (I avoid taking breaks to not remove and put on the PPE again) (Table 5). Item 41 was related to the work effort, to the presence of company rest areas and above all to the different thermal perception in the body parts covered by the PPE too (Table 6). Moreover, the workers who revealed a greater work effort reported no rest areas available in the company and declared a great different perception between the body parts covered and uncovered by the PPE. In addition, these HCW also declared difficulties ($p < 0.05$) in taking breaks because too busy (item 38). Finally, the kind of work and the use of the headgear influenced the responses to the item “I avoid taking breaks to not remove and put on again PPE” (43, Table 5).

Table 5. Difference between groups concerning issues related to worker’s behavior and awareness of good practices to increase the heat tolerance.

	Item		Kind of Work		Thermal Sensation with PPE		Glasses and Visor		Headgear	
N°		G	M (SD)	F/Sig	M(SD)	F/Sig	M(SD)	F/Sig	M(SD)	F/Sig
38	I’m too busy when I work and consequently I can’t take breaks	1	3.7 (1.1)	ns	3.5 (1.1)	ns	3.6 (1.1)	ns	3.5 (1.1)	ns
		2	3.7 (1.1)		3.7 (1.1)		3.6 (1.2)		3.8 (1.0)	
		3	3.5 (1.2)		3.6 (1.1)		3.7 (1.1)		3.7 (1.1)	
41	It is uncomfortable to take breaks to rehydrate	1	3.1 (1.4)	ns	2.8 (1.2)	ns	**2.9 (1.1)**	**5.7 ****	**2.8 (1.2)**	**8.0 *****
		2	3.4 (1.4)		3.1 (1.3)		**2.7 (1.4)**		**2.6 (1.5)**	
		3	2.8 (1.4)		3.2 (1.4)		**3.5 (1.4)**		**3.5 (1.4)**	
42	I avoid taking breaks to not remove and put on the PPE again	1	3.2 (1.4)	ns	2.4 (1.3)	ns	**2.7 (1.2)**	**5.5 ****	**2.7 (1.4)**	**6.5 *****
		2	3.2 (1.5)		3.0 (1.3)		**2.8 (1.5)**		**2.6 (1.4)**	
		3	2.7 (1.5)		3.2 (1.5)		**3.4 (1.5)**		**3.5 (1.5)**	
43	I avoid drinking and eating to reduce breaks to use toilet	1	**3.1 (1.5)**	**7.9 *****	2.6 (1.6)	ns	2.6 (1.5)	ns	**2.6 (1.5)**	**3.3 ***
		2	**3.2 (1.4)**		2.9 (1.4)		2.8 (1.5)		**2.9 (1.6)**	
		3	**2.2 (1.3)**		3.0 (1.5)		3.2 (1.4)		**3.2 (1.4)**	
44	I avoid taking breaks to reduce the risk of getting infected	1	2.7 (1.4)	ns	**2.9 (1.5)**	**3.1 ***	2.5 (1.4)	ns	2.5 (1.4)	ns
		2	2.9 (1.5)		**2.9 (1.4)**		3.0 (1.4)		3.0 (1.4)	
		3	2.7 (1.5)		**2.7 (1.5)**		2.8 (1.5)		2.9 (1.5)	
40	It is important to keep hydrated during the work shift	1	4.4 (0.9)	ns	4.6 (0.7)	ns	4.4 (0.7)	ns	4.5 (0.7)	ns
		2	4.5 (0.8)		4.3 (0.9)		4.6 (0.6)		4.4 (0.8)	
		3	4.6 (0.7)		4.6 (0.8)		4.6 (0.8)		4.5 (0.9)	
45	Slush drinks improve my tolerance to heat	1	2.1 (1.2)	ns	2.0 (1.5)	ns	2.2 (1.2)	ns	**2.3 (1.3)**	9.8 ***
		2	2.1 (1.3)		2.0 (1.1)		2.2 (1.3)		**2.1 (1.1)**	
		3	2.0 (1.2)		2.1 (1.2)		1.8 (1.1)		**1.8 (1.1)**	
34	Keeping fit will improve my heat tolerance	1	3.9 (1.1)	ns	**4.3 (0.8)**	**4.7 ****	3.9 (1.1)	ns	3.7 (1.1)	ns
		2	3.6 (1.2)		**3.9 (1.1)**		3.7 (1.1)		3.5 (1.2)	
		3	3.7 (1.2)		**3.5 (1.2)**		3.6 (1.2)		3.8 (1.2)	
35	A good hydration before the work shift will improve my heat tolerance	1	3.9 (1.1)	**3.4 ***	**4.6 (0.7)**	**6.6 *****	4.0 (1.1)	ns	4.0 (1.0)	ns
		2	3.6 (1.1)		**3.9 (1.2)**		4.0 (1.1)		3.7 (1.2)	
		3	4.2 (1.0)		**3.7 (1.1)**		3.8 (1.1)		3.9 (1.1)	
36	Adequate rest between shifts will improve my tolerance	1	**4.3 (1.0)**	**3.3 ***	4.4 (0.9)	ns	4.2 (0.9)	ns	4.3 (0.9)	ns
		2	**3.9 (1.2)**		4.3 (0.9)		4.1 (1.2)		3.9 (1.3)	
		3	**4.4 (0.9)**		4.0 (1.2)		4.2 (1.1)		4.2 (1.0)	

Group (G): Kind of work (1 general practitioner and hospital doctor, 2 nurse/pediatric nurse, 3 other); Thermal sensation with PPE (1 neutral or slightly hot, 2 hot, 3 very hot); Glasses and visor (1 not used, 2 from one to three hours, 3 more than four hours); Headgear (1 not used, 2 from 1 h to four hours, 3 more than four hours). A 5-point Likert scale (1 for strongly disagree and 5 for strongly agree) was used for questions. M is the Mean value; F is Fisher–Snedecor distribution; in brackets Standard deviation (SD). (Sig): *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$ and values in bold.

Table 6. Difference between groups concerning issues related to worker's behavior and awareness of good practices to increase the heat tolerance.

N°	Item		Work Effort		Company Procedure to Dress PPE		Rest Area		Parts of the Body	
		G	M(SD)	F/Sig	M(SD)	F/Sig	M(SD)	F/Sig	M(SD)	F/Sig
38	I'm too busy when I work and consequently I can't take breaks	**1**	**3.5 (1.1)**	**4.5 ***	3.5 (1.1)	ns	**3.5 (1.1)**	**4.5 ***	**3.6 (1.1)**	**4.6 ***
		2	**3.8 (1.1)**		3.8 (1.1)		**3.8 (1.1)**		**4.0 (1.0)**	
41	It's uncomfortable to take breaks to rehydrate	**1**	**2.8 (1.3)**	**5.6 ****	3.1 (1.3)	ns	**2.9 (1.3)**	**4.1 ***	**2.9 (1.4)**	**13.8 *****
		2	**3.3 (1.4)**		3.3 (1.4)		**3.3 (1.5)**		**3.8 (1.2)**	
42	I avoid taking breaks to not remove and put on the PPE again	1	2.8 (1.5)	ns	2.9 (1.4)	ns	3.0 (1.4)	ns	**2.9 (1.4)**	**5.0 ***
		2	3.2 (1.4)		3.3 (1.5)		3.1 (1.5)		**3.5 (1.5)**	
43	I avoid drinking and eating to reduce breaks to use toilet	1	2.8 (1.5)	ns	2.8 (1.4)	ns	2.9 (1.5)	ns	2.8 (1.4)	ns
		2	3.0 (1.5)		3.1 (1.5)		2.9 (1.5)		3.2 (1.6)	
44	I avoid taking breaks to reduce the risk of getting infected	1	2.7 (1.4)	ns	2.6 (1.4)	ns	2.8 (1.4)	ns	2.7 (1.4)	ns
		2	2.8 (1.5)		2.9 (1.4)		2.7 (1.5)		3.1 (1.5)	
40	It is important to keep hydrated during the work shift	1	4.4 (0.9)	ns	4.4 (0.9)	ns	4.5 (0.7)	ns	4.5 (0.8)	ns
		2	4.6 (0.8)		4.6 (0.6)		4.5 (0.9)		4.4 (0.8)	
45	Slush drinks improve my tolerance to heat	1	2.1 (1.1)	ns	**1.8 (1.1)**	**7.3 *****	2.2 (1.3)	ns	2.1 (1.2)	ns
		2	2.0 (1.3)		**2.3 (1.2)**		1.9 (1.1)		1.9 (1.2)	
34	Keeping fit will improve my heat tolerance	1	3.6 (1.1)	ns	**3.9 (1.1)**	**5.3 ***	3.7 (1.2)	ns	3.8 (1.1)	ns
		2	3.8 (1.2)		**3.5 (1.2)**		3.8 (1.1)		3.6 (1.1)	
35	A good hydration before the work shift will improve my heat tolerance	1	3.7 (1.2)	ns	4.0 (1.1)	ns	3.8 (1.1)	ns	3.9 (1.1)	ns
		2	4.0 (1.0)		3.7 (1.1)		3.9 (1.1)		3.7 (1.2)	
36	Adequate rest between shifts will improve my tolerance	1	**4.0 (1.2)**	**5.2 ***	4.3 (0.9)	Ns	**4.0 (1.1)**	**4.7 ***	4.2 (1.0)	ns
		2	**4.3 (0.9)**		4.0 (1.2)		**4.3 (1.0)**		3.9 (1.2)	

Group (G): Work effort (1 from moderate to rest, 2 from high to very high); Company procedure to dress PPE (1 yes, 2 no); Rest area (1 yes, 2 no); Different perception between parts of the body covered by PPE (1 yes, 2 no). A 5-point Likert scale (1 for strongly disagree and 5 for strongly agree) was used for questions. M is the Mean value; F is Fisher–Snedecor distribution; in brackets Standard deviation (SD). (Sig): *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$ and values in bold.

Interesting results also emerged linked to the items relating to worker awareness of some good practices addressed to increase heat tolerance. For example, the awareness that slush drinks improve the tolerance to heat (item 45) was significantly higher ($p < 0.001$) in subjects who did not use or use little headgear (Table 5) and in companies in which no specific procedures to dress PPE exist (Table 6). The awareness that taking breaks increases heat tolerance (item 34) is correlated to the thermal sensation (Table 5) and to the presence in the company of a specific procedure to dress PPE (Table 6). Furthermore, the kind of work and the work effort ($p < 0.05$) influenced the worker's awareness that adequate rest between shifts increases heat tolerance (item 36). The behavior adopted by worker before the shift, and in particular the maintenance of a good hydration (item 35) was also considered very important especially by workers who declared a neutral (M = 4.6, SD = 0.7) or slightly warm (M = 3.9, SD = 1.2) thermal sensation, compared to those who said of perceiving very hot (M = 3.7, SD = 1.1) (Table 5).

3.4. Masks, Gloves and Other PPE

As highlighted in the descriptive analysis, masks represented one of the most used PPE by HCW and for this reason, their impact on thermal stress perception was thoroughly evaluated taking into account the number of hours and the type of mask used. Many items and therefore many answers provided by HCW were significantly influenced by this equipment. In particular, the awareness that good behavioral practices outside the workplace, such as keeping fit and maintaining a good level of hydration before starting, were significantly (respectively $p < 0.05$, $p < 0.001$) influenced by the use of masks (Figure 3).

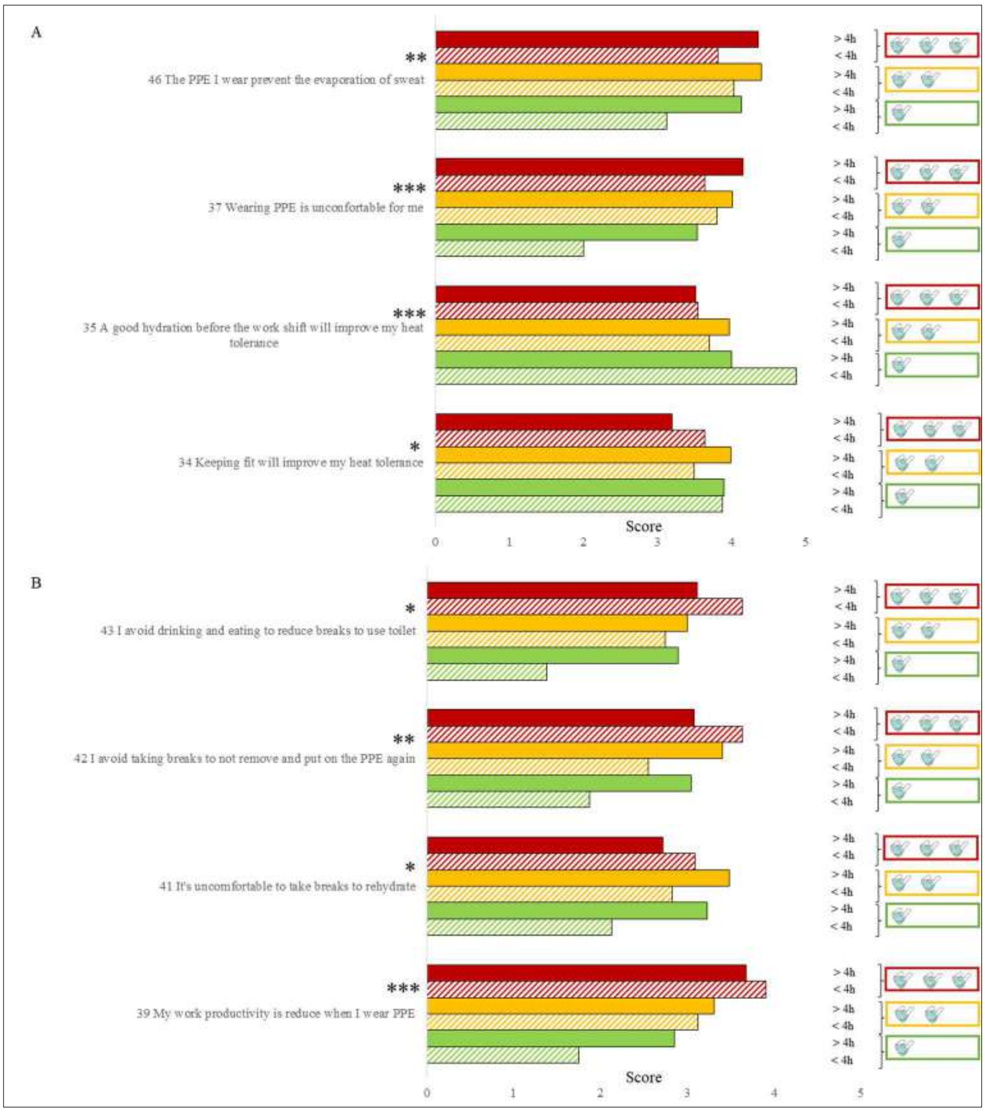

Figure 3. ANOVA to evaluate the effect of the use of the masks on the answers related to items 34, 35, 37 and 46 (**A**) and items 39, 41, 42 and 43 (**B**). Different kind of masks (from 1 up to 3 kind) and different time of use (<4 h or >4 h) was considered. A 5-point Likert scale (1 for strongly disagree and 5 for strongly agree) was used for questions. (Sig): *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

HCW who used different types of masks for a total time exceeding 4 h per day (M = 4.2, SD = 1.2) significantly ($p < 0.001$) considered PPE more uncomfortable than those who only used one type of mask for less than 4 h (M = 2.0, SD = 1.4). A very similar result was obtained with the productivity loss perception caused by the use of PPE which was significantly higher ($p < 0.001$) for the first group of HCW (M = 3.7, SD = 1.7) than the second one (M = 1.7, SD = 0.5). Furthermore, HCW who used less masks (fewer types) and for less time revealed a significant ($p < 0.01$) lower awareness of the role that PPE have in hindering the evaporation of sweat. The impact of masks on good practices during work shifts was significant too. In fact, those who used only one type of mask and for less than 4 h, were less motivated to take breaks during the work shift, in this way avoiding to take off and put on PPE ($p < 0.01$), to rehydrate ($p < 0.05$), for drinking and eating ($p < 0.05$), compared to HCW who wore multiple types of masks for more than 4 h a day.

The use of gloves also had a significant impact on the responses provided by workers (Figure 4).

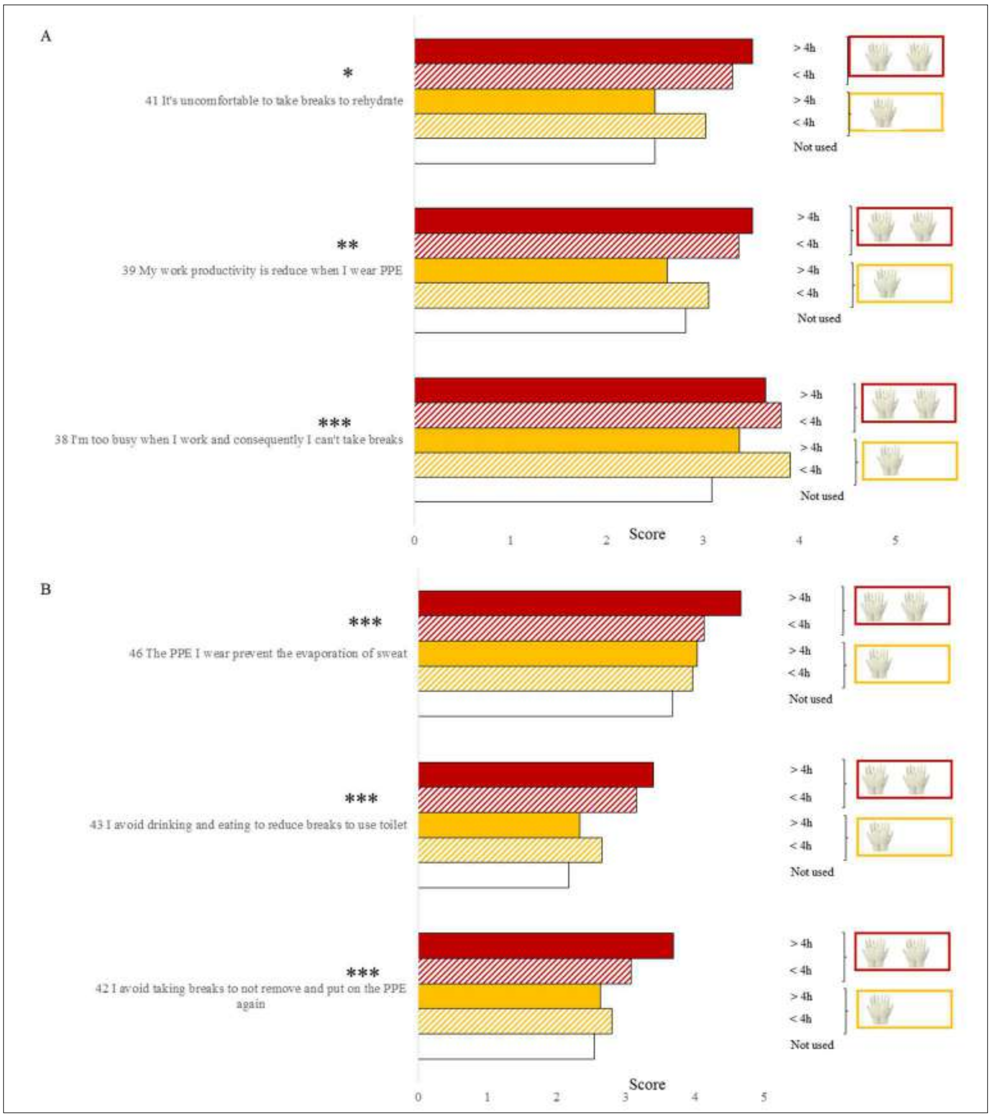

Figure 4. ANOVA to evaluate the effect of the use of the gloves on the answers related to items 38, 39, 41 (**A**) and items 42, 43, 46 (**B**). One or two pairs of overlapping gloves and dif-ferent time of use (<4 h or >4 h) was considered. A 5-point Likert scale (1 for strongly disagree and 5 for strongly agree) was used for questions. (Sig): *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

In particular, the subjects who used two pairs of overlapping gloves, for at least 4 h a day, perceived a higher productivity loss (M = 3.5, SD = 1.2) and revealed greater difficulty in taking breaks during the work shift to rehydrate too (M = 3.4, SD = 1.4), compared to HCW who used them for short time or who did not use them at all (M = 2.8, SD = 1.2). HCW who worn two pairs of overlapping gloves declared to avoid taking breaks to not remove and put on the PPE again (M = 3.4, SD = 1.4) and even preferred not to eat or drink to avoid going to the toilet (M 3.3, SD 1.4), compared to HWC who did not use gloves or who used them very little (M = 2.4, SD = 1.4).

Other PPE, in particular gown, disposable apron and shoes, seem to less influence the responses, and therefore were associated with a lower perception of the heat-stress-related risk. As for footwear, subjects who wore closed boots, work shoes, shoes cover or sanitary clogs with shoes cover, showed a significant ($p < 0.05$) greater perception (M = 4.3, SD = 1.0) of the role of PPE in hindering the evaporation of sweat, compared to those who did not wear these PPE (M = 3.7, SD = 1.1). In addition, workers that wore closed boots, work shoes or sanitary clogs (M = 3.3, M = 1.5) with shoes cover, avoided drinking and eating with the aim to reduce breaks to use toilet compared to the others (M = 2.5, SD = 1.4).

PPE-use-related symptoms were very common among HCW. With the aim of evaluating their impact on the thermal stress perception, HCW were divided into 6 groups according to the number of symptoms declared in the survey: from group 1 with one symptom to group 6 with more than 6 symptoms. Symptoms significantly influenced the productivity loss perception (F = 4.3, $p < 0.001$) related to the use of PPE (F = 6.2, $p < 0.001$) and to the emotions too (F = 4.1, $p < 0.001$). Furthermore, HCW who declared a higher number of symptoms (more than 4 symptoms), also declared more difficulty in taking breaks because they were too busy (F = 3.5, $p < 0.001$), or because they did not prefer to remove and put on the PPE again (F = 2.9, $p < 0.01$). Finally, they also reported to avoid drinking and eating in order to not to go to the toilet (F = 6.3, $p < 0.001$).

4. Discussion

This study represents one of the first surveys to investigate how heat-stress perception among Italian HCW was influenced by the use of COVID-19′s PPE. The knowledge of working conditions and health of workers involved in the healthcare sector, who are currently on the front line of the response to the Covid-19 pandemic, is a priority.

Recently, several studies have demonstrated that age, gender, socioeconomic deprivation, ethnicity could be predictive demographic and social risk factors for COVID-19. Moreover, also hypertension, diabetes and obesity are underlying health conditions that can increase the risk of the disease [31]. The interplay of this underlying conditions and the risk of contracting COVID-19 infection through work, is a multifocal concern [32]. This is a real concern for the assessment of the thermal stress associated with personal protective equipment among workers, too. Results of this survey confirmed a strong impact of COVID-19′s PPE in the heat stress perception of HCW, in line with the results obtained from similar studies carried out in England [27], in Germany [33], in Asia [6] but also in studies with wider participation [28]. The PCA identified 3 fundamental issues that represent the key elements on which to intervene in the management of the risk related to thermal stress in the health care sector:

1. perception of heat stress conditions in the workplace and productivity loss;
2. behavior during the working days;
3. awareness of good practices.

Concerning the first issue, the fact that most of the workers (78.5%) declared to perceive heat stress conditions especially in the body areas covered by the PPE, confirms findings from a previous study carried out in England [27] that found a very similar percentage (72.3%). This aspect is certainly linked to the use of PPE for a high number of hours per day, as confirmed by Lee et al. [6] in two Asian countries, and which also determines important heat-related symptoms such as thirst, excessive sweating, fatigue, headache, difficulty concentrating, skin reactions and general discomfort conditions, with potential important effects on both the health and productivity of HCW. Some studies also described dark-colored urine, dizziness, muscle or abdominal cramps, gastrointestinal disturbance, rapid heartbeat [27] and mental symptoms [33] as phenomena associated with the use of PPE. Tabah et al. [28] showed that adverse effects of PPE (headaches, thirst and exhaustion) were associated with longer shift durations.

An important aspect to take into account, in relation to the results obtained from this and other studies investigating the heat stress perception in HCW, is that the work environments are generally conditioned. However, despite this aspect, workers still perceive thermal stress conditions which are therefore mainly caused by the intense workloads and the prolonged use of PPE declared by HCW. This is confirmed by the fact that workers who wear masks and gloves for a longer period of time (the most used devices for the HCW) are those who declared the worst thermal stress and general discomfort related to the use of COVID-19′s PPE. These aspects, related to the management of personnel engaged in the health emergency due to the pandemic, highlight the importance of adopting specific preventive customized strategies to protect workers, with information according to the task, the PPE worn and the work effort [9]. The importance of personalizing preventive strategies to safeguard the health and productivity of workers is one of the emerging priorities in the occupational field [28,34] and the underway pandemic only accentuates this need. A recent study [35] conducted by the pulmonology, intensive care and infectious diseases Hospital departments of two Italian cities, Bari and Foggia, on 116 healthcare workers directly involved in the healthcare of patients affected by COVID-19, underlined this need. In this study, each participant completed an online questionnaire aimed to investigate the impact of the COVID-19 pandemic on workers' lifestyle changes and job performances. Comparing the results based on the type of mask (surgical mask vs. N95) used by each participant, the authors revealed that surgical masks reported a statistically higher average score for a greater number of disorders. In addition, considering the fact that this device is also used in the summer and outdoors by the general population, they suggested the importance of setting up a specific heat health warning system. Latest studies [36–38] highlighted that additional researches and comparative studies on various types of PPE are needed to determine optimal PPE for HCWs. In particular, their applicability in different environmental scenarios and in different situations of use must be tested. In a recent study [38], nineteen volunteers tested allocated head- or full body-ventilated PPE suits equipped with powered-air-purifying-respirators. This equipment was performed for different tasks during 6 working hours at 22 °C on one day and during 4 working hours at 28 °C on another day. Fluid loss, body temperature, heart rate was determined. Impaired visibility by flexible face shields, back pain related to the respirator of the fully ventilated suit and reduced dexterity due to multiple glove layers were major obstacles for workers. Heat stress and liquid loss were perceived as restrictive 28 °C but not 22 °C. These kinds of studies aimed at evaluating the duration and type of use of the main COVID-19-PPE are and will be increasingly fundamental in the perspective of the COVID-19 and other pandemic management.

The second issue "behavior during the working days" confirms this need because individual factors, such as work effort, tasks and the PPE, significantly influenced the negative behavior of workers during work shifts, such as refusing breaks to hydrate or rest because of overwork or fear of getting infected or to avoid taking off and re-wearing PPE. In particular, masks and gloves, especially if used for more than 4 h, were the PPE most related to negative behavior during the work shift. This finding highlights the importance of specific heat-related response plans ad-dressed to HCW with the aim of improve knowledge and promoting behavioral change to reduce thermal stress among workers.

The awareness related to the importance of good practices to reduce heat stress risk appeared greater in workers who perceived warmer in the areas covered by PPE, with particular reference to maintaining a good level of hydration and keeping fit. These finding partially confirmed previous studies. Lee et al. [6] reported that although HCWs agreed that both hydration and aerobic fitness would increase heat tolerance, more workers perceived hydration as a better strategy than keeping fit. On the other hand, a recent meta-analysis showed that the most effective heat mitigation strategy was improving aerobic fitness, with hydration being least effective [39]. The effect of the aerobic fitness to reduce core temperature was shown in a study compared thermoregulatory and cardiovascular responses to heat stress before and after 8 weeks of endurance training in previously sedentary males [40] and in a subsequent study conducted by Mora-Rodriguez et al. [41] on endurance-trained and untrained cyclists. Furthermore, fitness can also enhance heat dissipation mechanisms [42], which is especially important when wearing PPE.

It is also interesting to observe how workers who used fewer types of masks and for a shorter period of time declared lower awareness of the importance of maintaining a good level of hydration and keeping fit. A different use of PPE could also explain the difference between doctors and nurses in the awareness of the importance of hydration. Another interesting aspect already observed in previous studies [43] is the use of crushed ice during work shifts to mitigate thermal stress and which has shown significance effects above all in relation to the use of headgear and the presence of a specific company procedure to dress PPE. In particular, Lee at al. [6] provided and administered to Singapore HCW an ice slurry made from a commercially available sports drink and a judgment on thermal comfort was requested before and after the ingestion with a scale from cold (+3) to hot (+3). The median rating improved from 2 (warm) before ingestion to 0 (neutral) after ingestion and so the authors concluded that the dual role of ice slurry to cool and hydrate HCW rendered it more beneficial than hydration with fluids and so this practice should be considered more often and also recommended. In fact, the effectiveness of ingesting ice slurry in the mitigation of heat stress and therefore in improving performance is also known in outdoor sports [44].

It is also important to consider that, although workers prevalently carry out their tasks in a conditioned environment, the summer period is still a critical period because workers may be exposed to heat stress conditions when they are out from work, for example during night rest [45,46]. This situation makes the worker more vulnerable as they are exposed to dehydration conditions away from working hours which represent a further critical factor that adds to the stress associated with the necessary use of PPE. A recent study [47] revealed that about 70% of workers initiate work with a suboptimal hydration status, meaning that workers are dehydrated at onset of work and that rehydration from day to day may be a bigger issue than failure to drink during the working shift.

The main strength of this study is that the results are suitable to be used in the operational field suggesting the creation of organizational solutions. These solutions can contribute to reduce the heat risk for HCWs, such as the creation of specific and personalized heat warning systems, supported by local real-time micrometeorological monitoring positioned in strategic hospital locations for the emergency management, the programming of work activities and the reorganization of spaces, as for example, the creation of dedicated rest areas where workers can safely remove their PPE without risking to get infected. This could allow not only to safeguard the health of workers but also their productivity and therefore ensure better management of the hospital emergency connected to the pandemic.

The main limitation of this study is represented by the small and unbalanced sample of HCWs, which is composed by mainly doctors or nurses and therefore it would be appropriate to extend the sample to other healthcare professions. A potential bias of our study, due to the absence of a sample plan strategy (planned as a second step of the study) for submitting our survey, has to be considered. In addition, the mode of self-administration online can be considered as a limit because the worker may have difficulties in understanding the items or devote little attention to the answers; while on the other hand, however, online administration can allow to reach a greater number of workers and can avoid the conditioning effect due to direct administration by an operator too. Another limitation of the research is represented by the lack of simultaneous continuous microclimatic monitoring in the workplace and this aspect will have to be taken into consideration in subsequent studies in order to quantify the real thermal environment and its influence on the HCW heat stress perception.

The survey will be replicated during the summer of 2021 to increase the sample size with particular reference to the involvement of different categories of healthcare professions. Furthermore, by exploiting the results obtained with this first study, and especially the PCA, the questionnaire will be simplified. The simplification of the questionnaire will make it easier and faster to compile and hopefully workers will be more enticed to participate in the survey.

5. Conclusions

The COVID-19 pandemic emergency combined with workload for healthcare professionals call for the further implementation of adaptation strategies and specific interventions to respond to thermal stress of health and social care staff; thus, preserving both workers' health and productivity, with positive effects on the management of the health emergency linked to the pandemic.

Our findings are important for promoting and suggesting prevention measures in order to identify organizational and procedural solutions to reduce thermal stress for HCWs engaged in the management of the COVID-19 emergency, and also for potential future similar emergencies. In fact, the reorganization of internal hospital spaces, the creation of safe rest areas, where it is possible to respect the safety distances and temporarily take off the PPE, do not represent very complex and expensive solutions to be implemented. These relatively simple solutions can be a great help to safeguard the HCW. Imposing mandatory breaks in case of high environmental temperatures, or strict enforcement of specific work/rest ratios to limit the duration of PPE use, should also be considered. In addition, the adoption of company procedures designed to guide the worker to dress and remove the PPE with areas dedicated to this purpose could have a positive impact on the management of the emergency. The study reports a high perception of thermal stress among HCWs despite the fact that work environments are prevalently indoor and air conditioned, demonstrating the importance of individual factors such as workload and the type of clothing worn (PPE) in heat stress perception. This suggests the importance of adopting preventive heat-related strategies also including the personalization of information by developing appropriate heat health warning systems addressed to the occupational sector. A microclimatic monitoring in some strategic hospital areas should be considered too, in order to provide real-time information and therefore facilitating the emergency management plan. It would be desirable to implement national programs for the safeguard of HCW from heat stress, in line with national occupational health and safety policies. In conclusion, even in the health care sector, that might seem "more protected" from the effects of heat—because mainly indoors and in air-conditioned environments—the development of standards, guidelines, and codes of practice represent a priority in order to protect often vulnerable workers due to the prolonged use of PPE and the exposure times caused by COVID-19 emergency.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/ijerph18083861/s1, General anonymous questionnaire: healthcare workers' risk perception of heat stress in the workplace.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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Association between extreme ambient temperatures and general indistinct and work-related road crashes. A nationwide study in Italy

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ABSTRACT

Despite the relevance of road crashes and their impact on social and health care costs, the effects of extreme temperatures on road crashes risk have been scarcely investigated, particularly for those occurring in occupational activities. A nationwide epidemiological study was carried out to estimate the risk of general indistinct and work-related road crashes related with extreme temperatures and to identify crash and occupation parameters mostly involved. Data about road crashes, resulting in death or injury, occurring during years 2013–2015 in Italy, were collected from the National Institute of Statistics, for general indistinct road crashes, and from the compensation claim applications registered by the national workers' compensation authority, for work-related ones. Time series of hourly temperature were derived from the results provided by the meteorological model WRF applied at a national domain with 5 km resolution. To consider the different spatial-temporal characteristics of the two road crashes archives, the association with extreme temperatures was estimated by means of a case-crossover time-stratified approach using conditional logistic regression analysis, and a time-series analysis, using over-dispersed Poisson generalized linear regression model, for general indistinct and work-related datasets respectively. The analyses were controlled for other covariates and confounding variables (including precipitation). Non-linearity and lag effects were considered by using a distributed lag non-linear model. Relative risks were calculated for increment from 75th to 99th percentiles (hot) and from 25 to first percentile (cold) of temperature. Results for general indistinct crashes show a positive association with hot temperature (RR = 1.12, 95 % CI: 1.09–1.16) and a negative one for cold (RR = 0.93, 95 % CI: 0.91–0.96), while for work-related crashes a positive association was found for both hot and cold (RR = 1.06 (95 % CI: 1.01–1.11) and RR = 1.10 (95 % CI: 1.05–1.16). The use of motorcycles, the location of accident (urban vs out of town), presence of crossroads, as well as occupational factors like the use of a vehicle on duty were all found to produce higher risks of road crashes during extreme temperatures. Mitigation and prevention measures are needed to limit social and health care costs.

1. Introduction

Road traffic injuries represent a relevant public health problem. According to the WHO, road traffic crashes account for almost 1.3 million deaths a year around the world, and between 20 and 50 million sustain non-fatal injuries (WHO, 2018). In Italy, the National Institute of Statistics (ISTAT) registered about 170,000 road crashes during the year 2019, for which 3,173 persons died and 241,384 were injured. These road crashes have also an occupational origin. Workers use vehicles either for commuting (home-work travelling routes) and for their work (e.g. in the transport sector). A former Australian study found that three quarters of driver casualties occurred during commuting, with the rest occurring in the course of work with a higher risk for transport workers (Boufous and Williamson, 2006). A study carried out in France found very little variation among the number of work-related road crashes occurring over a decade (Charbotel et al., 2010). According to data

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collected by the Italian national workers' compensation authority (INAIL), the occupational accidents occurring using a transport vehicle represent about 14 % of the total registered occupational injuries, of which 11 % are related to commuting and 3% to work-related activities (INAIL, 2020).

Weather is considered to be a factor that affects the number of road crashes significantly, with different effects according to the mobility of population, type of road (highway, urban and provincial roads) and speed (Bergel-Hayat et al., 2013; Makowiec-Dąbrowska et al., 2019; Naik et al., 2016). Extreme weather events, defined as those meteorological conditions as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations (IPCC, 2014), may occur at a particular place and time of year, and contribute to increase the risk of crash, as in heat waves events, (Wu et al., 2018). Temperature plays an important role in the occurrence of traffic crashes (Basagaña et al., 2015; Bergel-Hayat et al., 2013; Daanen et al., 2003; Liu et al., 2017; Wu et al., 2018) involving driver performance–associated factors (Zhai et al., 2019). Cold temperatures have been often associated to a higher risk of road injuries and fatalities (Brijs et al., 2008; Lee et al., 2014; Shaheed et al., 2016). In winter, the number of injuries was found to increase as the temperature decreased to temperatures lower than 0 °C (Lee et al., 2014). Extremely low temperatures in winter were found to be even more significant than average temperatures (Bergel-Hayat et al., 2013). A study about the association between hot temperatures and road crashes reported a positive association between the increase in summer temperatures and road crashes with the risk ranging from +0.3 % (in Athens region) to +2.8 % (on rural roads of Netherlands) for 1 °C increase in mean monthly temperature (Bergel-Hayat et al., 2013). In Catalonia, during the summer period, a +1.1 % increase in the risk of road crashes was observed for 1 °C increase in daily maximum temperature (Basagaña et al., 2015). In general, most of above studies assessed the relationship between weather and road crash, using averaged meteorological data. The studies about the lagged effect of weather on safety are very limited (Xing et al., 2019). However, it is believed that the safety effects of some adverse weather events, such as rainstorm, could be deferred.

The association between risk factors and work-related road crashes has been investigated extensively. Most the studies are related to specific crashes involving truck vehicles with respect to weather and other key factors (Ahmed et al., 2018; Moomen et al., 2019; Naik et al., 2016; Uddin and Huynh, 2020), addressing for higher risks in windy, rainy and snowy conditions. Other studies analysed broader work-related categories and other risk factors like fatigue and sleepiness. A former systematic review identified, in fact, fatigue, stress and sleepiness consistently associated with increased risk of work-related accident (Öz et al., 2010; Robb et al., 2008). Other studies addressed the contribution of some driving behaviours (Mitchell et al., 2014), age of drivers (Duke et al., 2010; Newnam et al., 2018), exposure (Pei et al., 2012), scheduling issues, as well as difficulties of communication with superiors and physical constrains at work as possible risk factors (Fort et al., 2010). Although the link between extreme temperatures and no road occupational accidents has been studied by different authors (Marinaccio et al., 2019; Martínez-Solanas et al., 2018), the association between work-related road crashes and either average or extreme temperatures is rarely studied. Extreme meteorological conditions have an impact on road safety, by modifying both road conditions, visibility and driver behaviour. Extreme temperatures on workers are characterized by increasing perceived fatigue and decreasing reaction capacities (Daanen et al., 2003). Work-related exposure to heat can result in reduced productivity and adverse health effects on workers when driving, such as dehydration and sweaty palms (Makowiec-Dąbrowska et al., 2019).

In summary, there is a solid body of literature about the association of extreme weather, and specifically temperatures, with the occurrence of road crashes. However, there is a paucity of data regarding how the extreme weather may affect the risk of classes of road crashes like type of crashes (eg. impact vs rear-end collision or involving motorcycles), road structure (eg. intersection vs no intersection), involved group of population (eg. pedestrian, workers and sub-classes here within). In particular, there is a gap in information about the risk of work-related road crash under extreme temperatures. Questions about whether the risk of workers differs from that of the general population, or whether the risk of commuters is dissimilar from that of a professional driver are just examples. The consequences of a road crash in terms of days of duration of leave or degree of impairment is another not investigated aspect in the studies about the association with extreme temperatures.

A better understanding of how extreme temperatures affect the above determinants is useful not only to promote awareness of drivers' vulnerability during such events, but also for analysis and prevention, particularly for work-related events.

This study aims in evaluating the association between extreme temperatures and general indistinct and work-related road crashes occurring in Italy, based on accident data collected by two national archives and high spatial-temporal temperature data provided by a meteorological model. To identify risk factors useful for analysis and prevention, modifiers effect is investigated among both the accident characteristics and occupational parameters.

2. Materials and methods

2.1. Study design

The study about the association between extreme temperatures and road crashes, resulting in death or injury, was carried out by collecting the road crashes occurring in Italy during years from 2013 to 2015 registered by ISTAT, for general indistinct road crashes, and by INAIL for the work-related ones. Such data were then related with either highest and lowest temperatures, expressed as percentile, by means of two statistical models properly designed for the different spatial-temporal characteristics of the two archives, controlling for other covariates and confounding variables. In addition to the overall risks, effect modifications were investigated for a few variables of the two archives.

2.2. Road crashes data

In Italy, data about road crashes are routinely collected by ISTAT to produce statistical reports on this phenomenon. Although such data should contain information about professional drivers or commuters involved in the accident, the latter is rarely available. Consequently, the data provided by ISTAT can be considered as a descriptor of the general indistinct road crashes phenomena. The only available observatory of the work-related road crashes in Italy is the INAIL institute by means of compensation claim applications submitted as occupational accidents. Recent studies linked the two archives for the year 2015 and authors found that only 23 % (20,941) of individuals who claimed for compensation were contained in the general road crashes archive provided by ISTAT (Brusco et al., 2019). Missing matches can be due to many reasons such as incorrectness in the two registration systems, different sources of registration (police intervention vs occupational accident declaration) and missing declaration of an occupational accident with consequent lack of compensation claim application.

The two archives of road crashes used in this study will be described in the next subparagraphs.

2.2.1. The ISTAT general indistinct road crashes resulting in death or injury archive

ISTAT, on the basis on data recorded from different Authorities ("Carabinieri", Highway Police, and Local Police), collects data about road crashes in which an injury or fatality occurred. The collected data refer to some characteristics of the road accident, such as: information about time and location (in or out built up areas); road and meteorological conditions; crossroad structure (intersection, no-intersection); number and types of vehicles involved (car; heavy vehicle;

motorcycle; bike; other); type of accident (impact vs pedestrian/obstacle/vehicle in motion; rear-end collision; isolated off the road), as well as information on the geographic coordinates of the location of crashes. The original classification available for some variable was re-classified to summarise and improve numerosity for statistical analysis. The original classes and their re-aggregation are shown in Table S1 of Supplementary material (SM). Most of these variables were investigated for effect modification in this study. These data are gathered by means of questionnaires filled in by the involved Authorities, based on accident reports, harmonized by using a unique form delivered by ISTAT. The ISTAT archive represents the most complete and accurate information about road crashes available at the national level. The road crashes data were collected for years 2013–2015.

2.2.2. The INAIL work-related road crashes archive

The INAIL archive covers about 80 % of the Italian workforce (INAIL, 2019). It receives compensation claims applications for occupational injuries over the whole national territory, regarding all workers, except for some categories (armed forces, firefighters and police workers, air transport personnel, autonomous tradespeople and professionals with VAT registration). Data were anonymously treated through proper encrypting procedures in order to ensure privacy. The collected data includes: demographic (gender, age at injury); modality of occupational accident (commuting or working); economic sector of activity (ATECO classes), which were re-classified as exposed (water suppy/sewerage/waste, commerce, transports, accommodation and catering services, real estate activities, renting/travel agency/enterprise support, health and social services) and not exposed (all other ATECO classes) based on incidence rate of crashes by sector; information on the gravity of the injury, measured as the duration of leave (0−4; 5−30; 30+ days); and degree of impairment (0;1–100 %). Most of these variables were investigated for possible effect modification. It is worth noting that, while the ISTAT data provide information about the characteristics of a registered crash, the INAIL ones make available information about the occupational context. Consequently, they provide complementary information and results. In addition, while the ISTAT general indistinct road crashes were geo-referred, the work-related ones were provided for the municipality where the road crash occurred. Consequently, the daily counts of occupational road crashes was derived for each municipality (about 8092) together with the daily mean municipality temperature.

2.3. Meteorological data

By dealing with a nationwide study, it was impossible to obtain observed meteorological data (mainly temperature and rain) at the time and location of each road accident. We used data provided by a meteorological model to obtain such data. The meteorology module is made up by the Advance Research Weather Research and Forecasting (WRF-ARW), version 3.8.1, a fully-compressible non-hydrostatic prognostic model (Skamarock et al., 2008). WRF is an atmospheric modelling system designed for both research and numerical weather prediction. It deals with advanced numerical schemes for the computation of the atmospheric governing equations, data assimilation techniques and updated physical processes models and parameterizations. WRF has a large community of more than 48000 registered users in 160 countries. The ECMWF ERA5 reanalyses (Hersbach et al., 2020) have been used to drive WRF simulations that have been performed over two nested domains, covering Europe and Italy at 25 and 5 km resolution respectively. To improve the meteorological fields over the target domain (Italy), the observation nudging data assimilation scheme implemented in WRF has been applied using METAR, ship and buoy observations from NCEP/-MADIS (https://madis.noaa.gov/) archives (an example of the spatial distribution of such observations for the year 2015 is given in Fig. S1 of SM).

The model provided hourly meteorological data at cell level (5 km resolution) over the Italian territory during the years 2013–2015. The data about air temperature and amount of precipitation were used in this study. The model results were validated with observed values and were found to achieve good accuracy (r = 0.98 for temperature and 0.74 of accuracy for precipitation, the latter as cumulative value). Examples of modelled vs observed results are shown in Figs. S2 and S3 of SM.

Our hypothesis was that exposure to extreme temperatures and its consequent effect on road crashes, was not only due to the weather at the time of event but also to a prolonged exposure over the day. Mean daily temperatures can better describe this persistent effect with a possible lag component. Such an approach was already used to study the effect of heat waves on fatal road crashes (Wu et al., 2018). Consequently, daily air temperatures were derived at cell level for the ISTAT general indistinct road crashes dataset and at municipal level for work-related one. Conversely, precipitation is expected to have an effect on the likely of an accident over a shorter period close to the time of the event. Consequently, the hourly values of precipitation at cell level were used for the analysis of the ISTAT dataset, while for the work-related dataset a mean daily municipal precipitation, expressed as dichotomous variable (absence or presence of precipitation), was used to be consistent with the spatial nature of this archive. The presence of precipitation was set when the mean daily value of precipitation was above 0.1 mm.

2.4. Statistical analysis

Two different statistical analysis were used for general indistinct and work-related road crashes.

As for the general indistinct road crashes dataset, a case-crossover design was applied for the estimation of the association between temperature and precipitation with road crashes. Its design is a specific matched case-control study, where each event serves as his/her own control, i.e. the study is self-matched (Maclure, 1991). Specifically, for each road crash, a ‘case window’ and a ‘control window” are defined. The former is defined as the short time period just before the accident, while the latter is defined as a set of short time periods before or after the case, when the event did not occur. Control periods were selected using the “time-stratified” approach: the study period was divided into monthly strata, and control days for each case were selected as the same days in the week in the stratum, and the same hour within the day. This approach allows to control by design for long-term temporal trend, seasonality, day of week, time of the day, as well as for differences in traffic volume (under the hypothesis that at the same hour of the same day of the week of the same month in the same area, the traffic volume is constant). Exposure (e.g. air temperature and precipitation at the cell location) during the case window is compared to those during the control windows, and the relative risk of outcome (e.g. road crash) is estimated with a conditional logistic regression.

As for the general indistinct road crashes, being referred in both time and geo-location, each accident event has been assigned to a specific cell of the meteorological field provided by the WRF model, based on its geographical coordinates. The correspondent meteorological data (daily temperature and hourly precipitation both at cell level) were associated to the event (case) as well as for the control-case as required by the statistical model approach described above.

To account for potential non-linearity of the relationship between exposure and outcome (crash events), as well as of potential distributed lag effect, a distributed lag non-linear model (DLNM) has been applied (Gasparrini, 2014; Gasparrini and Leone, 2014) to model the relationship between temperature and road crashes. In addition, the effect of hourly precipitation in the general indistinct road crashes was controlled by providing its hourly values.

The model used for general indistinct road crashes was the following:

$$Logit(E[event]) = \propto + crossbasis(T) + crossbasis(precip) + holiday + pop$$

where crossbasis(T) is the function to generate the basis matrices for exposure-response and lag-response function to model the relationship between temperature and road crashes, using a natural cubic spline with an internal knot, placed at the 50th percentile of temperature distributions and the lag-response (lag window 0); crossbasis(precip) is the basis matrices for exposure-response and lag-response function to model the relationship between precipitation a different lags (0–6) and road crashes using a natural cubic spline; holiday and pop are two confounding factors related to “holidays” (a 4-levels variable) and population decreases during the summer (a 3-levels variable) respectively.

As for work-related road crashes, we used a time-series approach. As this kind of road crashes were available at municipal level only, the daily counts were used for statistical analysis of such data. A time series of municipal daily counts and mean meteorological data (mean daily temperature and presence or absence of precipitation as defined above) was built for each the 8,090 Italian municipality during the studied period. To consider the climatic peculiarities of each of 110 provinces in which Italy is divided, a specific over-dispersed Poisson generalized linear regression model was run for each province using data from the municipalities herein located. This approach is theoretical equivalent to the “time stratified” case crossover analysis used in the general indistinct road crashes dataset (Lu and Zeger, 2007).

As for general indistinct road crashes, a DLNM has been applied to account for potential non-linearity of the relationship between exposure and outcome, as well as of potential distributed lag effect. The following model was used for work-related road crashes:

$$\log(E[counts_i]) = \propto + \ crossbasis(T_i) + precip_i + holiday + pop \\ + \ year{*}month{*}dow{*}municipality_i + \ epidemic\_flu$$

where $counts_i$ is the number of road crashes in each municipalities of province i; $crossbasis(T_i)$ is the function to generate the basis matrices for exposure-response and lag-response function to model the relationship between the mean temperatures and road crashes in the municipalities of province i using a natural cubic spline with an internal knot, placed at the 50th percentile of temperature distributions and the lag-response (lag window 0); $precip_i$ is the presence or absence of precipitation in the municipalities of province i; holiday and pop are two confounding factor as defined in the general indistinct road crash model; year*month*dow*municipality is a quadruple interaction between municipality, year, month and day of the week used to control for long time trends and seasonality; epidemic_flu is a factor to control for influenza epidemics (a 2-levels variable). It is worth to note that the quadrupole term is able to control for differences in traffic volume, and they have been shown to produce consistent results when data on traffic volume are unavailable (Basagaña et al., 2015; Rosselló and Saenz-De-Miera, 2011).

Starting from the province-specific estimated coefficients, a meta-analytical regression was carried out using linear mixed-effects models to obtain overall national estimations.

The effect of extreme temperatures was defined for both general indistinct and work-related road crashes as the Relative Risk (RR) calculated by exponentiating the coefficient of the crossbasis function of temperature. Since the relationship between the temperature and the outcomes was estimated with a non-parametric approach in order to allow for non-linearity, we needed both a reference and an effect value to estimate a coefficient. The effect was estimated for temperature increases between the 75th (reference value) and the 99th percentile (hot) and for a decline in mean temperature between the 25th (reference value) and the 1th percentile (cold). The 95 % CI were also estimated for the RR.

2.5. *Effect modifications*

Effect modifications were investigated for a few parameters of the two datasets. As for the general indistinct road crash we evaluated the effect modification for pedestrian involved (yes, no), type of vehicle involved (car, motorcycle, heavy, bike, other), severity (dead, injured), type of accident (impact vs pedestrian/obstacle/vehicle in motion; rear-end collision; isolated off the road), localization of accident (out of town, inhabited), crossroads (no intersection, intersection). The work-related road crashes were evaluated for their specific working aspects such as gender (male, female), age class (15−34; 35−60; 60+), modality of working activity (commuting, work-related), economic sector (exposed, not exposed as defined above), duration of leave (<4; 4-30; 30+), nature of injury (bruise; dislocation/sprain/distraction; fracture), degree of impairment (0; 1–100 %).

3. Results

3.1. *Statistical description of road crashes*

Table 1 shows a statistical description of the general indistinct and work-related road crashes registered by ISTAT and INAIL during years 2013–2015. A total of 308,415 and 280,102 cases were found for general indistinct and work-related road crashes respectively. It should be noticed that while the former are single road crashes involving one or more individuals and vehicles, the latter, being based on compensation claim applications, refer to individuals who were involved in a work-related road accident.

According to results shown in Table 1, both type of crashes have a rather flat dependence from year and a decreasing north-south geographic gradient. However, as far as the incidence rates are concerned (number of crashes per amount of either employees or inhabitants), the latter geographical gradients are partially confirmed, with the islands reaching the second most involved macro-region. The number of individual injured is predominant with respect to those dead (99 vs 1% in work related crashes). Pedestrian are involved in about 10 % of registered crashes. The crashes occur mainly in urban areas (69 vs 39 %) and in areas where no-crossroads are located (60 vs 40 %). In 70 % of crashes, a car is involved, followed by motorcycles with 15 % of occurrence. The impact among vehicles in motion is the predominant type of accident (48 %), followed by rear-end collision (20 %).

Among the work-related road crashes, a light prevalence of male with respect to female is observed (58 vs 42 %). Workers with age between 35 and 60 are found to be more at risk (64 %) than younger one (33 %). The occupational road crashes occur more frequently during commuting (76 %) than when the vehicle is used for working activity (24 %) such as to transport of goods. Among the exposed economic sectors, we found the Ateco N (Renting/Travel agency/Enterprise support) and transports sectors with highest number of crashes by number of employees (30.2 and 27.9 respectively). However, in terms of absolute number of work-related crashes the most contributing sectors are the manufacturing (15.7 %), the commerce (13.1 %) and the transports (10.2 %). The compensation claim applications produced days of leave between 0 and 4 in 42 % of cases, and from 5 to 30 days in 35 % of them.

Maps of number of general indistinct and work-related road crashes are shown in Fig. S4 of SM. The geographical distributions of crashes are rather similar between the two datasets. Peaks in the number of crashes can be observed in the main metropolitan areas.

3.2. *Temperature exposure results*

Table 2 shows the main statistics of the temperature exposures by year derived by the WRF model results. Maps of 1st, 25th, 75th and 99th percentiles are shown in Fig. 1. The results show a similar statistical distribution for years 2013 and 2015 with temperature between -16 and 33 °C. A smaller range is instead observed during year 2014 (-12, 31 °C). The geographical analysis shows highest temperatures in the south region and in the Po valley located in the northern part of Italy, with values of 99th percentile between 27 and 31 °C. The coldest temperatures are observed in north of the country with values of 1st percentile between -16 and −8 °C. The effect of altitude and mountain ranges also create a clear thermal trend with lower percentile values in the Alps in

Table 1
Statistical description of general indistinct (left) and work-related (right) road crashes registered by ISTAT and INAIL respectively during years 2013-2015. Incidence rate of work-related crashes is based on the number of employees registered by INAIL on year 2015. Incidence rate of general indistinct crashes is based on the number of inhabitants registered by ISTAT on year 2015.

General indistinct road crashes	Cases (cases x1000 inhabitants)	%
Overall	308,415	100
2013	91,234	30
2014	107,722	35
2015	109,459	35
Accident by macro-region		
North-West	110,843 (6.9)	36
North-East	84,849 (7.3)	28
Center	55,416 (4.6)	18
South	46,080 (3.3)	15
Islands	9,792 (6.8)	3
Injured	448,784	100
2013	135,145	30
2014	155,498	35
2015	158,141	35
Dead	6,772	100
2013	2,123	31
2014	2,325	34
2015	2,324	34
Pedestrian		
No	276,325	90
Yes	32,090	10
Localization		
urban	212,031	69
out of town	96,384	31
Road structure		
Intersection	122,090	40
no-intersection	186,325	60
Type of vehicle		
car	394,564	70
heavy	43,346	8
motorcycle	85,209	15
bike	31,616	6
other	6,345	1
Type of accident		
impact vs stationary	30,204	10
impact vs pedestrian	30,840	10
impact vs motion	149,375	48
rear-end collision	61,274	20
isolated	36,722	12

Work-related road crashes	Cases (cases x1000 employees)	%
Overall	280,102	100
2013	97,714	35
2014	92,482	33
2015	89,906	32
Crashes by macro-region		
North-West	90,922 (16.3)	32
North-East	79,463 (21.8)	28
Center	65,308 (17.7)	23
South	27,541 (14.0)	10
Islands	16,868 (18.3)	6
Injured	278,590	99
Dead	1,512	1
Gender		
Male	162,973	58
Female	117,129	42
Age class		
15–34	93,707	33
35–60	179,129	64
60+	7,266	3
Modality		
Commuting	212,995	76
Work-related	67,107	24
Economic sector		
Not exposed	153,343	55
A-Agricolture/fishing	1,647 (13.9)	0.6
B-Mineral extraction	350 (6.7)	0.1
C-Manufacturing	43,907 (11.4)	15.7
D-Supply of electricity, gas, steam	1,402 (10.8)	0.5
F-Construction	16,185 (11.0)	5.8
J-Communication and inform. service	8,415 (13.6)	3.0
K-Financial and insurance activities	8,539 (12.4)	3.0
M-Professional and technical activities	10,164 (13.0)	3.6
O-Public administration	11,408 (14.4)	4.1
P-Education	2,856 (13.4)	1.0
R-Sport, artistic and entertainment	2,156 (14.5)	0.8
S-Other support services	5,962 (12.7)	2.1
T-Family activities	21 (6.6)	0.01
U-Extraterritorial organization and body	65 (9.6)	0.02
Undetermined	40,266	14.4
Exposed	126,759	45
E- Water suppy/Sewerage/Waste	4,160 (22.0)	1.5
G-Commerce	36,647 (15.4)	13.1
H-Transports	28,618 (27.9)	10.2
I-Accommodation and catering services	14,813 (19.1)	5.3
L-Real estate activities	2,131 (15.1)	0.8
N-Renting/Travel agency/Enterprise support	17,680 (30.2)	6.3
Q-Health and social assistance	22,710 (20.2)	8.1
Duration of leave [days]		
0–4	116,295	42
5–30	99,321	35
30+	64,486	23

Table 2
Main statistics of temperature exposures by year.

Year	Min	percentile					Max
		5	25	50	75	95	
2013	−16.68	2.07	8.26	15.64	21.22	26.82	33.39
2014	−12.70	5.18	10.42	15.84	20.92	25.40	31.73
2015	−16.21	3.44	9.08	15.34	21.92	28.04	33.08

the north and along the Apennines in central areas.

3.3. *General indistinct road crash risk analysis*

Fig. 2 shows the relative risks (RR) for hot and cold temperatures, as defined above, estimated for general indistinct road crashes. The exact values are shown in Table S2 of SM. On the overall analysis a positive association with hot temperature (RR = 1.12, 95 %CI: 1.09–1.16) and a negative one for cold (RR = 0.93, 95 %CI: 0.91−0.96) were found. A dose-response relationship with temperature was also estimated (Fig. S5 of SM) in which a positive effect is estimated for temperatures above 27 °C only.

By stratifying for possible effect modifiers, a higher risk for hot temperature were found for crashes not involving pedestrians with respect to those involving them. Among the type of vehicle, crashes involving motorcycles were more at risk for hot (RR = 1.21, 95 %CI: 1.14–1.28) than those involving cars, heavy vehicles, bikes and others (RRs between 0.97 and 1.14). Higher risks for hot were also estimated for events with persons dead with respect to injured one, for crashes occurring out of town with respect to inhabited areas, and for road with no intersection. However, as far as the confidence intervals are concerned, the above risks for hot partially overlap.

The stratified analysis for cold temperature exhibits a strong protective association for crashes involving either motorcycles (RR = 0.77, 95 %CI: 0.72−0.82) or bikes (RR = 0.69, 95 %CI: 0.62−0.76). A slight not statistical significant positive association with cold is instead estimated for crashes with deaths (RR = 1.01, 95 %CI: 0.82–1.24), those involving pedestrians (RR = 1.01, 95 %CI: 0.93–1.10), and for crashes

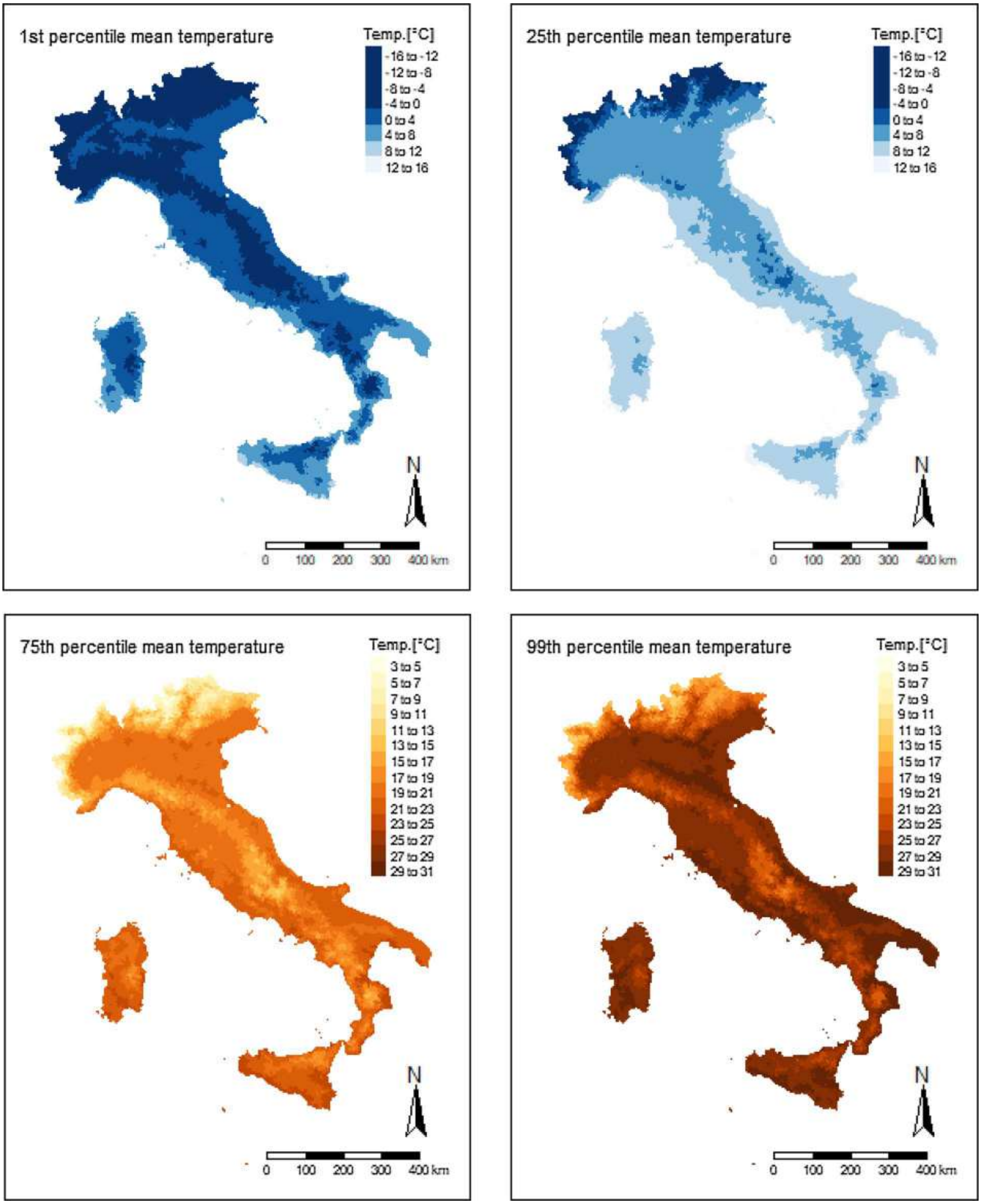

Fig. 1. Maps of 1st, 25th, 75th and 99th percentile of municipal temperature exposures based on results provided by the WRF meteorological model for years 2013–2015.

involving either the impact with pedestrians (RR = 1.02, 95 %CI: 0.94–1.11) or a rear-end collision (RR = 1.02, 95 %CI: 0.95–1.09).

3.4. Work-related road crash risk analysis

The RRs for hot and cold temperatures estimated for work-related road crashes are also shown in Fig. 2. The exact values are shown in Table S2 of SM. The correspondent dose-response function is shown in Fig. S5 of SM. Here the percent change of work-related road crashes by temperature percentile shows a positive association for both hot and cold temperatures, with much higher risks for the latter. The overall analysis shows a RR of 1.06 (95 %CI: 1.01–1.11) for hot and 1.10 (95 % CI: 1.05–1.16) for cold temperatures.

For hot temperature, the stratified analysis provides a higher risk for male (RR = 1.14, CI 1.07–1.22), for workers with age between 35 and 60 (RR = 1.09, 95 % CI: 1.03–1.15) and during on duty activities (RR =

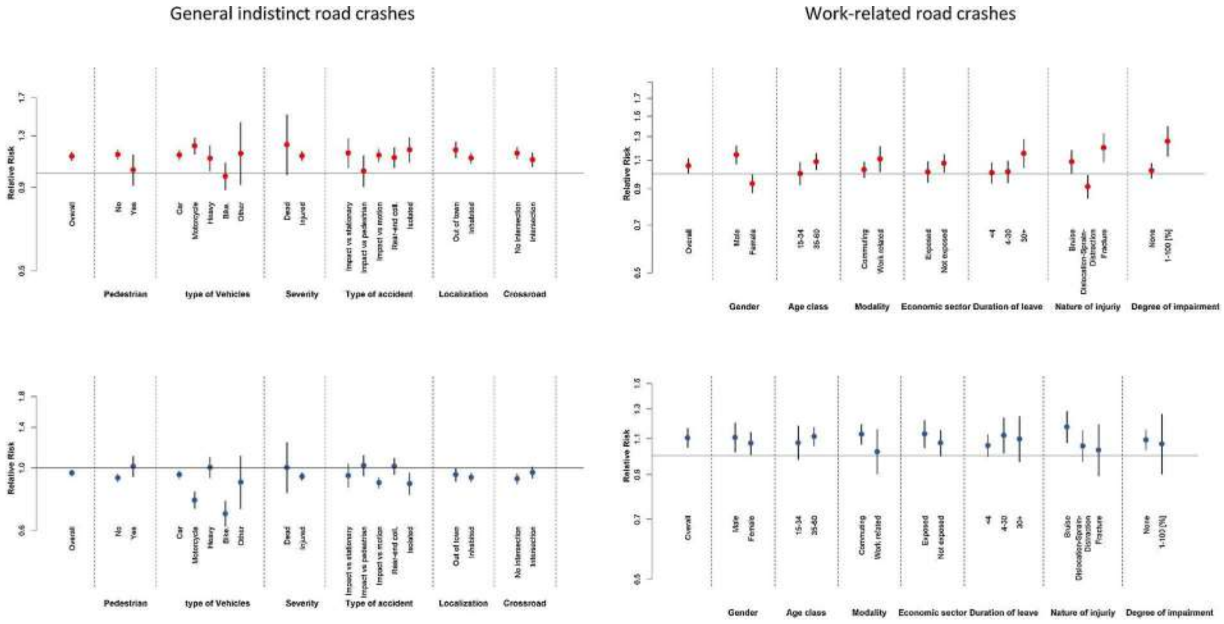

Fig. 2. Relative Risks by overall and effect modifiers for general indistinct (left) and work-related (right) road crashes, for hot (top) temperatures calculated for increments from 75th and 95th percentile and for cold (bottom) temperatures calculated for increments from 25th and 1st percentile.

1.11, 95 % CI: 1.01–1.21). In addition, the risk was higher for injuries involving fractures (RR = 1.20, 95 % CI: 1.09–1.32), and for those with degrees of impairment above 0% (RR = 1.26, 95 % CI: 1.13–1.39). The same analysis carried out for cold temperatures estimates a significant positive association for male (RR = 1.11, 95 % CI: 1.02–1.20), and for workers in age class 35−60 (RR = 1.11, 95 % CI: 1.06–1.17). Furthermore, the cold analysis shows higher risk for workers employed in exposed economic sectors (RR = 1.13, 95 % CI: 1.05–1.22); for crashes causing duration of leave below 4 days (RR = 1.06, 95 % CI: 1.00–1.12) and between 4 and 30 days (RR = 1.12, 95 % CI: 1.01–1.24); for crashes which caused injuries as bruise (RR = 1.17, 95 %CI: 1.08–1.28), and those causing none degree of impairment (RR = 1.09, 95 % CI: 1.03–1.15). Considering the confidence intervals, all these RRs have a certain degree of overlapping.

4. Discussion

The availability of both the national occupational injuries and the general indistinct road crashes datasets, as well as high spatial resolution temperature data, enabled us to investigate for the first time in Italy, about the risk for both heat and cold exposure of general indistinct and work-related road crashes resulting in death or injury, at national level.

Both general indistinct and work-related crashes were found positive associated with hot temperatures with the former at higher risk than the latter one (RRs 1.12 vs 1.06). Work-related crashes were also found positive associated with cold temperatures, while general indistinct ones were negative associated. Although the study design applied in the two datasets is different in both the spatial representativeness (cell based for general indistinct and daily counts at municipally level for work-related crashes), and the statistical analysis applied (case-crossover time stratified for general indistinct and time series analysis for work-related crashes), the discrepancy in RR observed for cold temperatures is unclear. A stratified analysis for geographical areas shows that in metropolitan areas (like Rome and Milan), where a large number of crashes occurs, a positive association with cold temperatures is estimated (Fig. S6 of SM). Conversely, in other geographical macro-areas, being the crashes more spatially spread, the statistical analysis does not have a sufficient number of cases to identify this kind of association. In addition, we could not exclude a possible overfitting of confounding factors like precipitation, which could smooth the cold effect.

The overall positive association with hot temperatures confirms the recent results obtained in literature for road crashes in general (Basagaña et al., 2015; Bergel-Hayat et al., 2013; Wu et al., 2018). This study found that this effect is predicted also for work-related road crashes.

The stratified analysis for general indistinct road crashes in hot and cold temperatures has shown that pedestrians are at risk in both hot and cold conditions, with the latter at higher risk than crashes not involving them. As far as the type of involved vehicle is concerned, motorcycles exhibit the strongest positive association for hot temperatures and the second most protective for cold one. These results seem to be related with the longer and shorter exposure time during wormer and colder seasons respectively. These kind of vehicles are expected to be used in sunny weather with consequent risk of accident occurring in hot temperatures. Conversely, under colder weather their use is more limited. During the last decade, the traffic congestion occurring in metropolitan areas has increased the use of such travelling modes. This has dramatically increased the number of crashes involving motorcycles with a correspondent increase in number of motorcyclists dead or injuried. Crashes involving cars or heavy vehicles are estimated to have roughly the same risk levels with positive association with hot conditions. Under cold temperatures, heavy vehicles are the only positive association, with a RR a bit higher than neutral. As expected, crashes involving bikes have the most protective association under colder conditions, mainly due to the lower exposure time in such weather.

The analysis by type of accident shows positive associations among the different kind of crashes under hot weather, with a rather equivalent risk among them, out of accident involving pedestrians. When the analysis is referred to cold temperatures, a slight positive association is estimated for crashes involving pedestrians and in rear-end collisions only. The latter result may be related with a few other co-factors like road and visibility conditions occurring under bad weather.

The RRs for localization of crashes exhibit higher risk for those occurring out of town and with no crossroads in hot conditions. The former result was also obtained in a study carried in United States, which estimated higher risk when driving in rural motorway during heat waves (Wu et al., 2018). Here speed can also have a role as a co-factor, particularly in crashes occurring in highways.

The stratified analysis for work-related road crashes shows a stronger positive association for male and a protective one for female in hot temperature conditions. The same analysis in cold weather shows positive association for both gender with higher risk for male. This gender effect is related with the specific working activities undertaken using a vehicle, which involves more male than female (eg. professional drivers) and are corroborated by the incidence results shown in this study (see Table 1). Similar results were reported for France with men accounting for the majority of causalities (Charbotel et al., 2010). Work-related crashes while on duty were found at higher risk than those occurring during commuting on hot temperature conditions. Conversely, under cold weather conditions, a higher statistically significant risk was found for workers commuting than those while on duty. The analysis by exposed (water suppy/sewerage/waste, commerce, transports, accommodation and catering services, real estate activities, renting/travel agency/enterprise support, health and social services) and not-exposed (all others) economic sectors shows a double risk for those working in exposed one (RRs 1.13 vs 1.07) under cold temperatures. A statistical significant association with hot were found for not exposed sectors. It is likely that workers occupied in risky sectors are more exposed in terms of travelled distance and in-driving working hours, which might affect fatigue, tiredness and difficulty in making decisions correlated with ambient temperature (Makowiec-Dąbrowska et al., 2019). An Australian study reports that a quarter of all occupational crashes were while on duty, with transport workers found as the most frequent victims (20.8 %), with drivers of heavy trucks representing about half (48 %) of all fatalities (Boufous and Williamson, 2006). Similar results were found in France (Charbotel et al., 2010; Hours et al., 2011), United States (Naik et al., 2016), Poland (Makowiec-Dąbrowska et al., 2019) and in a systematic review of work-related road crashes (Robb et al., 2008). The importance of transport sector in work-related road crashes is well known in literature, but manufacturing contribute is also reported (Boufous and Williamson, 2006; Hours et al., 2011). Unfortunately, this work could not investigate the association with extreme temperatures for single economic sectors due to the low number of cases at provincial level.

Both hot and cold temperatures are found to have a role on the severity of injuries caused by crashes. An increasing risk (RRs from 1.01 to 1.15) was found at increasing levels of duration of leave under hot temperatures, while crashes causing less than 4 and between 4 and 30 days of rest were positive associated with cold temperatures. Statistical significant modification of effect were found for crashes causing fracture or bruise under hot conditions, and bruise under cold temperatures. Furthermore, the risk was higher for crashes causing a degree of impairment above 1% under hot conditions. As for work-related dataset the information about the characteristics of crashes were not available (conversely to general indistinct dataset), we could not carry out a deeper analysis about these high severity crashes and their link with extreme temperatures.

This study has strengths and limitations. As for the former the use of time series of high resolution temperature data allows to match exposure to each event at both cell level (for general indistinct dataset) and municipal level (for work-related one). This approach made the possibility to overcome the limitations of either the spatial coverage of exposure estimations, when monitoring stations are used for assess it, or the lack of information about the meteorological conditions at the time of accident in the crash reports filled by the local authorities. Such meteorological data made possible a nationwide study allowing a better spatial-temporal characterization of exposure to outdoor temperatures, thus obtaining more accurate effect estimates. In addition, the availability of a time series of crashes data at national level, enabled us to study the impact of extreme temperatures exposure on both crashes characteristics (e.g. road, localization, type of vehicle) and occupational related parameters (e.g. commuting or on duty, economic sector, health consequences).

This study has also some limitations. We could not relate the crashes with both the individual aspects of involved drivers and the information about internal and external concurring factors linked with the accident. As for the individual aspects important features like fatigue, in cabin thermal stress or the use of air conditioning, physiological conditions of drivers and its driving performance or drug assumptions were not available. Other concurring circumstances like traffic, speed of involved vehicles and wind conditions were not available. All these information is impossible to be retrieved for an epidemiological study like this one. Another critical point was the uncertainty on the exact time of a crash used in general indistinct analysis, as authorities usually round it in their crash report. As the statistical analysis applied for general indistinct crashes was based on a case-crossover design, where case and control windows have to be identified, an erroneous identification of the crash time could cause a shift in the time slot containing the crash time and consequently a misclassification of the corresponding case and control windows. This should affect the correct assessment of precipitation at the time of accident, as hourly data were used. The assessment of temperature exposure was not involved in this possible misalignment, as daily average data were used. In addition, this assessment was not made at individual driver level but at ecological one (either cell or municipality one). Consequently, possible exposure error cannot be avoided. As outlined above such information was clearly not available and, considering the epidemiological nature of this study, it would have been a demanding task.

5. Conclusions

This study investigated about the effect of extreme outdoor temperatures on road crashes resulting in death or injury, occurring in Italy during years 2013–2015. General indistinct and work-related road crashes were analysed. Our results address for a positive association between hot temperatures and road crashes in both datasets. Work-related crashes were also found positive associated with cold temperatures, while general indistinct ones were negative associated. Some modification of effects were identified. We found motorcycles, localization of accident and crossroads to have a specific role in the higher risk of crashes under extreme temperatures. In addition, male, the use of vehicles for commuting and working in exposed sectors were found important determinants for risk of work-related road crashes under extreme temperature conditions. As climate changes is expected to exacerbate the exposure to extreme temperatures, the identification of the risks and its key parameters, is useful to plan prevention policies. The limitation of exposure (e.g. travel time) under extreme temperatures, particularly for employees working in the identified exposed economic sectors, or prevention policies suitable for categories at higher risk like men or motorcyclists, are just examples of policy implications provided by this study. Their implementation is expected to limit the impact of extreme temperatures on occupational injuries as well as on social and health care costs.

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Authors contribution

Claudio Gariazzo: Conceptualization, Data curation, Methodology, Writing - Original Draft; **Silvia Bruzzone**: Data curation, Methodology, Validation, Writing - review & editing; **Sandro Finardi**: Data curation, Writing - review & editing, Visualization; **Matteo Scortichini**: Software, Methodology, Data Curation, Validation, Visualization; **Liana Veronico**: Data Curation, Validation; **Alessandro Marinaccio**: Conceptualization, Methodology, Writing - review & editing.

Declaration of Competing Interest

The authors report no declarations of interest.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.aap.2021.106110.

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Heat warning and public and workers' health at the time of COVID-19 pandemic

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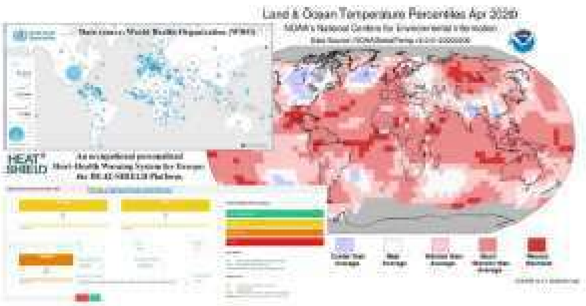
HIGHLIGHTS

- WHO produced guidelines about the use of PPE to reduce the transmission of SARS-CoV-2.
- The synergistic effect between heat and anti-COVID-19 measures must be studied.
- Researchers must study how PPE behave when used in outdoor warm condition.
- A PPE-inclusive customized heat-warning system is useful at the time of COVID-19.
- Interventions to review HHWSs in the context of COVID-19 are strongly required.

GRAPHICAL ABSTRACT



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Nationwide epidemiological study for estimating the effect of extreme outdoor temperature on occupational injuries in Italy

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ABSTRACT

Background: Despite the relevance for occupational safety policies, the health effects of temperature on occupational injuries have been scarcely investigated. A nationwide epidemiological study was carried out to estimate the risk of injuries for workers exposed to extreme temperature and identify economic sectors and jobs most at risk.

Materials and methods: The daily time series of work-related injuries in the industrial and services sector from the Italian national workers' compensation authority (INAIL) were collected for each of the 8090 Italian municipalities in the period 2006–2010. Daily air temperatures with a 1 × 1 km resolution derived from satellite land surface temperature data using mixed regression models were included. Distributed lag non-linear models (DLNM) were used to estimate the association between daily mean air temperature and injuries at municipal level. A meta-analysis was then carried out to retrieve national estimates. The relative risk (RR) and attributable cases of work-related injuries for an increase in mean temperature above the 75th percentile (heat) and for a decrease below the 25th percentile (cold) were estimated. Effect modification by gender, age, firm size, economic sector and job type were also assessed.

Results: The study considered 2,277,432 occupational injuries occurred in Italy in the period 2006–2010. There were significant effects for both heat and cold temperatures. The overall relative risks (RR) of occupational injury for heat and cold were 1.17 (95% CI: 1.14–1.21) and 1.23 (95% CI: 1.17–1.30), respectively. The number of occupational injuries attributable to temperatures above and below the thresholds was estimated to be 5211 per year. A higher risk of injury on hot days was found among males and young (age 15–34) workers occupied in small-medium size firms, while the opposite was observed on cold days. Construction workers showed the highest risk of injuries on hot days while fishing, transport, electricity, gas and water distribution workers did it on cold days.

Conclusions: Prevention of the occupational exposure to extreme temperatures is a concern for occupational health and safety policies, and will become a critical issue in future years considering climate change.

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Epidemiological studies may help identify vulnerable jobs, activities and workers in order to define prevention plans and training to reduce occupational exposure to extreme temperature and the risk of work-related injuries.

1. Introduction

Due to climate change, heat waves have become more frequent and intense in recent decades [IPCC, 2015]. The Mediterranean region has been identified as a climatic hot-spot most vulnerable to climate change [Giorgi, 2006; Ciardini et al., 2016]. The temperature increase, measured in the coastal regions during the last decades, was found to be larger than at the global scale, with remarkable seasonal and geographical differences [Toreti et al., 2010]. The epidemiological association among high temperature, heat waves and population health effects has been largely analysed, using mortality and morbidity measures as health outcomes [Basu, 2009; Ye et al., 2012; Gasparrini et al., 2015; Guo et al., 2017; Song et al., 2017]. There is undisputable evidence that hot weather contributes significantly to excess mortality, particularly among elderly and subjects with chronic diseases [Hales et al., 2014]. Cold temperature seems to affect mortality more indirectly, after longer exposure, during early extreme cold events and with significant variability for seasonality and climate conditions [Anderson and Bell, 2009; Díaz et al., 2019; Smith and Sheridan, 2019].

Despite the relevance for occupational safety policies, the health effects of extreme temperatures on occupational injuries have been scantly investigated. In the last decades, international institutions and public agencies have published documents promoting health programs and actions to improve working conditions and environments for all labour intensive jobs which are carried out in hot or cold indoor/outdoor conditions [CDC, 2008; NIOSH, 2016; UNDP, 2016]. They underlie that health effects of extreme temperature on workers are characterized by increasing perceived fatigue and decreasing reaction capacities. Work-related exposure to heat can result in reduced productivity and adverse health effects on workers, such as dehydration, spasms and growing risk of injuries that could be associated to sweaty palms, fogged-up safety glasses, and cognitive impairment (that is, mental confusion, impaired judgment, and poor coordination) [Dutta et al., 2015]. The relevance of loss in work capacity and productivity due to climate change has been repeatedly underlined and the associated costs have been estimated [Kjellstrom et al., 2016; Martínez-Solanas et al., 2018]. A recent survey carried out in Australia found that respondents were moderately concerned about workplace heat exposure, suggesting a need to strengthen workers' heat risk perception and refine current heat prevention strategies [Xiang et al., 2016]. For those jobs envisaging hot working conditions, such as smelters or metalworkers, heat waves represent an additional burden, which could lead to injuries [Xiang et al., 2016].

A systematic review of epidemiological studies [Bonafede et al., 2016a] on heat and cold temperature effects on work-related injuries identified categories of workers at risk and a meta-analysis of time-series and case-crossover studies have estimated a pooled risk between 1.002 and 1.014 (as mean value of pooled relative risks, according to different criteria of aggregation) [Binazzi et al., 2019]. Epidemiological studies appear to be limited in geographical extent, number of observations and exposure resolution. Two recent case-crossover studies have estimated that around 5% and 2.7% of occupational injuries in Adelaide (South Australia) and in Spain, respectively, were attributable to temperature [Martínez-Solanas et al., 2018; Varghese et al., 2019]. A study conducted in three major Italian cities: Milan, Turin and Rome, using occupational injuries collected by the Italian workers' compensation authority (INAIL), analysed the effects of temperature (high and cold). Results showed an effect of high temperature only among bricklayers, blacksmiths, mechanics, installers and asphalters, workers in the construction and energy sectors, and among outdoor workers or workers performing both outdoor and indoor tasks. Conversely, only weak effects were observed for cold [Schifano et al., 2019].

Scientific evidence concerning the relative risk of work related injuries for extreme outdoor temperature and the identification of economic sectors and activities majorly involved are relevant for policymakers and occupational health and safety practitioners to define guidelines and focused formation packages for prevention and adaptation of workplace extreme temperature exposure.

The ongoing project Big data in Environmental and occupational EPidemiology (BEEP) aims to collect and link environmental and health data from different sources to estimate the health effects and impacts in Italy (project details available at https://www.progettobeep.it/index.php/en/). The current study, carried out within the BEEP project, aims to estimate the risk of work-related injuries for extreme heat and cold outdoor temperatures, using worker's compensation claims in Italy from 2006 to 2010. Furthermore, effect modification by gender, age, firm size, economic sector and job type were also assessed.

2. Materials and methods

2.1. Workers' compensation claim data

This study considers occupational injuries ascertained in Italy in the period 2006–2010, with a claim protocol number by December 31, 2017. Data were extracted from the Italian national workers' compensation authority (INAIL) archives, which covers about 80% of the Italian workforce [INAIL, 2019; ISTAT, 2011]. INAIL receives claims for occupational injuries over the whole national territory, regarding all workers, except for some categories (armed forces, firefighters and police workers, air transport personnel, autonomous tradespeople and professionals with VAT registration), for which specific insurance systems have been established. A record-linkage procedure was performed using other INAIL archives to match each injury occurrence with information concerning the company\firm they worked for. We selected only injuries in industrial and services sector (excluding agriculture workers), according to the availability of firm size information only for these sectors. The label "agri-industry" in the analysed dataset has to be considered as the industrial transformation of agricultural products or refers to specific contractor workers. Data were anonymously treated through proper encrypting procedures in order to ensure privacy. Each subject was geographically assigned according to the municipality where injury occurred. The collected data includes demographic (gender, age at injury), occupational (economic sector of activity, type of job) and information on the gravity of the injury, measured as the duration of leave. Variables referring to the modalities of injury were not considered due to the large proportion of missing values. Causes of injury related to road accidents occurring during home-work-home travelling (e.g. commuting), students, and those not classified by INAIL as occupational accidents were excluded from the analyses.

2.2. Meteorological data

Italy is characterized by a cold humid subtropical or mild continental climate in the Northern regions and a Mediterranean climate with hot, dry summers and mild, wet winters in the central and southern regions. Daily air temperature with a 1 × 1 km resolution derived using land surface temperature (LST) data from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors on board the National Aeronautics and Space Administration (NASA) Terra satellite, air temperature (T_a) from monitoring networks and spatio-temporal land use data were utilized as temperature exposure. The methodology was developed elsewhere and details can be found in de'Donato et al. [2016; Kloog et al., 2012; Kloog et al., 2014]. Briefly, a 3-stage multivariate random effects model was developed in which, for stage 1, calibration between T_a measurements and LST data in pixels with both LST and T_a was defined for each year. For each day, random intercepts and slopes for LST were estimated to capture the day-to-day temporal variability of the T_a–LST relationship. The model was nested within climatic zones to account for the potential heterogeneity of the association across Italian climatic zones. The stage 2 model then predicted air temperature in grid cells without monitors but with available LST measurements. In the final stage, the model takes advantage of the association between grid cells LST values with T_a measurements located elsewhere, and of the association with available LST values in neighboring grid cells. Daily mean air temperatures at 1 × 1 km spatial resolution for the study period (2006–2010) were obtained for the Italian domain. The model performance was excellent as the results of a cross validation procedure had an average R^2 value of 0.97 and RMSPE of 1.4 °C across Italy. Average spatial and temporal correlations were 0.94 and 0.98, respectively, with RMSPE lower than 1 °C [de'Donato et al., 2016]. The 1 × 1 km gridded data were then averaged to obtain a daily mean temperature exposure for each municipality in Italy. Mean daily temperature, derived as described above, was the only measure available at national level with such a high spatial resolution for a 10-year period: hence, it was considered as the exposure of interest. Furthermore, it has been shown that the predictive ability of different temperature indicators in epidemiological studies is comparable [Barnett et al., 2010]: thus, it can be considered here to estimate work-related injuries at municipal level. The effect of humidity on temperature exposure has not been considered, but, as discussed in recent studies, the strong correlation between different measures of temperature means that, on average, they have the same predictive ability on estimating mortality, and potentially also on injuries occurrence [Barnett et al., 2010; Varghese et al., 2018, 2019].

2.3. Statistical analysis

The relationship between air temperature and injuries was evaluated with a time-series approach: for each of the 8090 Italian municipalities, the daily count of injuries was retrieved together with the daily mean temperature. Since Italy is divided in 20 regions and 110 provinces, a specific over-dispersed Poisson generalized linear regression model was run for each province. A Distributed Lag Nonlinear Model (DLNM) approach was used to take into account both the potential non-linearity of the dose response curve and a delayed effect of the exposure on the outcome [Gasparrini, 2014; Gasparrini and Leone, 2014]. The relationship between temperature and injuries was modelled through a B-spline with one internal knot, placed at the 50th percentile of region specific temperature distributions, and the lag-response with a categorical variable (lag window 0–2). To control for long time trends and seasonality, a quadruple interaction among municipality, year, month and day of the week has been included in the models. This choice was driven by the theoretical equivalence of such an approach to the "time stratified" case crossover analysis with controls selected in the same municipality, year, month and day of the week in which the case was observed [Lu and Zeger, 2007]. Other variables fitted in the model were: "holidays" (a 4-levels variable with value "1" on isolated days; "2" on Christmas, Easter and New Year's Day; "3" on the days surrounding Christmas, Easter and New Year's Day; "0" elsewhere); population decreases during the summer (a 3-levels variable with value "2" for the 2-week period around the 15th of August; "1" from 16 July to 31 August with the exception of the aforementioned 2-week period; "0" elsewhere); influenza epidemics (a 2-levels variable with value "1" on days of influenza epidemics, defined at regional level according to the National Influenza Surveillance System; "0" elsewhere). Then, from the province-specific estimated coefficients, an overall national dose-response curve was estimated, using a multivariate meta-analytical regression [Gasparrini et al., 2012]. Province estimates are reported in Supplemental Material (Table S1). The effect of high temperatures was defined as the Relative Risk (RR) of injury for temperature increases between the 75th and the 95th percentile (mild heat) and above the 95th percentile (extreme heat). The effect of low temperatures was defined as the risk of injury for a decline in mean temperature between the 25th and the 5th percentile (mild cold) and below the 5th percentile (extreme cold) of mean temperature. For the same temperature intervals, we also estimated the impact of temperatures in terms of the number of attributable cases, using a methodology previously described [Gasparrini, 2014]. For both effect and impact, 95% Confidence Intervals (CI) were estimated. Effect modification was evaluated by age-category (15–34, 35–60, 60 +), gender, firm-size (defined as number of employees: 0–10, 10–50, 50–250, 250 +), injury's severity (defined as duration of leave: 4–15 days, 15–30, 30–60, 60 +), economic sector and job type. Only sectors and job types that had been previously associated with outdoor temperatures in a literature review conducted by the Authors were selected [Bonafede et al., 2016a].

The analyses were run using R software (version 3.5.2) with the packages *gnm*, *dlnm* and *mvmeta*.

3. Results

In the period 2006–2010, 2,277,432 occupational injuries were reported in Italy and considered in the study. Characteristics of the dataset are provided in Table 1. The numbers of injuries decreased steadily in the considered period for both men and women, as did the gender ratio (M/F), passing from 3.73 in 2006 to 2.95 in 2010. More than half of included injuries are related to workers aged 35–60 years (61% in men and 69% in women). The duration of leave, considered as a proxy of injury severity, was on average < 15 days, without significant gender differences. The majority of injuries (37.9%) occurred in small firms (< 10 employees) according to the industrial Italian context which is characterized by the prevalence of small and medium enterprises.

The geographical distribution of mean daily temperatures for the 5th, 25th, 75th and 95th percentile for each of the municipalities in Italy are shown in Fig. 1. A clear north-south gradient can be seen for heat and cold, with warmer temperatures in the south and colder values in the north. Furthermore, altitude and mountain ranges also create a clear thermal trend with lower percentile values in the Alps in the north and along the Apennines in central areas. At municipal level, the 25th percentile ranges from − 8.8 °C to 13.0 °C, while the 75th percentile ranges from 2.9 °C to 23.4 °C. Temperature extremes (5th and 95th percentile of mean temperature) range between − 16.1 °C and 9.4 °C and between 8.2 °C and 28.7 °C respectively. The relationship between mean daily temperature and work-related injuries is represented by the U-shaped curve in Fig. 2. The curve for Italy is the estimated pooled curve obtained by the meta-regression model, as described in the Methods section. A significant risk of work-related injury can be observed, for heat and cold, as temperatures increase or decrease with different risk gradients as shown by the slope of the curve. The lowest point of exposure-response estimated curve has been identified at 25th percentile of temperature range.

The overall relative risks (RR) of occupational injury for different temperature ranges are shown in Table 2. For mild heat (temperature between 75th and 95th percentile) the RR was equal to 1.07 (95% CI: 1.06–1.08) and 1.09 (95% CI: 1.07–1.12) for extreme heat (higher than 95th percentile). For mild (25th -to 5th percentile) and extreme cold (lower than 5th percentile) the RR were estimated equal to 1.03 (95% CI: 1.02–1.04) and 1.20 (95% CI: 1.15–1.26), respectively. Province level estimates for heat and cold are reported in Supplementary material Table S1. A heterogeneous effect of both heat and cold can be observed across Italy. The lag structure indicates an increase in injury risk

Table 1
Descriptive statistics of occupational injuries in Italy for the period 2006–2010 included in the Italian national workers compensation authority (INAIL) archive. Number of cases by gender, year, age at injury, economic sector of activity, job category, firm size and duration of leave.

Variable	Modality	Men		Women	
		Observed	%	Observed	%
Year of injury	2006	396,325	22.57	106,258	20.38
	2007	385,926	21.98	106,321	20.39
	2008	361,867	20.61	105,096	20.16
	2009	310,277	17.67	101,536	19.48
	2010	301,707	17.18	102,119	19.59
Age at injury	15–34	636,435	36.24	154,119	29.56
	35–60	1,071,466	61.01	357,459	68.57
	> 60	48,201	2.74	9752	1.87
Duration of leave	< 15	836,520	47.64	248,173	47.60
	15–29	371,328	21.15	112,295	21.54
	30–60	273,146	15.55	80,300	15.40
	> 60	231,981	13.21	60,183	11.54
	Not available	43,127	2.46	20,379	3.91
Firm size (n° of employees)	< 10	732,622	41.72	129,714	24.88
	10–49	404,585	23.04	82,877	15.90
	50–250	261,047	14.87	78,745	15.10
	> 250	357,848	20.38	229,994	44.12
Economic sector of activity (selected)	Agri-industry	14,715	0.84	6185	1.19
	Fishing	1450	0.08	83	0.02
	Mining	5867	0.33	124	0.02
	Oil extraction	1236	0.07	33	0.01
	Electricity, gas, water	13,762	0.78	1770	0.34
	Construction	370,409	21.09	3888	0.75
	Transportation	210,199	11.97	41,735	8.01
	Other	1,138,464	64.83	467,512	89.68
Job types (selected)	Asphalter	2158	0.12	6	0.00
	Roadman	2937	0.17	76	0.01
	Electrical mechanic	4292	0.24	150	0.03
	Blacksmith	13,773	0.78	95	0.02
	Servant	12,534	0.71	27,340	5.24
	Installer	9623	0.55	79	0.02
	Warehouse worker	67,554	3.85	7026	1.35
	Operator	3571	0.20	87	0.02
	Mechanic	117,841	6.71	3885	0.75
	Other	1,521,819	86.66	482,586	92.57
Overall		1,756,102	77.11	521,330	22.89

associated with cold temperature on the same days (lag 0), whereas the association with the high temperature remains significant for the following two days (Fig. 3). The attributable number of temperature-linked work-related injuries was 26,054 (5976 for cold and 20,078 for heat, respectively) in the considered period, corresponding to an average of 5211 injuries per year. A total attributable fraction to temperature of 1.14% has been estimated (0.06%, 0.17%, 0.63% and 0.14% due to extremely cold, mild cold, mild heat and extremely heat temperature, respectively).

The RRs of occupational injuries by gender, age, duration of leave, firm size, economic sector and job types for heat (above the 75th percentile) and cold (below the 25th percentile) are reported in Table 3. For heat, a higher risk of injury was estimated among males (RR 1.20, 95% CI: 1.16–1.25), younger workers (RR 1.25, 95% CI: 1.19–1.30 and RR 1.14, 95% CI: 1.10–1.80, for 15–34 and 35–60 years, respectively), and workers employed in small-medium size firms (RR 1.20, 95% CI: 1.15–1.25, RR 1.19, 95% CI: 1.11–1.27 and RR 1.20, 95% CI: 1.10–1.31, for firms with 0–9, 10–49, 50–250 employees, respectively). The opposite was observed for cold, with a larger risk of injuries among women (RR 1.51, 95% CI: 1.35–1.69), older workers (RR 1.80, 95% CI: 1.29–2.50 in the workers older than 60 years) and in workers employed in larger size firms (RR 1.47, 95% CI: 1.27–1.70 for firms with > 250 employees). Construction is the economic sector at higher risk of injuries for exposures to heat (RR 1.30, 95% CI: 1.22–1.38); conversely, transport, fishing, electricity, gas and water and agriculture had a significant risk of injury for cold (RR 1.97, 95% CI: 1.42–2.73; RR 5.70, 95% CI: 2.80–11.58; RR 2.26, 95% CI: 1.15–4.46; RR 2.22, 95% CI: 1.24–3.97, respectively). When considering job types, installers, warehouse workers, operators and mechanics had significant risks of work-related injury when exposed to high temperatures (Table 3).

4. Discussion

The national occupational injuries dataset and the use of high spatial resolution temperature data enabled us to estimate the risk of work-related injuries for exposure to both heat and cold at national level for the first time in Italy.

Considering future climate change, the analyses of temperature impact on occupational injuries risks and the definition of safety policies are crucial and the interest for this topic is increasing. Recently, a countrywide analysis for Spain has been published, including an evaluation of associated economic costs, quantified as 0.03% of the Spanish Gross Domestic Product, equal to 370 million euros per year [Martínez-Solanas et al., 2018]. An estimated attributable fraction of 4.85% of all claims for occupational injuries due to temperature has been reported for the area of Adelaide (South Australia) [Varghese et al., 2019], while the cited Spanish study found a fraction of 2.7% [Martínez-Solanas et al., 2018]. Our study found a lower incidence with an attributable fraction of 1.14%. The overall RRs were found consistent in general with the quoted recent studies, although the respective RRs values cannot directly be compared either for the different metric used or for the different reference of temperatures. A previous study conducted on three Italian cities found similar effect estimates [Schifano et al., 2019]. A recent meta-analysis summarized evidence on extreme temperature exposure and work related injuries [Binazzi et al., 2019]. Furthermore, a positive relationship was found when considering three case-crossover studies [Spector et al., 2016; McInnes et al., 2017; Sheng et al., 2018] and five time-series studies [Xiang et al., 2014; Adam-Poupart et al., 2015; Garzon-Villalba et al., 2016; Martinez-Solanas et al., 2018; Riccò, 2018]. Nevertheless, the limited number of available epidemiological studies and the differences in population size, temperature exposure assessment, work-related injuries reckoning and the different statistical approaches suggest caution in the interpretation of the reported findings.

Our study found a positive association between occupational exposure to outdoor temperatures and work-related injuries, with a significant effect of heat and cold, for both moderate and extreme temperatures. The use of high spatial resolution (1 × 1 km) temperature data allows a better spatio-temporal characterization of worker exposure to outdoor temperature, thus obtaining more accurate effect estimates. In addition, the availability of a long time series of injuries data at national level, enabled us to study workers' vulnerability induced by job type, but also to evaluate geographical differences in effect estimates. The findings suggest a different pattern of risk associated with outdoor temperatures for heat and cold. Young male workers seem to be more vulnerable to occupational injury when exposed to heat, whereas, women and old age workers seem to be more susceptible to an occupational injury when exposed to low temperatures. These results are fully consistent with those also found in Spain [Martínez-Solanas et al., 2018] and with those obtained in Australia for the age at injury [Varghese et al., 2019]. As previously observed, the limited working experience and insufficient training could represent concurrent risk factors for young workers [McInnes et al., 2017]. The inadequate awareness of hazard, particularly for young male workers during hot days, seems to be the most reasonable explanation. This is remarkable from a risk prevention point of view, according to the opportunity of defining training and labour organizational measures for risk reduction.

Our findings provide an insight on the role of firm size in occupational injury due to outdoor extreme temperatures for the first time in

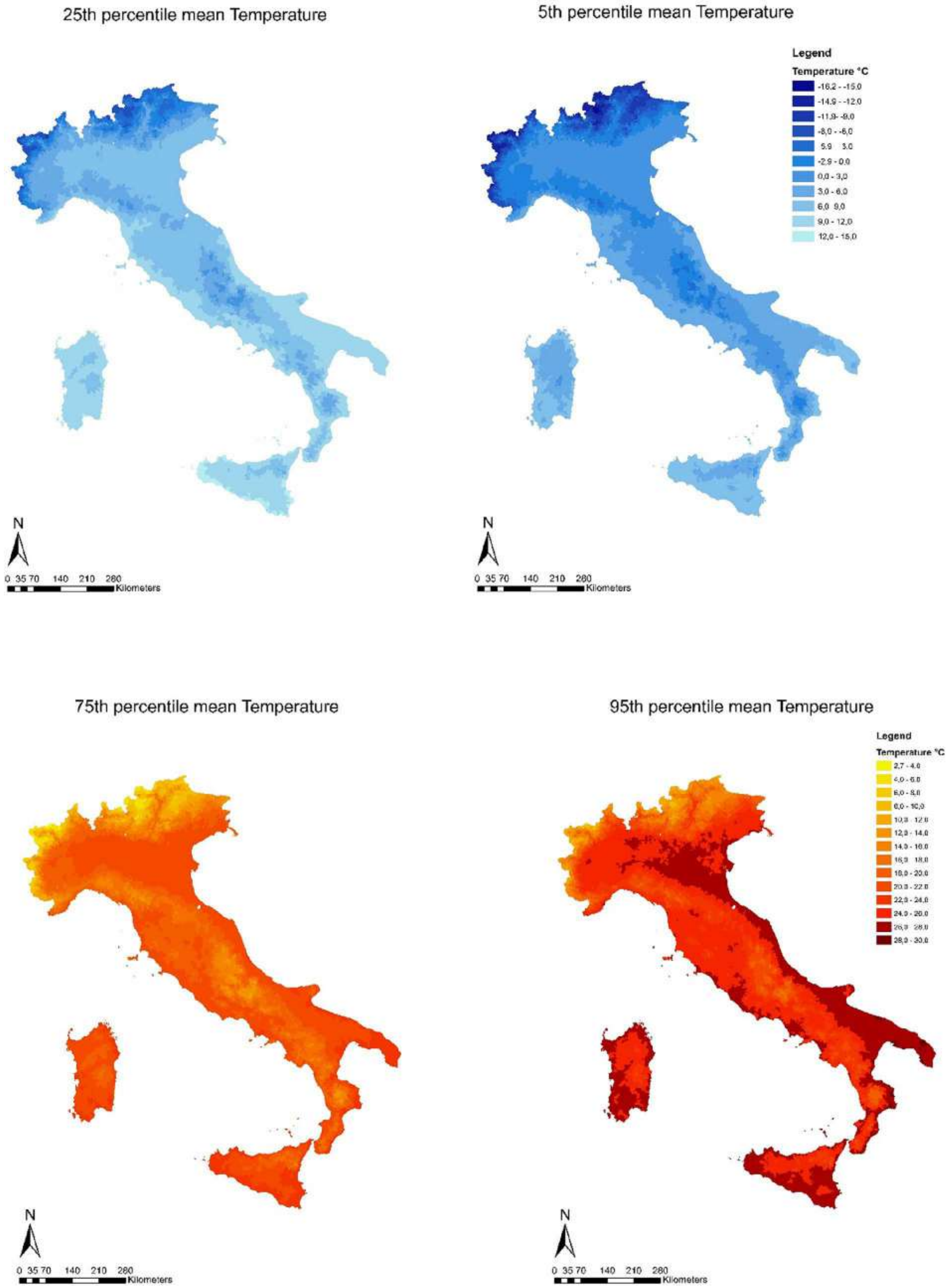

Fig. 1. Maps of 5th, 25th, 75th and 95th mean daily temperatures for each municipality in Italy during years 2006–2010.

Europe. The risk of injury linked to heat and cold is very different. Workers in large firms (> 250 employees) present a lower risk of injury for heat compared to workers employed in smaller firms. This finding somewhat contrasts results from an Australian study which estimates a higher risk [Varghese et al., 2019]. Conversely, for cold, the risk of injury was the highest in large firms. It has been repeatedly

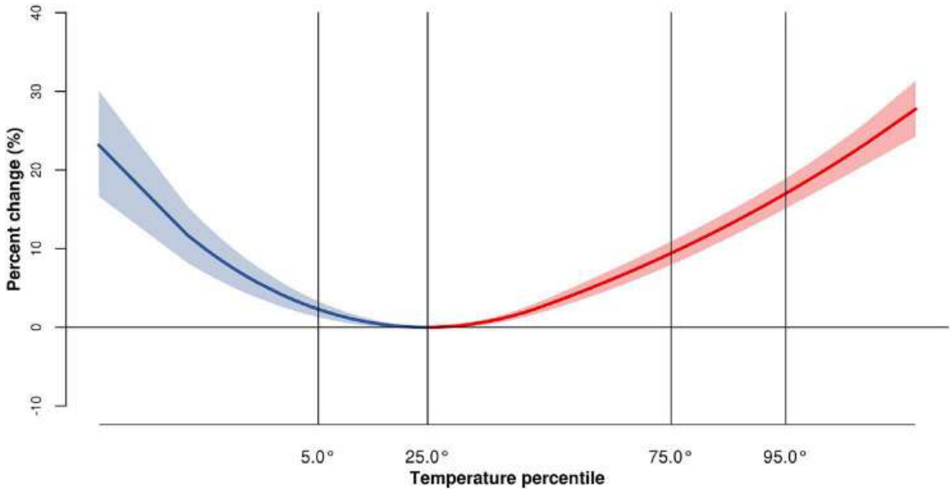

Fig. 2. Dose-response relationship. Percent change in work related injuries by temperature percentile. Blue and red areas correspond to cold and hot temperature effects. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

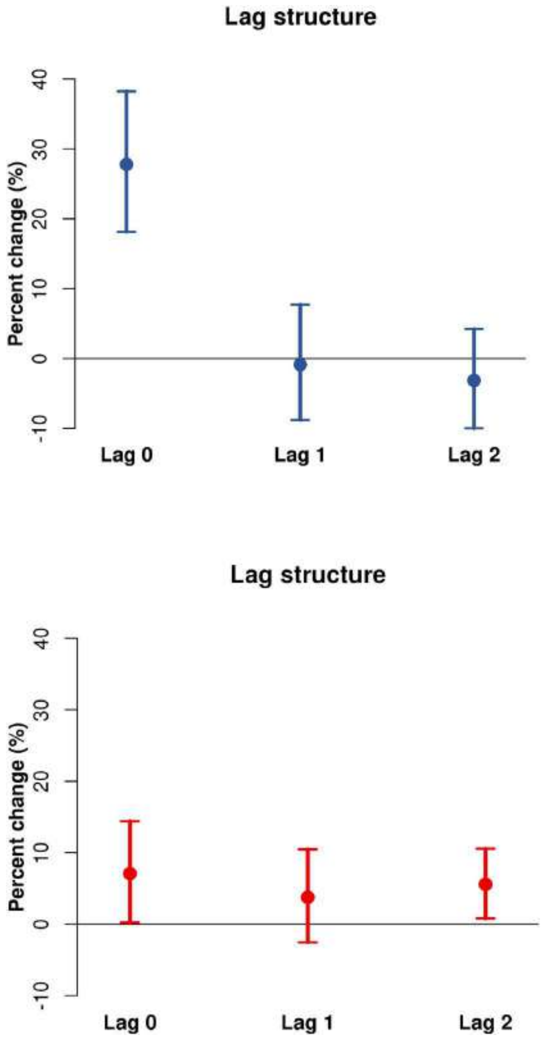

Fig. 3. Lag specific effects for the overall cumulative exposure-response relationship between outdoor temperature and occupational injuries for cold effects (a) and heat effects (b). Italy, 2006–2010.

Table 2
Relative Risks (RRs, 95% CI) in work related injuries and attributable number of injuries for heat and cold, by temperature percentile ranges.

	RR (95%CI)	Attributable number of injuries (95%CI)
Cold (< 25° percentile)	1.23 (1.17–1.30)	5976 (779–11,040)
Extreme cold (< 5° percentile)	1.20 (1.15–1.26)	1600 (501–2641)
Mild cold (5°–25° percentile)	1.03 (1.02–1.04)	4376 (278–8399)
Heat (> 75° percentile)	1.17 (1.14–1.21)	20,078 (13,042–26,924)
Extreme heat (> 95° percentile)	1.09 (1.07–1.12)	3725 (2012–5393)
Mild heat (75°–95° percentile)	1.07 (1.06–1.08)	16,353 (11,030–21,531)

demonstrated that workers in small enterprises have higher frequency of work accidents [Fabiano et al., 2004] and a poorer level of security performance [Sørensen et al., 2007]. Furthermore, employers in small firms resulted less confident of the usefulness of occupational prevention measures [Bonafede et al., 2016b]. Niskanen and colleagues have discussed the lower capacity to invest in health promotion, and limited monitoring injuries and absence from work in small enterprises [Niskanen et al., 2012]. Our findings appear coherent with the evidence on work related injury for heat exposure, whereas the increased risk in large size firms for exposure to cold could be related to the absence of adequate prevention and hazard awareness of both workers and employers: therefore, further investigation is need. This study also identified specific job types at higher risk, particularly for heat. However, these results should be taken with caution, as the information was quite generic in the INAIL archives and possible misclassification might exist.

Our results show a non-linear relationship between outdoor temperature and work-related injury in Italy, showing an association for both cold and heat, as previously shown in other Mediterranean areas [Morabito et al., 2014; Martínez-Solanas et al., 2018; Riccò, 2018]. The effect of cold is immediate (lag 0), while the effect of heat is observed up to 2 days after exposure: both are consistent with the results obtained in Spain [Martínez-Solanas et al., 2018]. The increased risk of injury in the transport sector without temporal delay during cold days could be interpreted in the light of the correlation between extreme cold weather and dangerous roads status [Bergel-Hayat et al., 2013; Malyshkina et al., 2008].

This study has also several limitations. The agriculture sector has not been included in the analyses, although the relevance of the risk of

Table 3
Relative Risks (RRs, 95% CI) of work related injuries for heat and cold by gender, age at injuries, duration of leave, economic sector of activity, job category and firm size.

Variable	Modality	Observed	Cold effects (< 25° percentile)	Heat effects (> 75° percentile)
		n	RR (95%CI)	RR (95%CI)
Gender	Men	1,756,102	1.16 (1.09–1.23)	1.20 (1.16–1.25)
	Women	521,330	1.51 (1.35–1.69)	1.08 (1.02–1.14)
Age at injury (years)	15–34	636,435	0.98 (0.89–1.07)	1.25 (1.19–1.30)
	35–60	1,071,466	1.35 (1.25–1.46)	1.14 (1.10–1.80)
	> 60	48,201	1.80 (1.29–2.50)	0.91 (0.78–1.08)
Duration of leave (days)	< 15	836,520	1.02 (0.94–1.11)	1.22 (1.18–1.27)
	15–29	371,328	1.43 (1.27–1.61)	1.13 (1.07–1.19)
	30–60	273,146	1.36 (1.21–1.53)	1.14 (1.07–1.21)
	> 60	231,981	1.54 (1.32–1.80)	1.07 (0.99–1.16)
Firm size (n° of employees)	< 10	732,622	1.11 (1.02–1.21)	1.20 (1.15–1.25)
	10–49	404,585	1.24 (1.09–1.42)	1.19 (1.11–1.27)
	50–250	261,047	1.22 (1.03–1.46)	1.20 (1.10–1.31)
	> 250	357,848	1.47 (1.27–1.70)	1.06 (1.00–1.18)
Economic sector of activity (selected)	Agri-industry	14,715	2.22 (1.24–3.97)	1.14 (0.88–1.46)
	Fishing	1450	5.70 (2.80–11.58)	0.66 (0.18–2.36)
	Mining	5867	2.29 (0.74–7.10)	0.84 (0.46–1.53)
	Oil extraction	1236	3.42 (0.48–24.32)	0.78 (0.34–1.78)
	Electricity, gas, water	13,762	2.26 (1.15–4.46)	1.18 (0.80–1.73)
	Construction	370,409	0.81 (0.64–1.02)	1.30 (1.22–1.38)
	Transportation	210,199	1.97 (1.42–2.73)	1.11 (0.96–1.30)
Job types (selected)	Asphalter	2158	0.67 (0.18–2.50)	1.03 (0.42–2.52)
	Roadman	2937	1.05 (0.36–3.07)	2.10 (0.91–4.84)
	Electrical mechanic	4292	1.30 (0.43–3.92)	1.95 (0.98–3.88)
	Blacksmith	13,773	0.75 (0.35–1.57)	1.01 (0.60–1.69)
	Servant	12,534	1.69 (0.96–2.98)	1.09 (0.84–1.40)
	Installer	9623	0.66 (0.21–2.11)	1.73 (0.95–3.17)
	Warehouse worker	67,554	0.95 (0.57–1.61)	1.46 (1.13–1.90)
	Operator	3571	1.67 (0.45–6.12)	1.76 (1.16–2.65)
	Mechanic	117,841	1.05 (075–1.49)	1.33 (1.14–1.56)

occupational injury for agriculture workers in hot season was observed for both men and women [Martínez-Solanas et al., 2018]. Non-registered seasonal agricultural workers, mainly working immigrates, could not be considered in this study, as no compensation claims were produced. Recently, the role of socio-cultural conditions in the risk of occupational injuries, and stress perception for migrant workers during heat waves, has been shown and discussed [Riccò et al., 2019; Messeri et al., 2019]. A future prospective of our research is to carry out a specific analysis of injuries in agriculture using the high resolution temperature data for all Italian rural areas. The same applies to workers covered by insurance agencies other than INAIL, but this is a smaller proportion and restricted to some specific sectors. Nevertheless, nationwide compensation work-related injury claims provide a reliable source of data on occupational health.

The present study considers only outdoor exposure without taking into account indoor effects, or the combined effect, which could provide additional insights on subgroups of workers most at risk for exposures to extreme temperatures. Furthermore, there might still be some exposure error as we are considering a mean exposure value for all subjects and not individual exposures. Such information was clearly not available and, considering the sample size, it would have been a demanding task. Exposure assessment by the means of personalised temperature and physiological indicators measurement has been indicated as the remarkable direction for future research [Kuras et al., 2017].

Although biological mechanisms explaining the association between extreme temperature exposure and occupational injuries are complex, it appears ascertained that thermal discomfort can resolve in carelessness, fatigue, lack of alertness, loss of concentration, disorientation and reduced vigilance and it is not disputable that these conditions during working activities contribute to increase the risk of injury [Varghese et al., 2018]. The complexity of biological mechanisms contributed to make difficult to identify the role of extreme temperature in the injuries risk at workplace: indeed, epidemiological methods to indirectly estimate the extent and the modalities of the association are required."

In conclusion, our study provides valuable estimates on the risk of injuries among workers for exposures to heat and cold at national level, which can be used by policy makers and stakeholders to develop prevention measures and raise awareness to the risk related to current and future extreme weather events. The identified pattern of subgroup at high risk could help to guide regulators and governments for developing targeted injury prevention measures. Forecast scenarios of climate change suggest considering the prevention of occupational exposure to extreme outdoor temperature a priority in occupational safety and health field.

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Article

Heat Stress Perception among Native and Migrant Workers in Italian Industries—Case Studies from the Construction and Agricultural Sectors

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Abstract: Climate change will increase the frequency and severity of hazard events such as heat waves, with important effects in several European regions. It is of importance to consider overall effects as well as specific impact on vulnerable population groups such as outdoor workers. The agricultural and construction sectors represent two strategic occupational fields that in relatively recent years involve an increasing number of migrant workers, and therefore require a better management of cultural aspects, that may interact with and impact on heat-related health risk. For this reason, the present study evaluated heat-stress perception and management among native and immigrant workers in Europe. As part of the EU's Horizon 2020 HEAT-SHIELD project (grant agreement No. 668786), two agricultural and one construction companies, traditionally employing migrant workers, were evaluated with a questionnaire survey during the summer months of 2017. The data collected (104 case studies) were analyzed using descriptive statistics (Chi-squared tests) and the analysis of variance was performed with ANOVA test. From the results, migrant workers declared that work required greater effort than do native Italian workers (χ^2 = 17.1, p = 0.001) but reported less impact from heat on productivity (χ^2 = 10.6; p = 0.014) and thermal discomfort. In addition, migrant workers were mainly informed through written or oral communications, while native workers received information on heat-health issues through training courses. These findings are of importance for future information and mitigation actions to address socio-cultural gaps and reduce heat-stress vulnerability.

Keywords: migrant; heat waves; heat perception; Wet Bulb Globe Temperature (WBGT); Universal Thermal Climate Index (UTCI); occupational risk

1. Introduction

Numerous studies have documented that the human-induced climate change has increased the frequency and severity of hazard events such as heat waves across the globe and recent studies evidenced that several areas of Europe are at high risk [1–4]. In particular, besides the Mediterranean region, several Western European regions and the Balkans could see increases of heat wave intensity in the 21st century [5–7]. The greater intensity and persistence of heat stress conditions to which the population will be subjected, therefore, urgently requires the implementation of efficient heat-related adaptation strategies, with particular attention to the most vulnerable population groups. Workers represent an important part of the population potentially at high-risk of heat exposure for many easily understandable reasons, with potential consequences for their health and work productivity [8,9]. Occupational exposures to high temperatures without sufficient protection may also increase the risk of heat-related illnesses and injuries [10], in particular for outdoor workers. Agriculture and construction sectors are the most exposed and are characterized by a high number of migrant workers with cultural aspects (religious, linguistic, adaptation) that contribute to further increase the risk [11].

Cultural aspects related to the ethnicity in workplaces represent certainly very important heat-related occupational vulnerability factors, even if, at the moment, they have not been investigated in depth. In particular, only a few studies have specifically addressed the issue of different cultural aspect related to the ethnicity, as a risk factor for heat-related human health [12] clearly indicating a knowledge gap which needs to be addressed in the face of climate change. An ethnic group is a category of people who identify with each other based on similarities such as common ancestry, history, country of origin, language, religious grounds, society or cultural tradition [13]. This aspect is of great importance given that, in many countries, specific occupational sectors prevalently involve migrant workers. In the past decade, in Italy, the presence of migrant workers increased by 80%: specifically, an increase from 1.4 million units in 2007 to 2.4 million was observed in 2016, when the number of Italian employees decreased by about one million units [14]. Moreover, the global economic crisis that also affected our country since the beginning of this century, further worsened the conditions of migrant workers, generally employed in precarious, laborious and risky, manual, low-tech and unskilled jobs, summarized as 3Ds jobs (dangerous, dirty and demanding/degrading work) that Italians are reluctant to perform [15]. In 2016, in Italy, positively assessed work injuries involved more than 61,000 migrant workers (15% of the total), of which more than 45,000 occurred to non-EU citizens (−14.4% compared to 2012) and about 16,000 to Community workers (−18.3%). The majority of the injured workers from the European Union come from Romania (61.3% in 2012–2016), while Moroccan (16.5%) and Albanian workers (13.4%) are the most affected non-EU citizens [16].

Despite growing attention by public opinion and companies on heat-related risks for workers' health and safety, individual risk perceptions [17] constitute an important variable for illness and injuries prevention.

At European level, the ongoing HEAT-SHIELD project (https://www.heat-shield.eu/) has the mission to investigate the negative impacts of workplace heat-stress perception on health and productivity of workers employed in five strategic European sectors (tourism, agriculture, manufacturing, construction and transportation), with the aim to develop preventive solutions to protect the health and productivity in the work place from excessive heat. For this reason, in Italy, since summer 2017, some case studies have been organized, gathering information on topics related to the heat-stress perception and management collected through the submission of questionnaires to native and migrant workers employed in the agricultural and construction sectors. There is currently no information available on this topic, even if a significant increase in cultural diversity in the work population has been observed and, during periods of extreme heat, there may be disparities in the adaptive capacity of minority groups [18,19]. The main aim of this study is to investigate how cultural aspects can influence heat-stress perception and management among native and immigrant workers, in order to inform health care decision making aimed at reducing socio-cultural gaps and their influences on heat-stress vulnerability.

2. Materials and Methods

The study was carried out in Central Italy, in an area located to the south-west of the Apennine mountains and particularly, in the plane and low hill of the Provinces of Florence and Pistoia (Tuscany). This area is characterized by a sub-Mediterranean climate with hot and dry summer. As part of the HEAT-SHIELD project (European Union's Horizon 2020 grant agreement No. 668786), the Italian partners selected some companies involved in the agricultural and construction sectors. The companies' recruitment was carried out after a series of meeting with local stakeholders, including health authorities, trade unions, employers' associations and associations of professionals responsible for control and vigilance within the work places.

Three companies of the agricultural and construction sectors, traditionally employing migrant workers, were identified, which also showed extreme interest in participating in the survey:

Palagio farm, operating in the wine and olive oil sectors since 2000, located in the municipality of Figline Valdarno (Florence Province). The estate has an extension of about 350 hectares and 18 farm workers involved in June and July are particularly busy in the pruning and lacing of the vines while from the middle of August and until the end of September they harvest grape. The daily working time is from 8:00 a.m. to 5:00 p.m., with 1-h lunch break, and no change in working hours is foreseen during the summer.

Oscar Tintori farm deals with the cultivation of citrus fruits in the greenhouse since 1970. The company is located in Pescia (Province of Pistoia) and it is divided into two units distant about 2 km from each other: the sale point and the area dedicated to crops. The organization of the company provides 12 workers employed in greenhouse activities and their daily working time during the summer is rescheduled (shifted by 2 h): from 6.00 a.m. to 2:00 p.m., with 1-h lunch break.

Temporary business associations set up for the construction of the tramway in Florence (Grandi Lavori Fincosit, Trafiter and Alstom). More than 300 construction workers were involved in the construction of the tramline on a large area of about 10 km in length and in one of the most urbanized areas of the city. During the summer period the daily working time is shifted by 1-h, starting work at 7:00 a.m. and finishing at 3:00 p.m.), with 1-h lunch break.

2.1. Workers Recruiment

The recruitment of workers to be involved in the study was carried out on a voluntary basis. All workers of the selected companies were given the opportunity to take part in the study, leaving free choice of adhesion to every single worker. The ethics committee of the University of Florence provided consent to conduct the questionnaire/data collection and analyze participants' data. The ethics committee authorized the process of the worker's personal data based on the Italian Legislative Decree 30.6.03 n. 196 of the Privacy Code. Each worker signed an informed consent in which the project aims and the workers 'commitments required for the study were described.

2.2. Heat-Shield Questionnaire

A self-administered questionnaire survey (see Supplementary Material) was carried out in the summer months of 2017 in order to collect information on workers' risk perception of heat stress in the workplace and possible productivity losses due to extreme heat. The survey (Annex 1) was an adapted version of the original one developed by Kjellstrom et al. within the "Hothaps programme", a multi-centre health research and prevention programme aimed at quantifying the extent to which working people are affected by, or adapt to, heat exposure in the workplace, and climate change role in increasing such effects [20]. The original version was also used also by Dutta et al. to characterize the effects of heat on construction workers from a site in Gandhinagar, India [21]. The estimated time to complete the questionnaire was around ten minutes. The questionnaire is divided into 3 sections including the physiological characteristics of the subject, the information about the work activity performed and the workers' heat perception.

In addition, safety measures to protect against extreme heat were assessed by asking workers to indicate whether any leaflet publications, information sessions or training sessions are available in the workplace, and their level of satisfaction regarding safety measures in place. The answers could vary on a four-point scale from “not at all satisfied” to “extremely satisfied”; in addition, the “unsure” answer option was also available.

For the purpose of the present study, only sections related to workers’ socio-cultural, educational and occupational context, to workers’ perception of heat stress and productivity losses due to extreme heat and to safety measures adopted in the workplace were taken into consideration in the statistical analysis.

2.3. Environmental Monitoring and Heat Stress Assessment

In each company, during the 2017 summer season, a microclimatic monitoring was carried out through the installation of a complete weathers station (HOBO U30 NRC) able to measure air temperature (°C), relative humidity (%), atmospheric pressure (hPa), black globe temperature (°C), wind speed (ms^{-1}) and solar radiation (W/m^2). In particular, the black globe temperature was measured inside a 150 mm diameter black globe (with emittance equal to 0.95) inside which a temperature sensor (pt100) is positioned and validated by the comparison with a standard WBGT heat stress monitor instrument. The shape, the size and emissivity of this globe are chosen so as to simulate the human body and the relative convective and radiative exchanges with the surrounding surfaces. In outdoor environments, radiative exchanges depend on solar radiation (direct and diffuse) and on the heat flow emitted by radiation from surfaces at a given temperature. The solar radiation was measured by silicon pyranometer sensor that offers a measurement range of 0 to 1280 W/m^2 over a spectral range of 300 to 1100 nm. Wind speed was measured by a “Wind Speed Smart Sensor” that provides data reporting average wind speed (from 0 to 76 m/s) and highest 3 s gust for each logging interval. Air temperature and relative humidity was measured by a 12-bit Smart Sensor (temperature range −40 °C to 75 °C).

These data were used to evaluate thermal stress conditions in the workplaces. Two biometeorological indicators, the Universal Thermal Climate Index (UTCI) [22] and the Wet Bulb Globe Temperature (WBGT) [23,24] index was assessed. In particular, WBGT was calculated using the heat stress calculation tool provided by the Climate Chip (Climate Change Health Impact & Prevention) web-platform (http://www.climatechip.org/), instead the UTCI was calculated by using the UTCI software code “version a 0.002”, freely available online (http://www.utci.org/). Both indices were calculated using the microclimatic parameters measured by the weather station.

The UTCI represents the state-of-the-art of thermal-stress assessment, while the WBGT is a thermal stress indicator specifically used for the working environment and that allow to provide useful suggestions on the work-rest scheduling. In particular, the WBGT index represents a reference standard used by international organizations involved in the protection of workers’ health [24–26], and also for this reason this index was selected as a reference in the European project HEAT-SHIELD.

It is however important to consider that both indices are expressed in °C but, because different methodologies were adopted to develop these biometeorological indicators, different heat-stress scales represent the results of these indexes, higher for UTCI than WBGT.

2.4. Statistical Analysis

This study analyzed data of 104 case studies conducted during summer 2017 (from May to September). Within 3 companies in Central Italy, a monitoring on critical and non-critical summer days, that covered environmental, behavioral and perception parameters, was carried out.

The data collected were analyzed using descriptive statistics (frequency, mean, standard deviation) and analytical tests. Chi-squared tests were used to determine the association between the nationality and some variables related to the perception of heat and effort. The statistical significance of differences in mean scores by nationality was calculated using ANOVA test. Missing data were used only in descriptive analysis, not in statistical tests. All analyses were performed by using SPSS version 22.0 [27]. The statistical significance was set at $p < 0.05$.

3. Results

3.1. Microclimate and Heat Stress

The environmental monitoring has shown average values of air temperature during the typical working time (from 8.00 a.m. to 5.00 p.m.), ranging between 14.5 °C and 36.5 °C (dashed line in Figure 1).

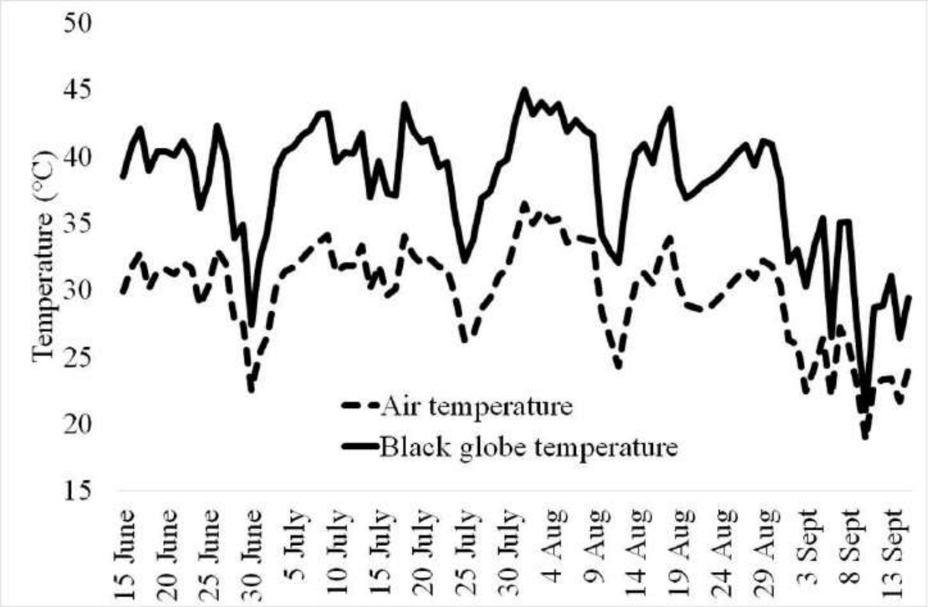

Figure 1. Air temperature (continuous line) and black globe temperature (dashed line) measured during the working time of the day (8:00 a.m.–5:00 p.m.) in the three work sites involved in the study during the summer 2017.

During the studied period, well-defined periods with a persistent daily average air temperature above 32 °C were clearly identified, corresponding to four heat waves that affected a large part of southern Europe, including the Tuscany region, during the summer season of 2017. Black globe-temperature values (continuous line in Figure 1), which take into account the radiative contribution, were always higher than air temperatures, with peaks near 45 °C in the first ten days of August. In Figure 2, the average and maximum monthly values of WBGT during the working time were shown together with the recommended rest times in the hour according to the WBGT ISO standard [25,26].

The highest thermal stress UTCI values were recorded in August (41.8 °C), while the lowest values in September (32.3 °C). Considering a worker who performs an activity that requires an average effort of 300 watts, the ISO standard WBGT would have required an average break of 30 min in August, instead no breaks during working hours would be necessary in September. As for the months of June and July, the maximum UTCI during working hours was close to 40°C (39.6 °C and 40.8 °C respectively) and would have required an average break of 15 min per hour. If, on the other hand, daily mean values are taken into account, the heat stress value calculated according to the WBGT ISO standard would not require rests despite the equivalent temperature identified according to the UTCI index identifies a heat stress level. This is because the average value causes information about the worst conditions that occurred during the day to be lost. In practice, the highest WBGT values that occur during the central hours of the day are averaged with WBGT values recorded in the early morning hours, thus providing an average value that tends to underestimate the conditions that actually occur in the warmest hours.

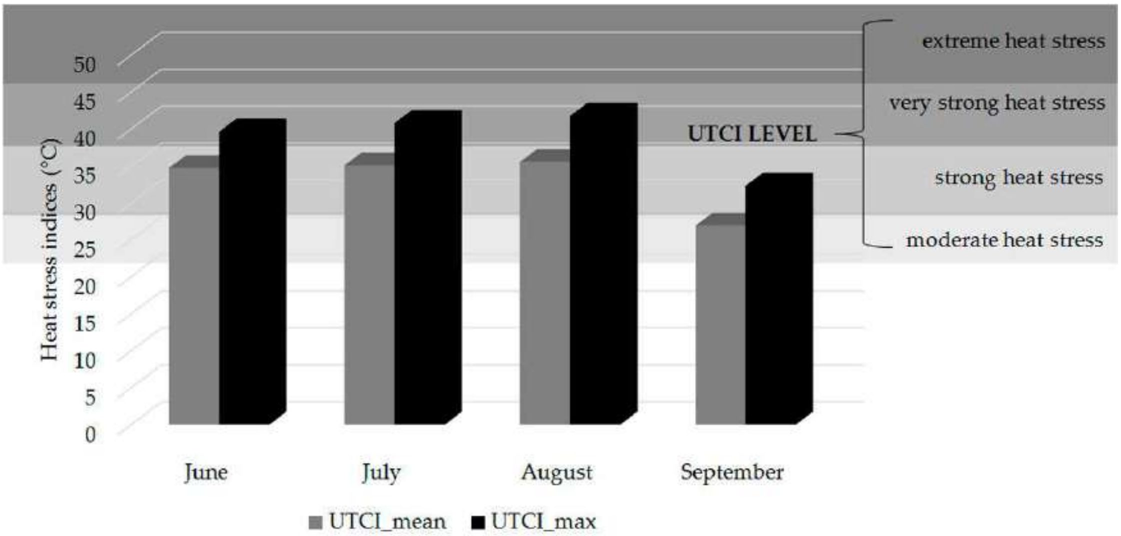

Figure 2. Mean and Maximum Universal Thermal Climate Index (UTCI) index for each month during the working time at the three work sites involved in the study (summer 2017) and the recommended rest according to the WBGT ISO standard for a worker that perform an activity that requires an effort of 300 watt. The bands of different shades of gray indicate instead the heat stress thresholds according to the Universal Thermal Climate Index (UTCI).

Figure 3 shows WBGT values (maximum and mean) and the risk thresholds that required a behavioral modification to counteract the heat stress according to the American Conference of Governmental Industrial Hygienists (ACGIH) for acclimatized workers engaged in moderate (300 W) and high (400 W) work efforts. It is clearly evident that most of the average thermal conditions monitored during the studied period required behavioral actions for a worker involved in high work efforts, while for moderate activities actions were generally required if workers were exposed to the maximum thermal stress conditions (Figure 3).

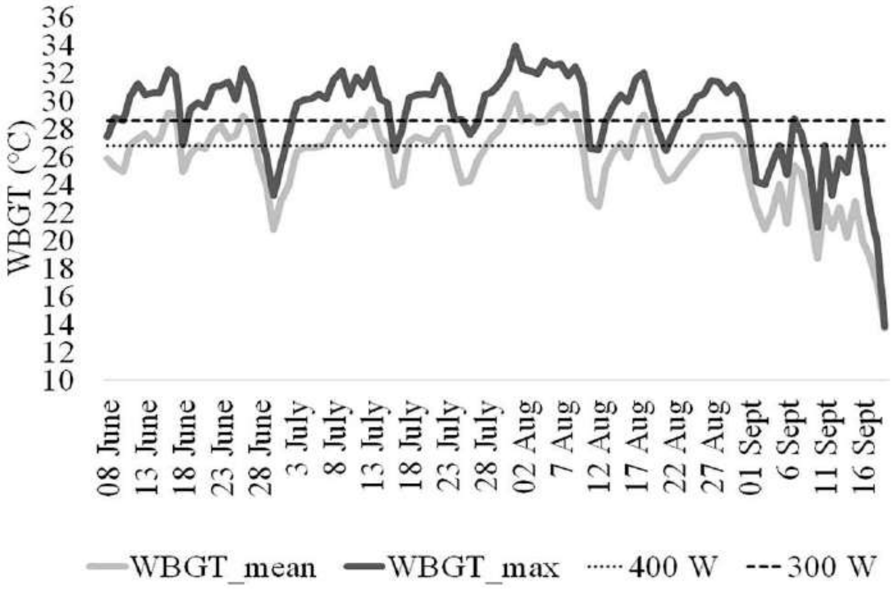

Figure 3. Mean and maximum daily Wet-Bulb Globe Temperature (WBGT) index during the working time of the day at the three work sites involved in the study, summer 2017. The dashed lines represent the WBGT ISO standard thresholds respectively for a high (400 W) and a moderate (300 W) work effort as declared by the native workers.

3.2. Differences between Native and Migrant Workers

The total number of workers in the selected companies was 330 and among them, those who agreed to participate in the study, were 104 (96 men and 8 women) from 3 Tuscan companies: two in agriculture sector (outdoor, n = 16; greenhouse, n = 10), and one in construction sector (outdoor, n = 78). Table 1 shows the distribution of workers by place of birth and sector.

Table 1. Workers by birth place and sector.

Workers		Agriculture	Construction	Total
Birth place	Italy	17	49	66
	Albania	2	22	24
	Romania	4	3	7
	Moldova	1	2	3
	Morocco	1	1	2
	Germany	1	1	2
	Total	26	78	104

Among migrants, the largest group (n = 22) consists of the Albanian workers employed in the construction sector.

The average age of participants was 46.7 years (*SD* = 9.6) for native, and 41.8 (*SD* = 6.5) for migrant workers (Table 2).

Table 2. Sample characteristics and statistical associations.

Workers		Native Workers		Migrant Workers			
		n [a]	% [b]	n [a]	% [b]	χ^{2} [c]	p [d]
Gender	Male	60	90.9	36	94.7	0.498	0.481
	Female	6	9.1	2	5.3		
Age groups	≤39	18	27.3	14	36.8	11.818	0.003
	40–49	20	30.3	20	52.6		
	≥50	28	42.4	4	10.5		
Level of education	Apprenticeship	1	1.5	2	5.3	6.04	0.11
	Trade school	2	3.0	5	13.2		
	Secondary	37	56.1	17	44.7		
	Higher secondary	13	19.7	12	31.6		
	Missing	13	19.7	2	5.3		
Income	Below the average of the work country	2	3.0	0	0.0	3.053	0.217
	Within the average	19	28.8	9	23.7		
	Above the average	0	0.0	1	2.6		
	Missing	45	68.2	28	73.7		
Seasonal worker	Yes	7	10.6	1	2.6	2.643	0.104
	No	50	75.8	36	94.7		
	Missing	9	13.6	1	2.6		
Type of industry work environment	Agriculture outdoor	9	13.6	7	18.4	9.233	0.01
	Agriculture greenhouse	8	12.2	2	5.3		
	Construction	49	74.2	29	76.3		

[a] Number of workers for each category; [b] Percentage of workers for each category; [c] Chi-squared test value; [d] p value significance.

In terms of age, the largest age group was of that of workers over 50 years for natives (n = 28, 42.4%) and the one between 40 and 49 years old for migrant workers (n = 20, 52.6%). There were

18 natives and 14 migrants aged less than 39. Most of both natives ($n = 50$; 87.7%) and migrants ($n = 29$; 80.6%) had a middle or high school diploma. Most claimed that their income was in line with the one of the companies in same sector (19 natives, 28.8%, 9 migrants, 23.7%) and were not seasonal workers (50 natives and 36 migrants).

As shown in Table 3, which compares the scores assigned to different items by nationality based on the Chi-square test, compared to native workers, migrant workers reported a higher physical effort ($\chi^2 = 17.1$, $p = 0.001$).

Table 3. Chi-squared analysis results of the first part of the questionnaire submitted to workers.

Question	Answer Options	Native Workers		Migrant Workers			
		Mean	*SD* [a]	Mean	*SD* [a]	χ^2 [b]	*p*
How physically demanding is your job?	Light (1)–Moderate (2)–Heavy (3)–Very heavy (4)	2.58	0.767	2.93	0.815	17.129	0.001
How do you perceive the temperature while working during heat waves?	Neither warm nor cool (1)–Slightly warm (2)–Warm (3)–Hot (4)–Very hot (5)	4.31	0.731	4.06	0.719	13.924	0.008
Do you notice that you are less productive during a heat wave (e.g., you need more energy for the same work)?	No (1)–Yes, for less than 10% (2)–Yes for 10% to 30% (3)–Yes, for more than 30% (4)	2.43	0.708	2.17	0.814	10.57	0.014
Have you ever been informed by your employer or adviser how to act during heat waves?	No (1)–Yes, through written and oral news (2) –Yes, through safety courses (3)	2.64	0.496	2.32	0.658	21.15	<0.001
Do you receive warnings and advice from your employer or adviser during heat waves?	No (1)–Yes (2)	1.75	0.4	1.67	0.5	0	0.994
Are you satisfied or dissatisfied with measures currently adopted in your workplace for reducing the effects of heat?	Dissatisfied (1)–Undecided (2)–Satisfied (3)–Strongly satisfied (4)	3.4	0.827	3.5	0.641	39.581	<0.001

[a] Standard deviation; [b] chi-squared test value; [c] *p* value significance.

In particular, most of them declared a high effort while, on the contrary, natives declared a moderate effort. On the basis of perceived and declared physical exertion, migrant workers reached the heat risk threshold (WBGT $\geq$ 27.9 °C) more easily than native workers (WBGT $\geq$ 29.3 °C) in the period May–September 2018. This result is observed in terms of both maximum and average WBGT values (Figure 3).

The heat perceived during work in the presence of a heat wave was however greater for native workers ($\chi^2 = 13.9$; $p = 0.008$), as well as the perception of the decline in productivity ($\chi^2 = 10.6$; $p = 0.014$). Most of workers (60%) that did not experience a loss of productivity were migrant. Native workers also reported to become more informed about the behaviors to be adopted during heat waves through safety courses (65% of natives) compared to migrant workers ($\chi^2 = 21.15$; $p = <0.001$). This latter, instead, declared to have been more informed through written (18.4%) or oral news (34.2%). Only 5.3% answered that they were not informed, 1 native and 4 migrants. However, migrant workers claim to be more satisfied than Italian workers with measures currently adopted in their workplace for reducing the effects of heat ($\chi^2 = 39.58$; $p = <0.001$). There is no statistically significant association between nationality in receiving advises when heat waves are in progress ($\chi^2 = 0$; $p = 0.994$).

The results of ANOVA test (Table 4) showed a significant difference between native and migrant workers in terms of the number of years they have been working in that sector ($p < 0.001$).

In addition, a significant difference was observed between natives and migrants regarding the number of hours worked outdoors in the summertime ($p = 0.01$). The number of hours (on average) worked indoor in the summertime is also different ($p < 0.01$).

Table 4. ANOVA analysis results.

Question	Native Workers		Migrant Workers			
	Mean	***SD*** [a]	**Mean**	***SD*** [a]	***F***	***p*** [b]
How many years have you been working in this sector?	19.24	9.427	12.62	5.445	44.737	<0.001
How many hours per day do you usually (on average) work outside in the summertime?	5.23	3.835	6.31	3.246	6.732	0.01
How many hours per day do you usually (on average) work outdoor in the summertime?	2.9	3.789	1.74	3.281	6.861	0.009

[a] Standard deviation; [b] *p* value.

4. Discussion

This study represents one of the first to assess how heat-stress perception in work place is influenced by socio-cultural aspects. Knowledge of the working conditions and occupational health of immigrant and ethnic minorities is important for initiating preventive and integrational efforts. The interviewed migrants in this study declared to carry out works that require greater effort than do native workers, it's consistent consistently with the representation of immigrants in low-skilled, high-risk manual jobs [28]. Immigrants tend to be healthier upon arrival than natives, although this health advantage declines over time [29], therefore might hold more physically strenuous jobs than natives. These physically strenuous jobs are prevalent in sectors like construction, meatpacking, and agriculture [30]. Indeed, migrant workers are also on average younger and with less work experience in the specific sector, and in addition, during summertime, they usually work outdoors more hours per day [31]. Furthermore, the different perception of job risk, linguistic barriers and cultural factors that reduce the effectiveness of any training, make migrant workers probably less able to negotiate the type of tasks they perform than native workers [32]. However, migrants claim to perceive less heat and to experience a lower productivity drop compared to native workers. This is probably because migrants have a higher heat tolerance threshold or a poorer perception of health risk, although the social desirability bias cannot be excluded: the greater job insecurity experienced by migrant workers might have influenced the answers provided [18,32].

An important dimension of job quality is related to occupational health and safety system in place. A relevant result of this study is related to the information and training provided by employer or adviser during heat waves on how to carry out work activities. Migrant workers claim to mainly be informed through written or oral communications, while native workers mainly through training courses. As for migrant workers, the difficulty in understanding the language is an important factor in the perception of the heat risk in the workplace, our results suggest the need to implement measures specifically targeting migrants. In particular, health and safety training, taking into account language difficulties, cultural and religious aspects, should be promoted in sectors where migrants are more widely employed [12,31]. Particular attention should also be paid to encourage the use of personal protective equipment and, if possible, realized with materials that do not increase the heat perception. Moreover, the results show that migrants are more satisfied than native workers with measures adopted in their workplace for reducing the heat effects. The greatest satisfaction could be explained by previous experiences made by migrant workers in their countries of origin with health and safety systems worse than the native one. Special measures to increase awareness of safety rights in the workplace, especially in sectors with a high level of injury and lower perception of risk, are also required [31].

The main strength of this study is that it is the first attempt to investigate heat related perception from the perspective of workers through self-completion questionnaires. It is important to understand workers' perceptions of extreme heat exposure in workplace, as this information may provide evidence for updating heat prevention strategies to reduce the impact of climate change on workers' health and safety. The prevention strategies also include the creation of specific behavioral guidelines for the working sector, calibrated for the different occupational sectors. Within these, particular importance should be given to maintaining a good level of hydration of the subject, not only during the performance of the work activities but also outside of working hours, taking up many liquids and foods with high water content and rich in mineral salts such as fruits and vegetables, [33], as well as avoiding alcoholic beverages that further exacerbate dehydration. Recent studies show that, during the summer, the level of dehydration is already very high even before starting work. In particular, some monitoring carried out on workers (urine sampling) showed that most of them were already strongly dehydrated before starting their day's work [34,35]. This entails a strong stress and also causes an alteration of the perception of effort and therefore of risk [36]. It is evident that the dietary habits that underlie the maintenance of a good level of hydration and nutrition are strictly dependent on cultural aspects (e.g., subjects of Muslim origin are at greater risk during the Ramadan period) [37]. The results of a recent study showed that from the Eastern-Mediterranean Region workers exhibit a significantly increased risk for occupational injuries during Ramadan in periods characterized by heat-waves, while their frequency was somehow reduced for days associated with Ramadan characterized by increased but not extreme temperatures [38].

The main limitation of this study is the limited and unbalanced sample (just over 100 workers of which 63% are natives). Moreover, the migrant group is not homogeneous, being prevalently composed by Albanians that work in the constructions sector, whereas the 25% of the sample that works in agriculture is represented by North Africans. Nevertheless, the study managed to highlight statistically significant differences, supporting the fact that cultural diversity issues in the workplace should be seriously taken into consideration in the coming years. In order to avoid bias in the results, we should not consider immigrants as a homogeneous group of individuals and the specificity of each nationality should be taken into account. Therefore, with a different sample, further information could be obtained. In addition, we must also consider that migrant workers are younger than Italian, and this could imply a different perception of heat and efforts. It is well known that the main reason for immigration is economic opportunity, and that migrants are generally younger and an important fraction of the active population in Italy. Furthermore, they are often less qualified job seekers, and may be particularly at risk as they are often less qualified than their native counterparts and could be subject to employment discrimination [39]. Another potential bias is the underreporting due to communication difficulties during the interview and to social desirability bias, particularly frequent among migrant workers concerned about possible reprisal or staying away from work too much time [40].

5. Conclusions

In the future the increasingly effects of climate change will make necessary mitigation strategies to face the effects of high temperatures on the population, especially the most vulnerable categories, including workers.

Our findings are important for promoting and regulating prevention measures related to heat waves and their impact on workers. In addition, climate change is expected to trigger growing population movements within and across borders, as a result of such factors as increasing frequency and intensity of extreme weather events and, for this reason, the number of migrant workers will tend to increase further in the coming years. Because of cultural differences compared to their places of origin, these workers may perceive the risk related to high temperatures in the workplace differently than native workers.

This study shows that there are ethnical differences concerning the perception of effort and heat, as well as about information on how to deal with it. The low proportion of respondents unsatisfied with current measures adopted to inform on and reduce the effects of heat, recommends a better attention of employers to their workers' health and safety.

For informing on and reducing the effects of heat, indicates a good attention by employers on the health and safety of their workers. However, it is necessary to take into consideration that the migrant workers have greater job insecurity, compared to native ones, and so the possible fear in answering to the questionnaire should not be underestimated.

For the future, it will be necessary to create larger and more homogeneous samples to make ethnic comparisons also effective regardless of the age, type of job and country of origin. However, these preliminary results already highlight the strong need to intensify training courses for migrants, which should take into consideration linguistic barriers as well as cultural and religious differences. Religious aspects, in fact, have not yet been considered but they could be an important variable that regulates the habits in drinking and eating, thus influencing the state of health of workers.

Supplementary Materials: The following are available online at http://www.mdpi.com/1660-4601/16/7/1090/s1, General anonymous questionnaire: workers' risk perception of heat stress in the workplace.

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RESEARCH ARTICLE

Evaluation of the impact of heat stress on the occurrence of occupational injuries: Meta-analysis of observational studies

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Background: Growing evidence indicates that the exposure to high heat levels in the workplace results in health problems in workers. A meta-analysis was carried out to summarize the epidemiological evidence of the effects of heat exposure on the risk of occupational injuries.

Methods: A search strategy was conducted to retrieve studies on the effects of climate change on occupational injury risk. Among the 406 identified, 5 time-series and 3 case-crossover studies were selected for meta-analysis.

Results: Pooled risk estimates for time-series and case-crossover studies combined, and then separated, were 1.005 (95%CI: 1.001-1009), 1.002 (95%CI: 0.998-1.005), and 1.014 (95%CI: 1.012-1.017), respectively. Subgroup analyses found increased risks (not statistically significant) for male gender, age <25 years and agriculture.

Conclusions: The present findings can orient further research to assess the effects of heat at workplace and consequently to establish better health policies for managing such exposure in at-risk regions.

KEYWORDS
climate change, global warming, heat wave, occupational injury, temperature

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The association between extreme weather conditions and work-related injuries and diseases. A systematic review of epidemiological studies

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Abstract

Introduction. The relationship between extreme temperature and population health has been well documented. Our objective was to assess the evidence supporting an association between extreme temperature and work related injuries.

Methods. We carried out a systematic search with no date limits using PubMed, the Cochrane central register of controlled trials, EMBASE, Web of Science and the internet sites of key organizations on environmental and occupational health and safety. Risk of bias was evaluated with Cochrane procedure.

Results. Among 270 studies selected at the first step, we analyzed 20 studies according to inclusion criteria (4 and 16 referring to extreme cold and heat temperature, respectively).

Discussion. Despite the relevance for policy makers and for occupational safety authorities, the associations between extreme temperature and work related injuries is seldom analyzed. The estimation of risk, the identification of specific jobs involved and the characterization of the complex mechanisms involved could help to define prevention measures.

Key words
- occupational health
- occupational injuries
- climate change
- environmental health
- temperature

BACKGROUND

Changes in many extreme weather and climate events have been observed progressively in the last decades. Some of these changes have been linked to human influences, including a decrease in cold and an increase in warm temperature extremes. The most recent Intergovernmental Panel on Climate Change (IPCC) reported that extreme weather events have become more frequent and intense in recent years [1].

The relationship between high temperatures, heat waves and population health has been well documented. Epidemiological evidence suggests that extremely hot weather contributes to excess morbidity and mortality, particularly among the elderly, patients suffering chronic diseases and under pharmacological therapies [2-6]. Epidemiological findings also suggest that cold temperatures affect mortality more indirectly than heat and by the means of longer exposures [7-9]. One of the most indisputable consequences of climate change is the increased frequency and intensity of heat waves. The number of deaths due to the 2003 heat wave in eight European countries was close to 35 000 people in three weeks [10, 11].

There has been a growing research concern in the literature about the impact of heat-related events on workers' health and safety in recent years, nonetheless the extent of effect on occupational safety and health of climate change is still under debate and largely unknown. Furthermore the evidences related to the categories of workers affected by heat (or cold) exposure remains controversial. Same evidences have been reported concerning hot. Workplace heat exposure can increase the risk of occupational injuries and accidents [12-16]. Short-term acute extreme heat exposure may disrupt core body temperature balance and result in heat-related illnesses. Adverse long-term health effects of chronic workplace heat exposure have also been reported. Heat gain can be a combination of heat from

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the external thermal environment and internal heat generation by metabolism associated with physical activity. In the workplace, there are two types of external heat exposure sources: weather-related and process-generated. With predicted increased heat waves with global warming, weather-related heat exposure is presenting an increasing challenge for occupational health and safety.

Recently two scientific reviews have demonstrated the association between intense and prolonged occupational exposure to heat temperature and health effect on workers such as dehydration and spasms, increased perceived fatigue and reduced productivity [17, 18]. Occupational exposure to cold temperature could increase cardiovascular and respiratory diseases risks, musculoskeletal and dermatologic disorders and could induce injuries related to hypothermia [19]. Specific individual (age, gender, health general conditions) and occupational (job type, seniority) factors were involved in risk of health effects due to both heat and cold temperature. Previous studies have shown that job categories majorly involved were construction sector, agriculture, waste management and disposal, steel workers and transport [12-16, 20, 21] but findings are still controversial and generally obtained in different observational conditions.

In this work we aimed to conduct a systematic review in order to assess and summarize the scientific evidence on the potential health impacts of occupational exposure to high or low extreme temperature. The purpose was to: i) examine the available published papers concerning the epidemiological associations between extreme weather and work-related injuries; ii) identify which industrial sectors, occupations, genders and age groups are more vulnerable to extreme weather, according to selected papers in order to provide evidence for policy makers and stakeholders involved in occupational safety and health. This could help in identifying evidence-based elements for the implementation of targeted public health interventions geared to increase adaptive capacity, through enhancing the level of awareness of heat/cold-related risks or to reduce susceptibility of workers.

MATERIALS AND METHODS

In the field of environmental health, research syntheses lag behind comprehensive, rigorous and transparent systematic review methods developed in clinical sciences. To close this gap, many researchers and international institutions show an increasing interest in applying these procedures to questions related to environmental health and to provide a reproducible framework to evaluate the quality of the evidence in the environmental field [22-26]. For this purpose we applied a systematic review methodology as a tool to synthesize findings from relevant studies. Such methods (which include a literature review with a well-defined research question, uses systematic and explicit methods to identify, select and appraise research, analyze data from selected studies, and , if possible, integrates results of chosen studies by a meta-analysis) already exist to evaluate clinical evidence [27, 28] for evidence-based decisions for health-care interventions.

For this review we included studies meeting the following eligibility criteria:

a. prospectively designed and controlled studies (including randomized controlled trials, non-randomized controlled trials), administrative cohort studies, case-control, case crossover, ecological correlational studies and ecological time series studies;
b. working population of all ages, sex and ethnic groups;
c. use of a defined, objective information source for high and low temperature (*e.g.* not obtained retrospectively from patient but measured from meteorological stations);
d. the outcome measure was overall mortality, any trauma or work-related injuries, morbidity (*e.g.* emergency visits for symptoms or signs related to heat or cold);
e. estimates of either odds, risk or hazard ratios or available data allowing for their calculation.

We considered only literature discussing studies on humans. Studies dealing with the synergistic effect of air pollution and temperature on the incidence of work-related injuries were also considered (*e.g.* effect of heat on low and high pollution days).

We excluded studies that did not report original results (reviews, letters, comments) or did not provide sufficient data (*e.g.* lack of information about the number of cases and controls or about the used method).

Exploratory studies, such as time-trend exploratory studies, were not included. Only etiologic studies are included.

Search methods for identification of studies

We carried out a systematic search to identify peer-reviewed, primary research papers. The following bibliographic databases were searched: PubMed (January 1966 to September 2014), the Cochrane Central Register of Controlled trials (CENTRAL, The Cochrane Library, September 2014), EMBASE (January 1974 to November 2014), and Web of Science (September 2014).

A specific search strategy were developed for each database used, accounting for differences in controlled vocabulary and syntax rules. *Table 1* give details of the search for MEDLINE.

We also searched the internet sites of key organizations on environmental area such as:

- Occupational Safety Health Agency (www.osha.gov/)
- European for Safety & Health Agency (https://osha.europa.eu/)
- WHO (www.who.int/en/)
- Centers for Disease Control and Prevention - CDC (www.cdc.gov/).

Data extraction and assessment of bias

Two authors independently screened titles and abstracts of studies obtained by the search strategy. Each potentially relevant study located in the search was obtained in full text and assessed for inclusion independently by two authors. In case of disagreement a third author was consulted.

A standardized data extraction form was used to col-

Table 1
Search strategy for MEDLINE complete (via EBSCO)

1. TI Hot N2 temperature OR TI high N2 temperature OR TI summer N2 temperature OR TI extreme N2 temperature OR TI ambient N2 temperature OR AB Hot N2 temperature OR AB high N2 temperature OR AB summer N2 temperature OR AB extreme N2 temperature OR AB ambient N2 temperature
2. TI heat N1 wave* OR AB heat N1 wave*
3. TI heatwave* OR AB heatwave*
4. MH "Hot temperature/adverse effect"
5. #1 OR #2 OR #3 OR #4
6. MH cold temperature
7. TI cold N2 temperature OR TI low N2 temperature OR TI extreme N2 temperature OR TI outdoor N2 temperature OR AB cold N2 temperature OR AB low N2 temperature OR AB TI extreme N2 temperature OR AB outdoor N2 temperature
8. #6 OR #7
9. AB work* OR TI work*
10. TI workplace OR AB workplace
11. MH Workplace
12. TI occupation* OR AB occupation*
13. #9 OR #10 OR #11 OR #12
14. MH animals NOT MH humans
15. #5 AND #13
16. #8 AND #13
17. #15 NOT #14
18. #16 NOT #14

lect data from each relevant study. Extracted information included:

- general study details (citation, study design);
- setting (size of the company, country, industry subsector, and trade and job);
- participant details, including key demographic characteristics;
- exposure measurement details;
- confounders variables considered;
- crude and adjusted outcome data;
- key elements for preventive measures (*e.g.* recommendations, advice for categories of workers) to translate into workers healthcare protocols.

For each included study we evaluated the methodological quality of the evidence assessing the risk of bias defined as characteristics of a study that can introduce a systematic error in the magnitude or direction of study findings [28]. We explored the potential risk of bias using the tool already developed by Johnson *et al*. 2014 [22] by adapting existing risk of bias guidance used to evaluate human studies in the clinical sciences: the Cochrane Collaboration's Risk of Bias tool [28] and the Agency for Healthcare Research and Quality's criteria [29]. Two authors independently assessed the following risk of bias:

- recruitment strategy;
- blinding;
- confounding;
- exposure assessment;
- outcome assessment;
- incomplete outcome data;
- selective outcome reporting;
- conflict of interest;
- other bias.

We graded each potential source of bias as high, low or unclear and provided a quote from the study report together with a justification for our judgment in the "Risk of bias" tables. We summarized in a graph the risk of bias judgements across different studies for each of the domains listed.

Data analysis

Considering the heterogeneity of the study design, outcome measures and participants included the studies we planned not to produce a pooled estimate, but to present a narrative summary of findings. The narrative report would classify and present studies according to type of exposure.

RESULTS

The present review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [30]. Our systematic review identified 270 potential articles. After duplicates were removed, 176 articles were further screened on title and abstract and 42 full texts retrieved. Finally, we found 8 papers that investigated extreme temperature-related illnesses including 2 papers [21, 31] that assessed the impact for heat and cold exposure both. *Figure 1* shows the study selection process. Of the 26 studies that met the inclusion criteria, we excluded 18 studies available on line (*Supplementary Materials*) from our review for a variety of reasons, primarily because they used a study design not considered in the review.

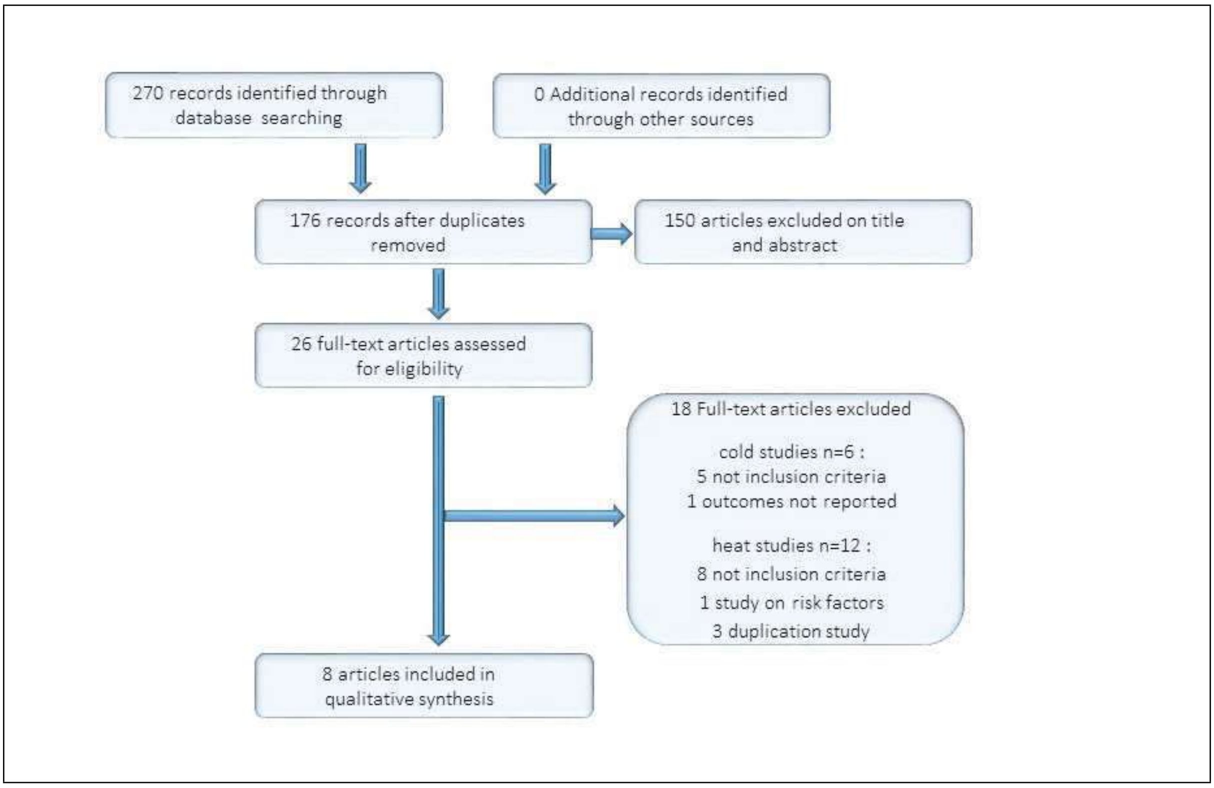


Figure 1
Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) flow diagram.

Study characteristics

Table 2 provide an overview of the 8 eligible studies. All studies meeting the inclusion criteria were observational studies, five adopted an ecologic time series design [21, 31-34], two were correlational studies [35, 36], and one a case-control study [37]. Four studies took place in the United States [31, 32, 37, 36], two in Italy [21, 35], and in Australia [33, 34]. Time of publication ranged from 2000 to 2015.

The studies used daily maximum temperature [31-34, 36], daily mean temperature [21, 31], apparent temperature [35]. A study considered heat waves [33] as exposure variable and the study of Bell [36] considered cold days (<0 °F and 0-10 °F). Only two studies analyzed the dose-response relationship between temperature and the health outcomes finding a reversed U-shaped exposure-response relationship [34, 35], or linear relationship [32] or linear above/below a threshold [21, 31]. The same studies explored the delayed effect of temperature, with similar results of an acute effect (within 3 days) [21, 32, 34] for both high and low temperatures. The effect of high and low temperature and work injuries was studied through parametric and non parametric regression models (*i.e.* GEE, GAM, negative binomial regression) in six studies and through non parametric tests in one study [35]. A study [31] estimated the effect of high and low temperature through Bayesian analysis. A case control study [37] analyzed cases of heat-associated deaths registered in a local surveillance system to assess the risk of death in workers. Regression models were adjusted for other meteorological variables (barometric pressure, wind speed) and calendar factors (years, months, weekdays and holidays). None of the study included air pollution among potential confounders, except Fortune *et al.* [31]. A study [35] had a limited statistical power. In the study of Bell *et al.* [36] potential confounders were not taken into account.

Effect estimates were presented for work-related injuries in five studies [21,32-34,36] using workers' compensation databases while two study provided risk estimates of temperature-related morbidities such as emergency room visits and hospitalizations defined from administrative databases using the ICD-10 [31] and ICD-9 codes [35]. All studies, except Morabito *et al.* [35] and Fortune *et al.* [31], provided risk estimates by categories of workers (*i.e.* for working age, gender, occupational sectors, job activity, work location).

Tables 3a and 3b summarize the data reported studies characteristics.

Risk of bias assessment for individual studies

The risk of bias of the included studies was summarized in *Figure 2* and *Figure 3*. Given the nature of exposure and study design, we judged that for these eight studies the knowledge of exposure status (blinding) is not an element capable of introducing risk of bias. Four studies had a low risk of bias for recruitment since studies reported no main differences in terms of baseline characteristics among groups.

For all studies we assigned a low risk of bias related to incomplete outcome data, conflict of interest. All studies used routine administrative data which we assumed

Table 2
Overview of included studies

Source	**Location**	**Years of study**	**Study design**	**Population**
Adam-Poupart 2014 [32]	16 regions Quebec Canada	May and September 2003-2010	Ecologic Time series analysis: daily counts of compensations for work-related injuries and daily summer temperatures	N = 374 078 Work-related injuries compensation
Fortune 2014 [31]	Ontario Canada	1 January 2004-31December 2010	Ecologic time series analysis: to examine the associations between occupational, temperature-related emergency department visits and meteorological data	N = 171 463 occupational emergency department encounters
Morabito *et al.* 2014 [21]	Tuscany Italy	2003-2010	Ecologic time series analysis: to investigate short-term effect of high/low air temperature on outdoor occupational injuries	N = 162 399 outdoor occupational injuries
Xiang 2014a [33]	Adelaide Australia	1 July 2001- 30 June 2010 (only warm season)	Ecologic time series analysis: investigate the association between high temperature and work-related injuries during a 9-year period	N = 125 267 workers' compensation (summer only)
Xiang 2014b [34]	Adelaide Australia	July 2001-June 2010 (only warm season)	Ecologic time series analysis: investigate the association between heatwave and work-related injuries during a 9-year period	Workers' compensation claim N = 125 267
Petitti 2013 [37]	Arizona USA	1 January 2002-31 December 2009	Case control study	N = 444 cases of heat-associated deaths and 925 controls
Morabito *et al.* 2006 [35]	Florence, Prato Italy	June-September 1998-2003	Ecologic correlational study: analyze the relationship between hot weather conditions and hospital admissions	N = 835 hospital admissions
Bell *et al.* 2000 [36]	7 states: IL, IN, KY, OH, PA, VA, WV United States	1985-1990	Ecologic correlational study: relationship between cold environmental temperature and slip and fall-related injuries	N = 18 628 injuries

to have a high degree of completeness and quality since they are managed by public bodies. All studies adjusted for the most relevant confounder.

Without access to pre-registered protocol it was difficult to know whether or not there was reporting bias. However, we assigned a "probably low risk" for all studies because there was insufficient information to evaluate the risk of selective reporting but, being studies were exploratory in nature, they fully reported all multiple exposures-outcomes associations investigated.

We judged that there was high risk of outcome misclassification in six studies due to the lack of specificity of the outcome assessment in relation to heat-cold exposure or lack of validation of outcome data.

Four studies were considered having a high risk of exposure assessment bias due to the lack of validation of meteorological data and the use of average exposures for large geographic area.

Among other bias we considered the ecological bias in all studies except for Petitti 2013 [37] that was affected by inaccurate information on occupation status. Moreover all time-series studies had no information on population at risk in a specific time point leading to over or underestimation of relative risk.

Work-related injuries/illness and heat

All papers identified [21, 31-35, 37] assessing the effect of high temperature/heatwaves on workers' health showed an association with injuries in the workplace.

In a study from Quebec, Canada, Adam-Poupart *et al.* [32] observed a +0.2% increase in risk of daily work-related injury compensations per 1 °C increase in temperatures. Higher risk was observed for men, workers aged less than 45 years, various industrial sectors with both indoor and outdoor activities. Manual occupations were not systematically at higher risk than non-manual and mixed ones.

Fortune *et al.* [31] reported 273 emergency visits for heat illness from 2004 to 2010 with an increase of 75% in the rate of visits per degree Celsius above 22 °C. Emergency visits increased also with ozone exposure (+2%).

Similar findings was obtained by two Australian studies that used two different exposure indicators (temperature above a threshold and heatwaves) to examine how fluctuations in ambient temperature were associated with the number of daily injuries using data from compensation claims. Xiang[a] *et al.* [33] found that as temperatures rise, the number of daily injuries keep increasing but only up to a certain temperature, from which point on the number of injuries starts to decrease; probably due the fact that some work activities may be stopped in situations during extremely hot days where heat warnings are issued. The authors also identified that young people and males workers in industrial sectors were at higher risk. An increased risk was found in sectors that mostly work outdoors, such as agriculture,

Table 3a.
Exposure: high temperature. Characteristics of included studies and results*

Study	Heat exposure indicator	Outcomes	Main results**	Key for preventive measures
Adam-Poupart 2015 [32]	Daily maximum temperature (Tmax)	Work-related injuries	For all regions: IRR[a] = 1.002 (1.002-1.003) For an exposure at lag 3-day moving averages IRR = 1.003 (1.001-1.004) Men IRR = 1.003 (95% CI 1.002-1.005) *Age* 15-24 years = 1.008 (CI 1.005-1.010) 25-44 years = 1.003 (1.001-1.004) *Occupation* Outside IRR = 1.004 (1.001-1.006) Inside IRR = 1.003 (1.000-1.005)	None
Fortune 2014 [31]	Maximum temperature (Tmax) > 22 °C	Emergency department visits for heat illness using ICD-10-CA Codes T67:Effects of heat and light X30: Exposure to excessive natural heat W92: Exposure to excessive heat of man-made origin	Posterior median Relative rate[b] = 1.75 (1.56-1.99) Maximum air pollutant concentration Ozone Posterior median Relative rate[b] = 1.02 (1.00-1.04)	Occupational health risks are not limited to extreme temperatures when public health warnings are typically activated
Morabito 2014 [21]	Daily meteorological data of air temperature (T, °C), relative humidity (RH, %), wind speed (V, ms–1) and geopotential height (Hgt, m) Threshold ≥ 90°percentile (heat effect: 16,9 °C)	Outdoor Injuries	No significant result for all different geographical areas and mobility conditions *Workers who spend little time outdoors* Coastal area: % change in outdoor occupational injuries per 1 °C increase of air temperature = 8.2 (2.5-13.9)	None
Xiang 2014a [33]	Daily maximum temperature (Tmax) Heatwave ≥ 3 consecutive days with Tmax ≥ 35 °C	Work-related injury and illnesses (traumatic injuries, wounds, lacerations, and amputations, and musculoskeletal and connective tissue diseases)	*Gender* Women: IRR[c] = 0.935 (0.897-0.974) *Occupation* Laborers' and related workers' IRR = 1.054 (1.023-1.086) Tradespersons IRR = 1.056 (1.028-1.084) Intermediate clerical and service workers IRR=0.884 (0.831-0.941) Professionals IRR = 0.950 (0.912-1.028) *Industrial sector* Outdoor: IRR = 1.062 (1.022-1.103) Agricolture: IRR = 1.447 (1.125-1.861) Men: IRR = 1.653 (1.198-2.281) Age >55: IRR = 1.673 (1.049-2.667) Construction: IRR = 1.012 (0.936-1.093) Electricity, gas, water: IRR = 1.297 (1.049-1.604) Men: IRR = 1.387 (1.165-1.652) >55: IRR = 1.763 (1.161-2.676) Heat stress: IRR = 1.763 (1.161-2.676) Wounds laceration: IRR = 1.005 (1.028-1.154) Burns: IRR = 1.161 (1.010-1.334)	Male laborers and tradespersons >55 years of age in agriculture, forestry and fishing and electricity, gas and water industries are susceptible workers

(Continues)

Table 3a. (Continued)

Study	**Heat exposure indicator**	**Outcomes**	**Main results****	**Key for preventive measures**
Xiang 2014b [34]	Daily maximum temperature (Tmax) Thresholds = 37.7 °C	Work's Injuries	Total effect: IRR = 1.002 (1.001-1.004) Men: IRR = 1.004 (1.002-1.006) Age ≤24: IRR = 1.004 (1.000-1.007) Business size: IRR 1.007 (1.003-1.011) *Occupation* Outdoor industries: IRR=1.005 (1.001-1.009) Labourers: IRR = 1.005 (1.001-1.008) Tradespersons: IRR = 1.002 (1.000-1.004) Intermediate production and transport: IRR = 1.003 (1.001-1.006) Agriculture, fishing and forestry: IRR = 1.007 (1.001-1.013) Construction: IRR = 1.006 (1.002-1.011) Electricity, gas and water': IRR = 1.029 (1.002-1.058) when Tmax was above 37.2 °C	None
Petitti 2013 [37]	Heat-related cases (n = 444)	Heat-related mortality	*Constructions* Men: Age-adj OR = 2.32 (1.55-3.48) Non-Hispanic white Age-adj OR = 2.10 (1.26-3.50) *Agriculture* Men: Age-adj OR = 3.50 (1.94-6.32) Non-Hispanic white Age-adj OR = 3.16 (1.01-9.88) *Occupation unknown* Men: Age-adj OR = 10.17 (5.38-19.43) Women OR = 6.32 (1.48-27.08)	None

*Only statistically significant results are reported in the Table; **95% confidence interval; [a]IRR= incidence rate ratio per 1 °C increase in Tmax; [b]rate of emergency department encounters for occupational heat illness per degree Celsius above 22 °C in the region's average maximum temperature; [c]percent change in the number of daily work-related injury claims during heatwave periods compared with non-heatwave periods; RR = relative risk; OR = odds ratio; IRR = incidence rate ratio; Tmax = maximum temperature.

construction and transport. Exclusively injuries among workers in the electricity, gas and water industries increased during extremely high temperatures.

Similar results was obtained by Xiang[b] *et al.* [34] that investigated the impact of heatwaves (consecutive extreme heat exposure) on work-related illnesses in a temperate Australian city. He found that males, workers in agriculture, forestry and fishing and electricity, gas and water industries had a significant increase of risk of occupational injuries. However, in this study people over 55 years old were at higher risk and increased risk was found in construction workers.

Morabito *et al.* [35], in Tuscany region, Italy, found that the peak of work-related accidents occurs at high but not extreme temperature. The authors suggest a timing of heat effect, with stronger effect of high temperatures recorded earlier in the summer season. Considering all occupational injuries recorded by National Institute of Insurance for Occupational Illness and Injury in Tuscany, the authors found no association for workers who generally spend half or most of their time outdoors, such as construction, land and forestry workers. However, these latter outdoor workers showed significant linear associations of injuries with typical (far-from-extreme) temperatures (between 10th and 90th percentile of temperature). This finding is in agreement with the Australian study.

A case control study [37] conducted in Maricopa County, Arizona, showed an association of heat-associated death with construction/extraction and agriculture occupations in men with a high risk in older men (>65 years).

Work-related injuries/illness and cold

Three studies [21, 31, 36] estimated the associations between low temperature and heat-related injuries or illnesses in workers. Morabito *et al.* [21] found that, among 162 399 workers, those working in plain areas and using vehicles other than cars (two-wheeled vehicles and other types-of-vehicles) had a higher risk of increased occupational injuries when temperature is below -0.8 °C. The authors suggested that, in these cases, workers are relatively unaccustomed to cold, and near freezing temperature might represent a stress factor compared with workers in typically cooler hill/mountain areas. No increase of injuries associated with low temperature were observed in workers who usually spent about half or most of their time outdoors, such as construction, land and forestry workers.

All the above suggests to recommend the interruption of some outdoor activities, especially by non-acclimatized workers when cold warnings are issued, in order to avoid injuries. Construction, land an forestry workers probably are more careful under certain weather conditions and, by themselves, limit their outdoor activities when temperature anomalies occur.

Fortune [31] found a significant increase (+15%) in emergency department visits for cold-related illness for

Table 3b.
Exposure: low temperature. Characteristics of included studies and results*

Study	Cold exposure indicator	Outcomes measured	Main results**	Key for preventive measures
Fortune 2014 [31]	Minimum temperature (regional average)	Emergency department visits Using ICD 10 classification: T33 – Superficial frostbite; T34 – Frostbite with tissue necrosis; T35- Frostbite involving multiple body regions and unspecific frostbite; T68- Hypothermia; T69- Other effects of reduced temperature; X31-Exposure to excessive natural cold; W93-Exposure to excessive cold of man-made origin	<0 °C : Posterior median Relative rate[a] = 0.85 (0.80-0.91) >0 °C: Posterior median Relative rate[a] = 0.90 (0.81-1.00) Maximum wind speed: Posterior median Relative rate[a] = 1.06 (1.02-1.11)	Occupational health risks are not limited to extreme temperatures when public health warnings are typically activated
Morabito 2014 [21]	Daily meteorological data of air temperature (T, °C), relative humidity (RH, %), wind speed (V, ms–1) and geopotential height (Hgt, m) Threshold below the 10th centiles (cold effect: –0.8 °C)	Outdoor Injuries	*% change of Outdoor Injuries* Whole of Tuscany: (n = 162 399) = 2.3% (1.3%-3.3%)[§] Inland plain: (n = 100 837) = 3.1% (1.3%-4.9%)[§] Coastal plain: (n = 61 562) = 2.4% (0.8-4.0) *** *In vehicles* Whole of Tuscany: (n = 62 581) = 3.4% (2.0-4.8) [§] *Standing/walking outdoors* Whole of Tuscany: (n = 99 818) =1.6% (0.4-2.8)*** *Types-of-vehicles* Two-wheeled vehicles Whole of Tuscany: (n = 17,872) = 5.0%(2.1-7.9)[§] Other types-of-vehicles Whole of Tuscany: (n = 18,121) = 7.1% (4.4-9.8)[§] *Types-of-jobs* Workers who spend little time outdoors Whole of Tuscany (n = 30,167) = 3.8% (1.8-5.8)[§]	Need of develop a geographically differentiated operative outdoor temperature occupational health warning system
Bell 2000 [36]	Average daily temperatures from the major metropolitan weather stations for each state	Incidence of slip and falls-related injuries at <=0 °C >0±10 °C >10 °C 3 location categories: mostly enclosed, outdoor, enclosed/outdoor	Enclosed/outdoor vs mostly enclosed RR = 0.62 (0.58-0.67) Outdoor injuries vs mostly enclosed RR = 0.79 (0.72-0.88) Mostly enclosed ≤ 0 °C *vs* >10 °C: RR = 1.73 (1.48-2.03) Enclosed/outdoor injuries >0-10 °C *vs* >10 °C: RR = 1.17 (1.05-1.30) Enclosed/outdoor injuries ≤ 0 °C vs >10 °C: RR = 1.55 (1.36-1.78) Outdoor injuries >0 -10 °C vs >10 °C: RR = 1.08 (0.89-1.32) Outdoor injuries ≤ 0 °C vs >10 °C: RR = 1.78 (1.40-2.29)	Any intervention methods geared toward reducing injury incidents facilitated by cold weather must also be directed toward workers who do not have full-time outside work

*Only statistically significant results are reported in the Table; **95% confidence interval; *** p < 0.01; [a]Posterior median Relative rate = rate of emergency department encounters for occupational heat illness per degree Celsius below 22 °C in the region's average maximum temperature; [§] p < 0.001; ICD 10 = International Classification of Disease; RR = relative risk.

each degree decrease in the minimum temperature. A significant effect of wind speed as also observed (+6%)

Bell *et al.* [36] in seven US states, reported that slips and falls were the second most numerous type of injury among above-ground mining workers, accounting for 25% of the total number of injuries. The authors reported that the proportional injury ratio of slips and falls increased significantly as the temperature decreased.

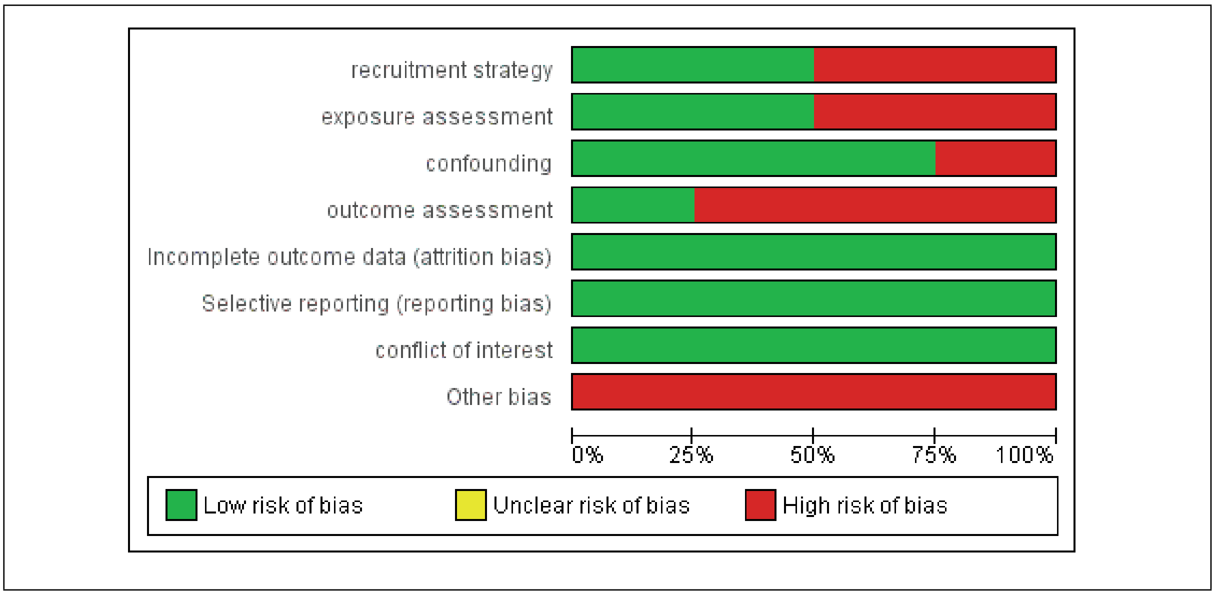
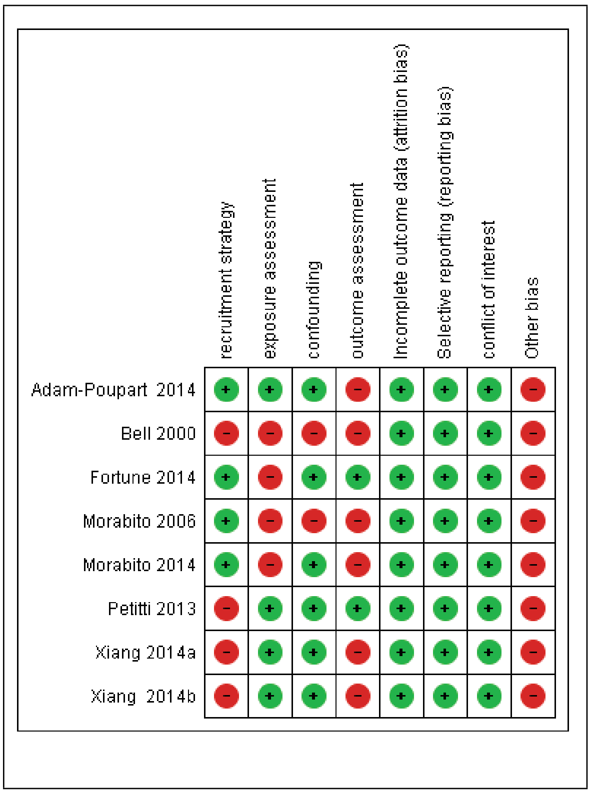


Figure 2

Risk of bias graph: review authors' judgements about each risk of bias item presented as percentages across all included studies.



	recruitment strategy	exposure assessment	confounding	outcome assessment	Incomplete outcome data (attrition bias)	Selective reporting (reporting bias)	conflict of interest	Other bias
Adam-Poupart 2014	+	+	+	−	+	+	+	−
Bell 2000	−	−	−	−	+	+	+	−
Fortune 2014	+	−	+	+	+	+	+	−
Morabito 2006	+	−	−	−	+	+	+	−
Morabito 2014	+	−	+	−	+	+	+	−
Petitti 2013	−	+	+	+	+	+	+	−
Xiang 2014a	−	+	+	−	+	+	+	−
Xiang 2014b	−	+	+	−	+	+	+	−

Figure 3

Risk of bias summary: review authors' judgements about each risk of bias item for each included study.

This pattern also was evident in three work locations (enclosed, outdoors, enclosed/outdoor) when examined separately. Over all temperatures, slips and falls were a more important source of injury for the enclosed location than other locations.

DISCUSSION

Our work shows a relationship between extreme temperature (particularly for heat temperature) and work related injuries despite the few number of published studies.

We specifically identified studies in the following sectors: agriculture, fishing, construction, electrical and transport industries [21, 31-34, 37]. The most frequent kinds of injuries were slips, trips, falls, and wounds, lacerations and amputations [32-34].

The ecological study design and the lack of specificity of heat and cold related health effect on workers were the relevant sources of low quality in the studies involved in this systematic review. The risk of bias due to exposure misclassification is another concern for the included studies, due to the lack of validation and the limited geographic coverage of meteorological data. On the other hand even in the well conducted etiologic time-trend study the lack of information on daily variations of population at risk (*i.e.* workers) impairs the possibility to make any causal inference from the study results. This review underlines the need of cohort and case-control studies that overcome this limit and provide accurate estimate of relative risk of heat and cold effects on workers.

All selected studies underlined the complexity of relationship between heat temperature and occupational injury risk. The characteristics of job and procedure, the level of awareness, life habits and work organizations play a relevant role and a complete framework of studies regarding all these issues is still lacking. As showed in the recent review by Xiang and colleagues [38] the prevention measures (including information and training about risk) are the basic tool to reduce work related injuries due to extreme temperature.

Recently the most important international Institute and Agency of public health have produced guidelines and recommendations about the risks of overheating for workers and gives practical guidance on how to avoid it [39, 40, 41]. All these documents underlined the role of prevention and in particular: i) to provide information about the risk for workers and employers; ii) to define programs for gradually adapting to extreme temperature; iii) to implement work organizations including turnover of workers exposed to heat temperature; iv) to avoid specific hard work in extreme weather conditions; v) to monitor the temperature and consider it in the program of job organization.

The most relevant occupational risk with extreme heat temperature is the dehydration with the consequence reduction of reactivity and quickness of reflexes. The use of cotton clothes and broad-brimmed heat and a correct use of breaks during working time are prevention measures with a simple implementation needing low resources and a good presumable effect in injuries risks reduction and control.

CONCLUSIONS

Despite the relationship between extreme temperature and population health has been well documented and several epidemiological studies have repeatedly demonstrated that hot weather (and hot waves particularly) contributes to excess morbidity and mortality, very few is known about the effect on work related injuries. Workers categories and job involved are not well documented and the extent of work injuries correlated to extreme ambient temperature at population level is not generally evaluated. The few available studies underlined the role of prevention and that it is important for policy makers and occupational health and safety authorities to receive scientific evidence regarding which categories of workers are at risk of injuries related to extreme temperature for adaptation purposes. The estimation of risk, the identification of specific jobs involved and the characterization of the complex mechanisms involved could help to define prevention measures particularly concerning work organization.

Author's contribution statement

Alessandro Marinaccio and Paola Michelozzi conceived the study. Michela Bonafede and Simona Vecchi defined its design, screened and selected studies, analyzed data and wrote the manuscript. Federica Asta and Patrizia Schifano participated to conceive the study, to define its design and to interpret data. All authors critically revised the manuscript and contributed for important intellectual contents.

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Conflict of interest statement

There are no potential conflicts of interest or any financial or personal relationships with other people or organizations that could inappropriately bias conduct and findings of this study.

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