CAMBIAMENTI CLIMATICI ED IMPATTI SULLA SALUTE E SICUREZZA DEI LAVORATORI: il progetto Worklimate

Articoli scientifici prodotti nell'ambito del progetto Worklimate o da ricercatori coinvolti nel progetto e su temi di ricerca attinenti il progetto.

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WORKLIMATE
CLIMA LAVORO PREVENZIONE

Consiglio Nazionale delle Ricerche
Istituto per la BioEconomia
Dipartimento di Scienze Bio Agroalimentari

PRESENTAZIONE

Il progetto di ricerca WORKLIMATE, promosso e finanziato da Inail in collaborazione con il Consiglio Nazionale delle Ricerche - Istituto per la Bioeconomia (CNR-IBE), e con la partecipazione delle Aziende USL Toscana Centro e Toscana Sud Est, del Dipartimento di Epidemiologia del Servizio Sanitario Regionale del Lazio e del Consorzio LaMMA, ha sviluppato una serie di attività di ricerca sul tema delle misure di impatto del cambiamento climatico sulla salute e sicurezza dei lavoratori.

Sono state prodotte analisi epidemiologiche per valutare l'associazione fra condizioni termiche estreme (caldo e freddo) e rischio di infortunio sul lavoro e specifici approfondimenti di questo tema hanno riguardato il settore dell'edilizia e dell'agricoltura. Sono stati analizzati i costi sociali associati e sono state condotte web surveys per indagare la percezione e la conoscenza degli effetti del caldo negli ambienti di lavoro da parte dei lavoratori e per valutare l'impatto dello stress da caldo associato all'utilizzo di dispositivi di protezione individuale per lavoratori del settore sanitario durante la prima ondata della pandemia COVID-19. Sono stati condotti casi-studio con monitoraggi meteo-climatici e comportamentali in un campione di aziende e sono stati effettuati test con giacche ventilate in camera climatica e sul luogo di lavoro. È stata infine sviluppata una piattaforma previsionale del rischio caldo indirizzata a vari profili di lavoratori integrata da una WebApp che permette una completa personalizzazione della previsione ad esclusivo utilizzo di chi si occupa di salute e sicurezza sul lavoro. Per i temi di ricerca sviluppati dal progetto sono disponibili articoli scientifici pubblicati su riviste dotate di procedure di peer review e, in molti casi, con modalità di "open access". Uno degli obiettivi del progetto è di contribuire tramite tale lavoro di diffusione dei risultati ad accrescere la consapevolezza delle connessioni fra cambiamento climatico e salute e sicurezza nei luoghi di lavoro.

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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

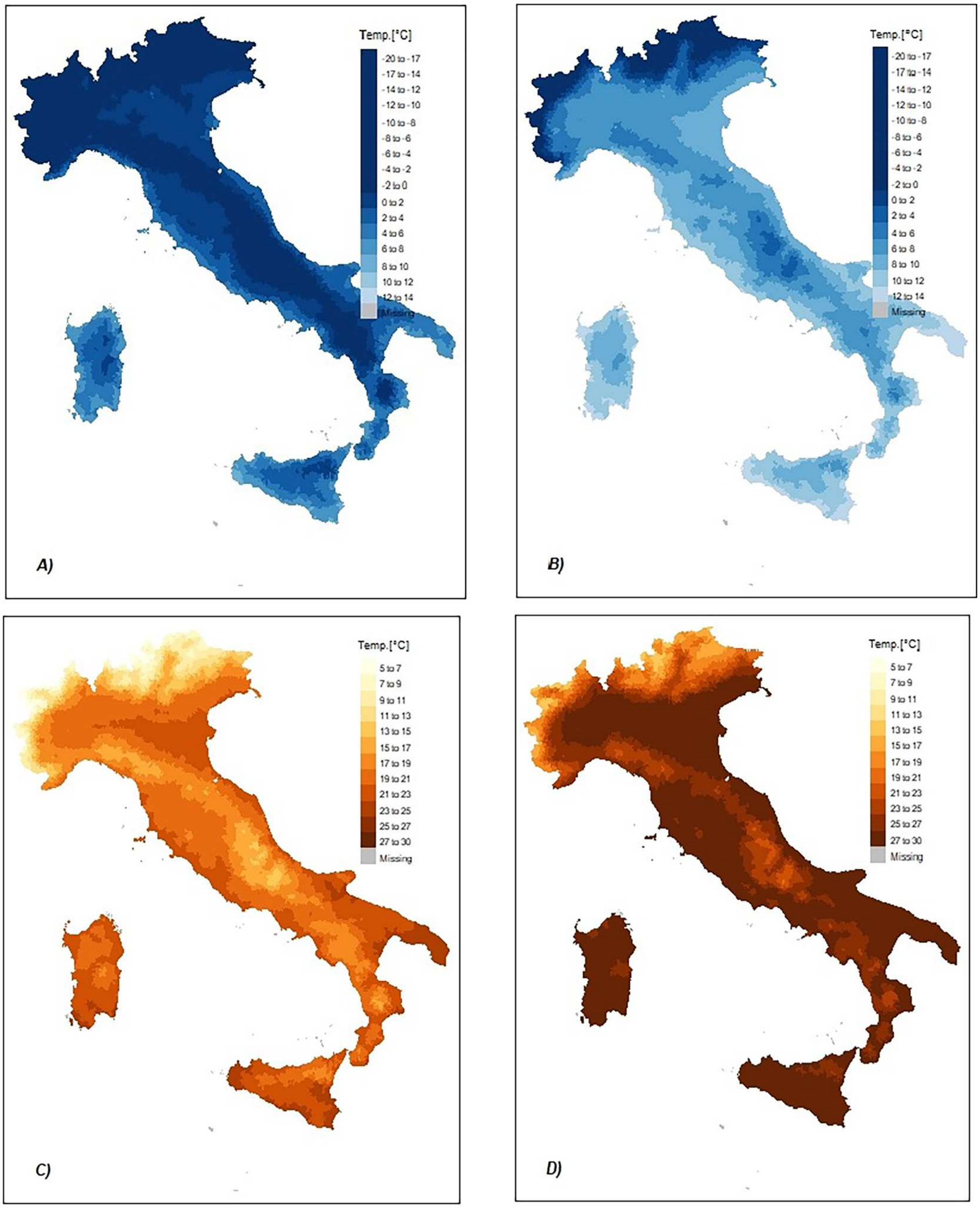

Fig. 1. Maps of the first (A), 25th (B), 75th (C) and 99th (D) percentiles of mean daily air temperature at municipal level based on ERA5 data from year 2014 to 2019.

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

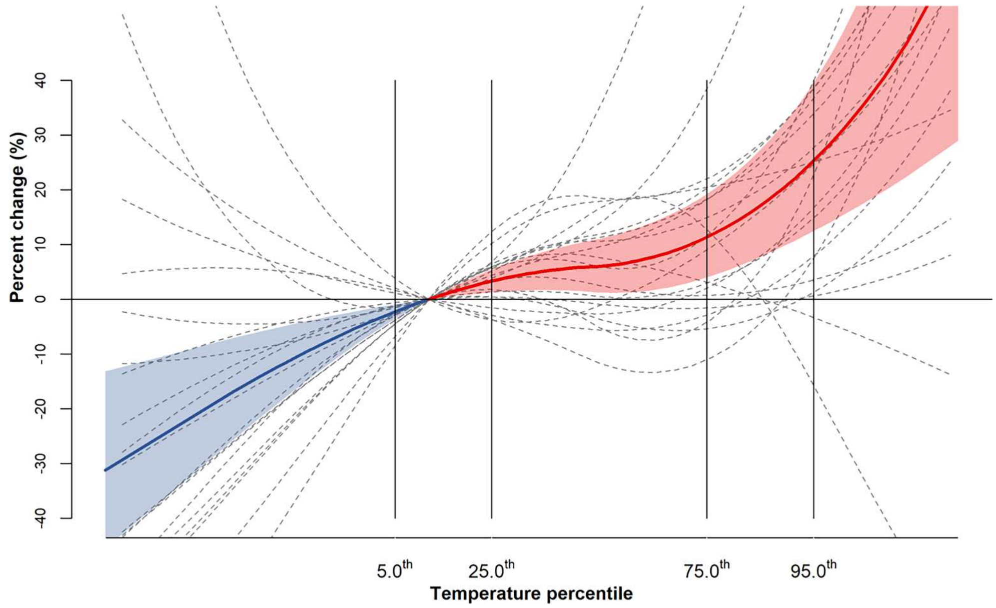

Fig. 2. Exposure-response relationship. Percent change in occupational injuries in the construction sector by temperature percentile. Blue and red areas correspond to low and high temperature effects. Dashed lines represent the region specific functions. (For interpretation of the references to colour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

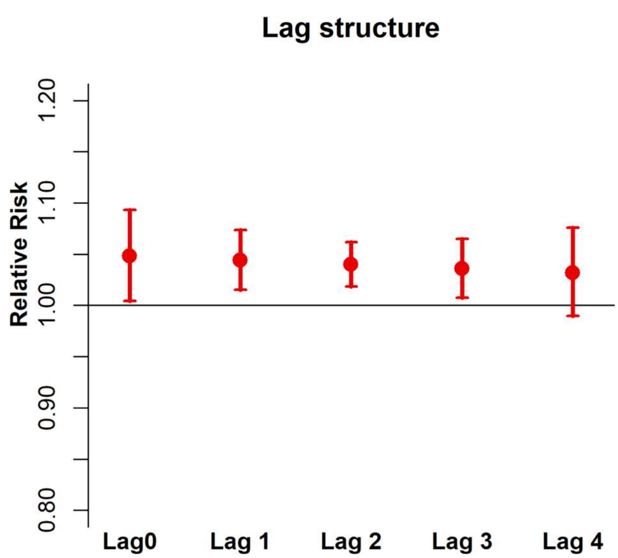

Fig. 3. Lag specific effects for the overall cumulative exposure–response relationship between outdoor temperature and occupational injuries in the construction sector for heat effects. Italy, 2014–2019.

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.

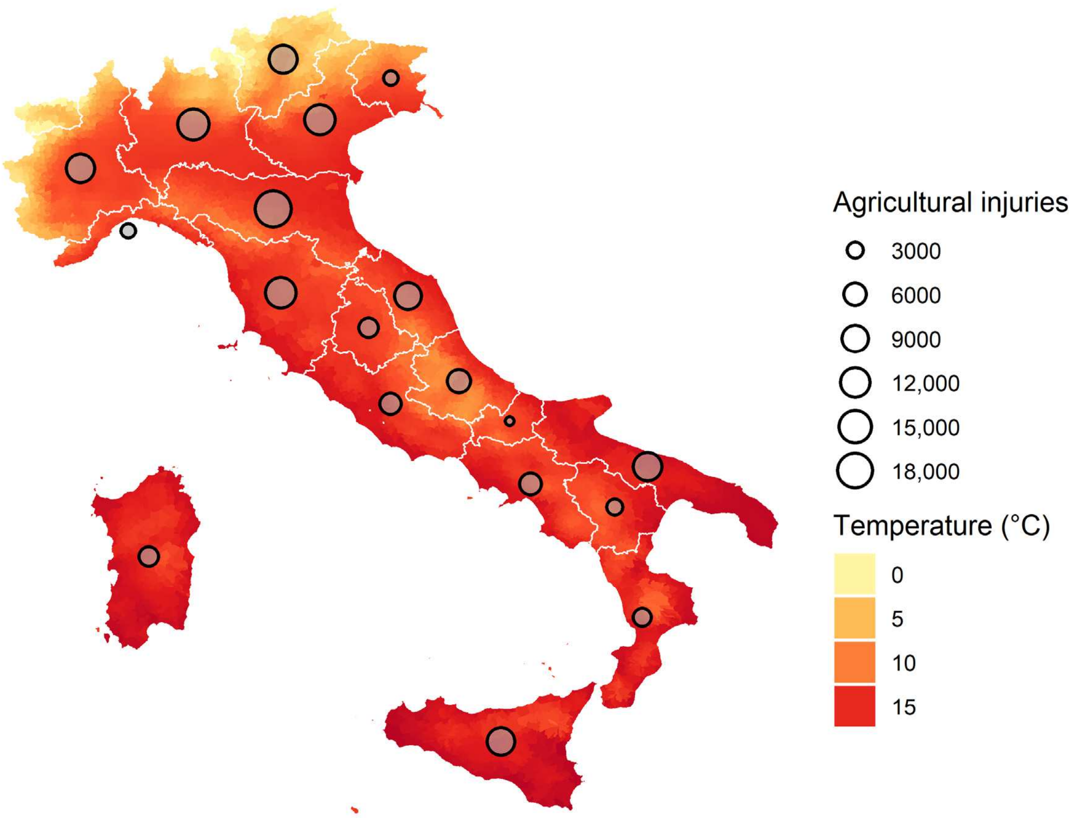

Figure 1. Daily mean air temperature and occupational injuries in the agricultural sector in Italy in the period 2014–2018. Air temperature is expressed at municipal resolution, while injuries are at the regional level.

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.

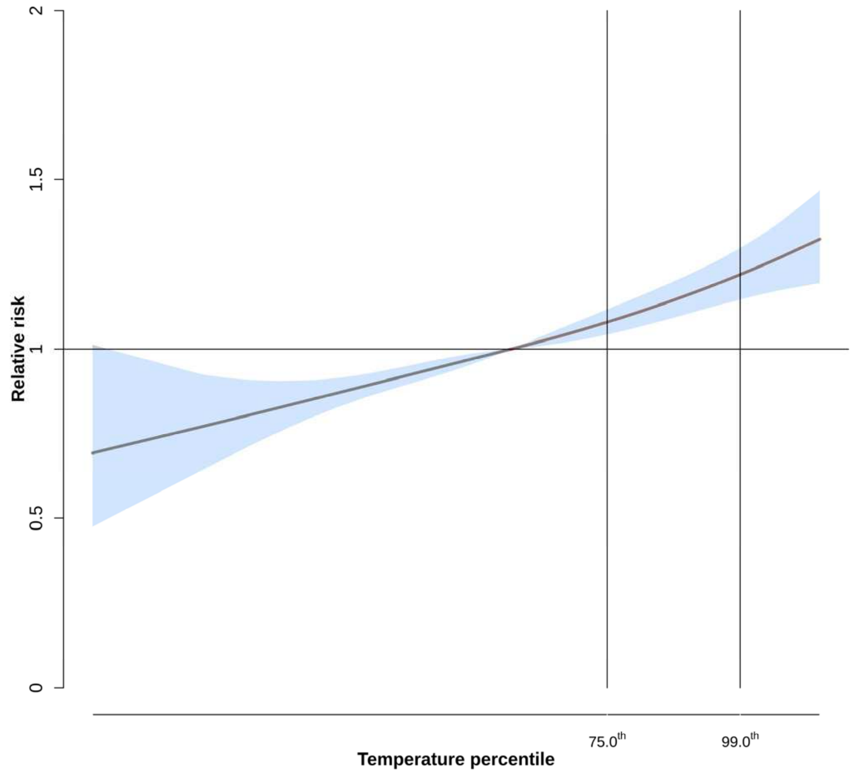

Figure 2. Meta-analytical exposure-response curve between daily mean air temperature and occupational injuries in the agricultural sector in Italy in the period 2014–2018. Estimates are expressed as Relative Risks (thick lines) and 95% confidence bands.

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.

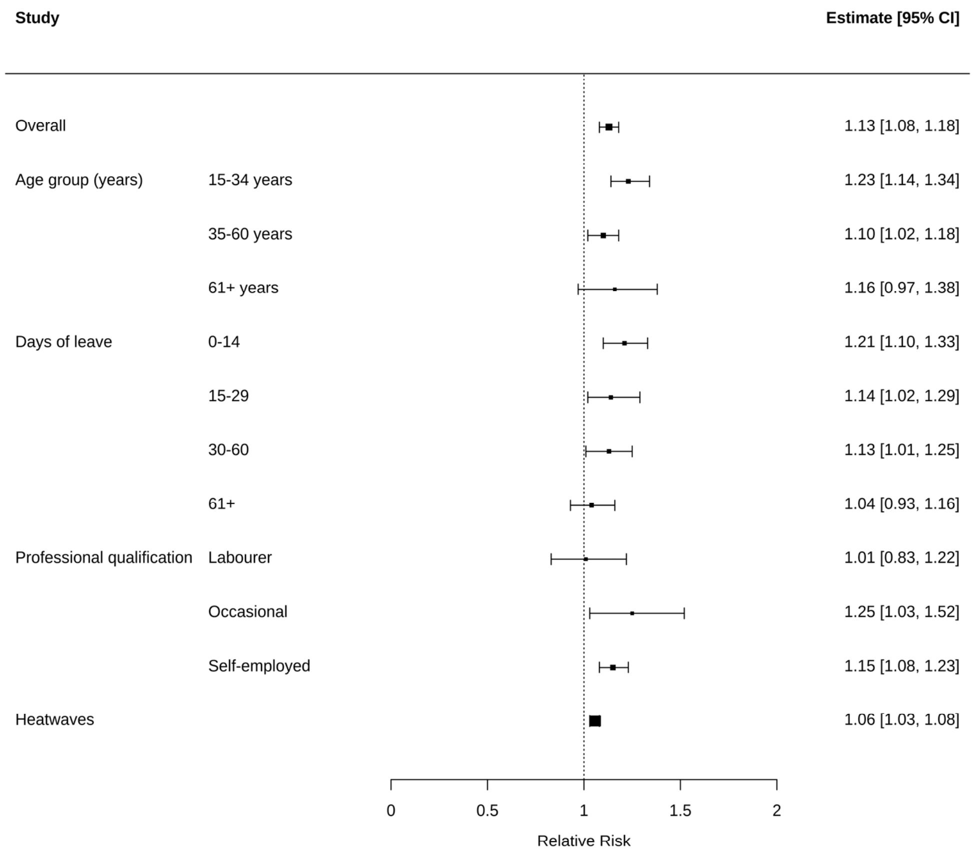

Figure 3. Relative Risks (and 95% confidence intervals) of work-related injuries in the agricultural sector for increases in daily mean temperature between 75th to 99th percentile (period 2014–2018). Square size represents the robustness of the estimates.

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

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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 pre-testing 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.

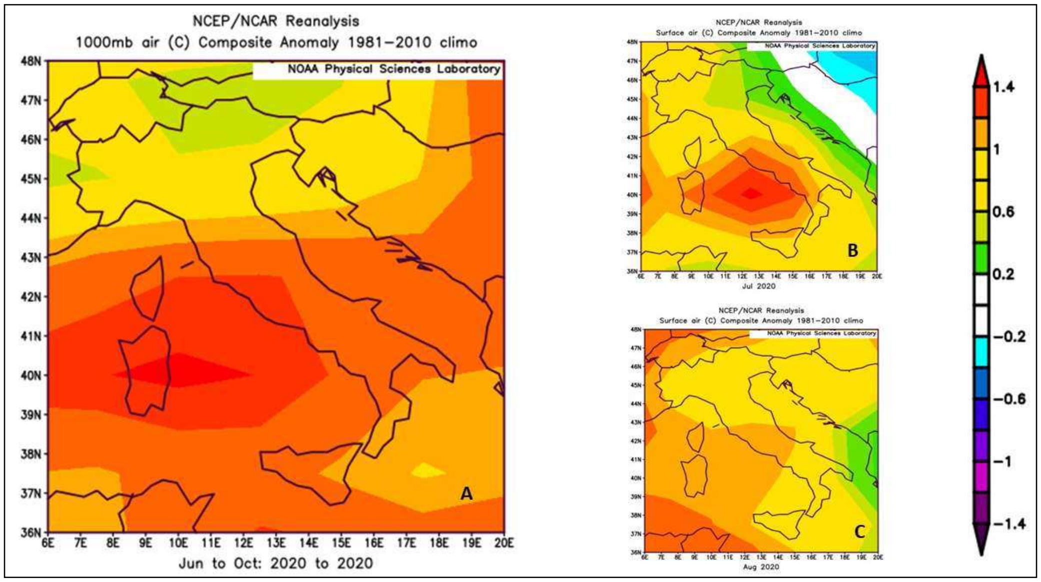

Figure 1. Air temperatures anomalies in Italy during the period June–October 2020 (**A**), July (**B**), and August 2020 (**C**) compared to the reference period 1981–2010. Data obtained from https://psl.noaa.gov/cgi-bin/data/composites/printpage.pl, accessed on 27 January 2022.

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).

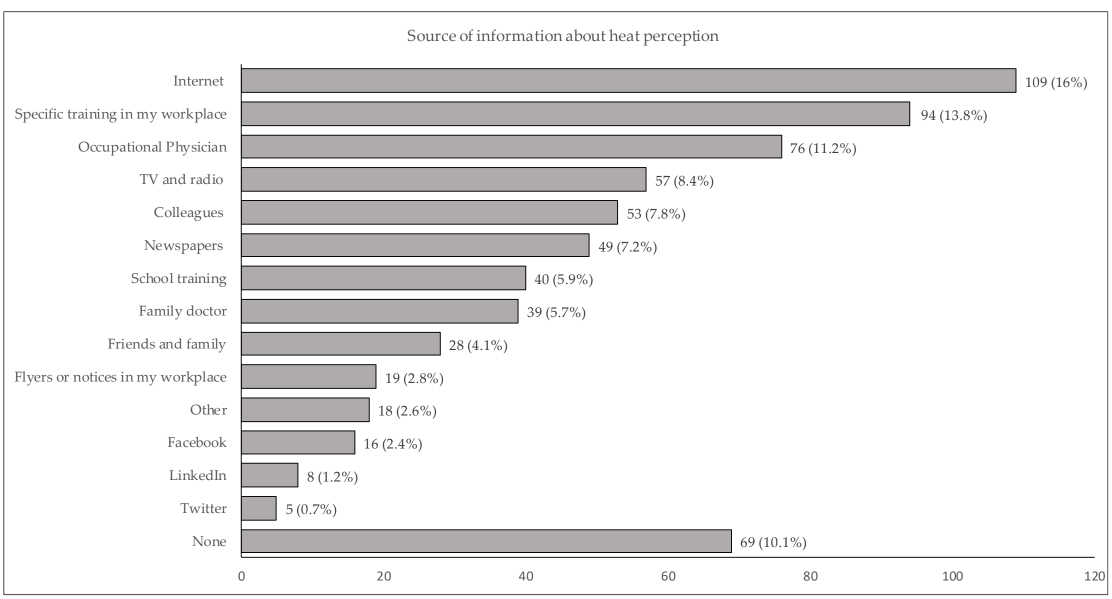

Figure 2. Frequencies and percentages of answers to the question 77—What are your main sources of information on the prevention of heat-related diseases in the workplace? (Multiple choice).

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).

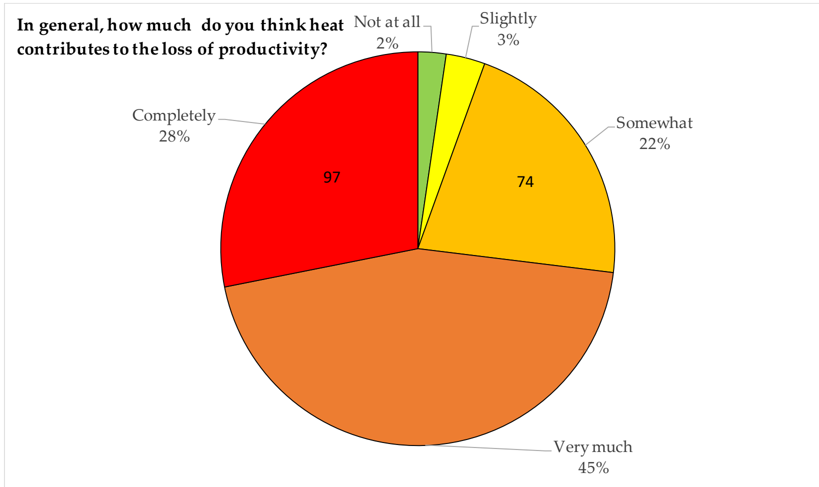

Figure 3. Frequencies and percentages of answers to the question 80—In general, how much do you think heat contributes to the loss of productivity?

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).

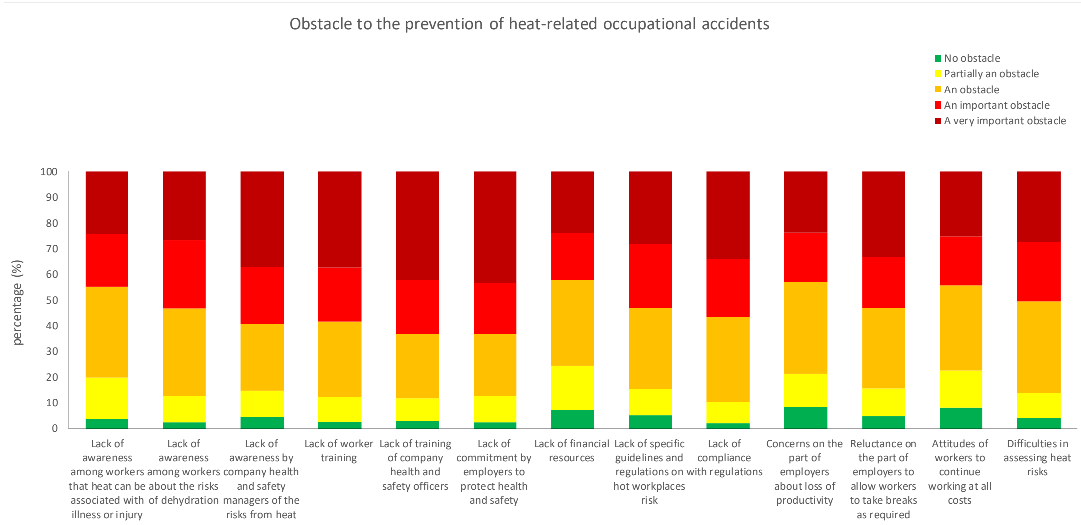

Figure 4. Percentages of answers to question 81—To what extent do you think that each of the following conditions can hinder prevention of heat-related occupational injuries? (A 5-point Likert scale from 1 = no obstacle at all to 5 = a very important obstacle).

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 pre-testing 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

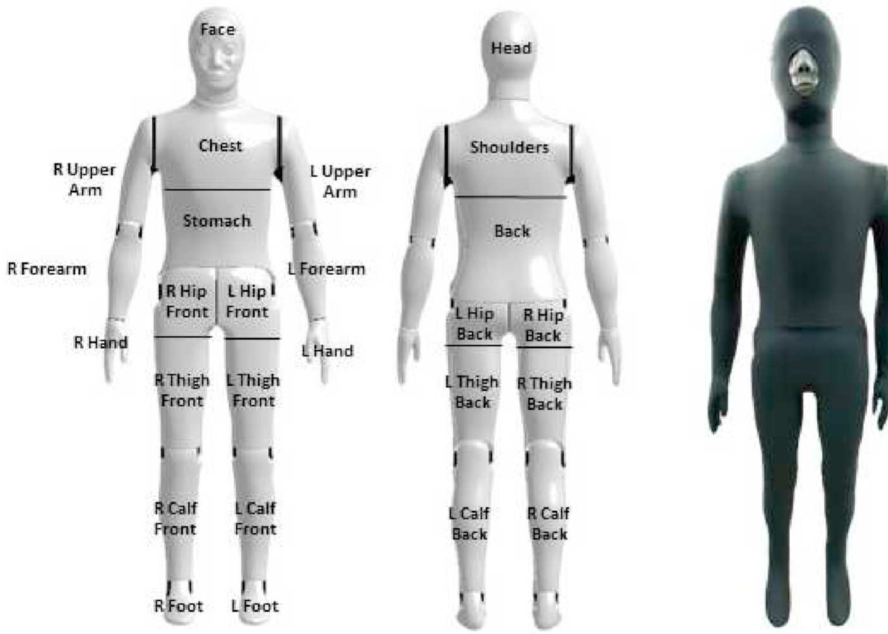

Fig. 2. The twenty-six thermal zones of Newton manikin and the fabric skin used in the "wet" tests.

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 $i = 1 \ldots 26$) 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

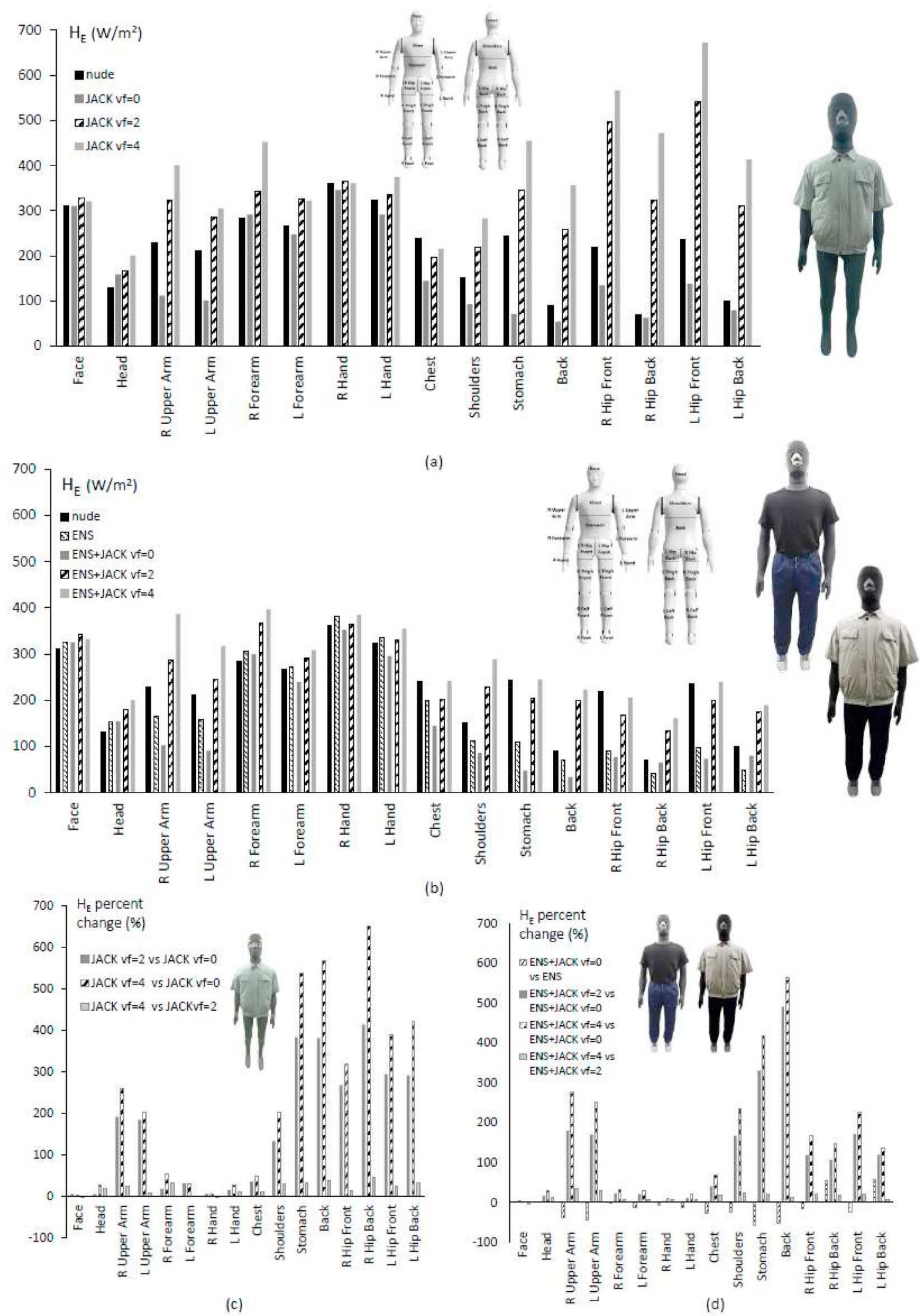

Fig. 3. H_E values of the selected thermal zones: (a) manikin dressed with only JACK; (b) manikin dressed with ENS and ENS + JACK. H_E percent changes:(c) manikin dressed with only JACK; (d) manikin dressed with ENS and ENS + JACK.

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

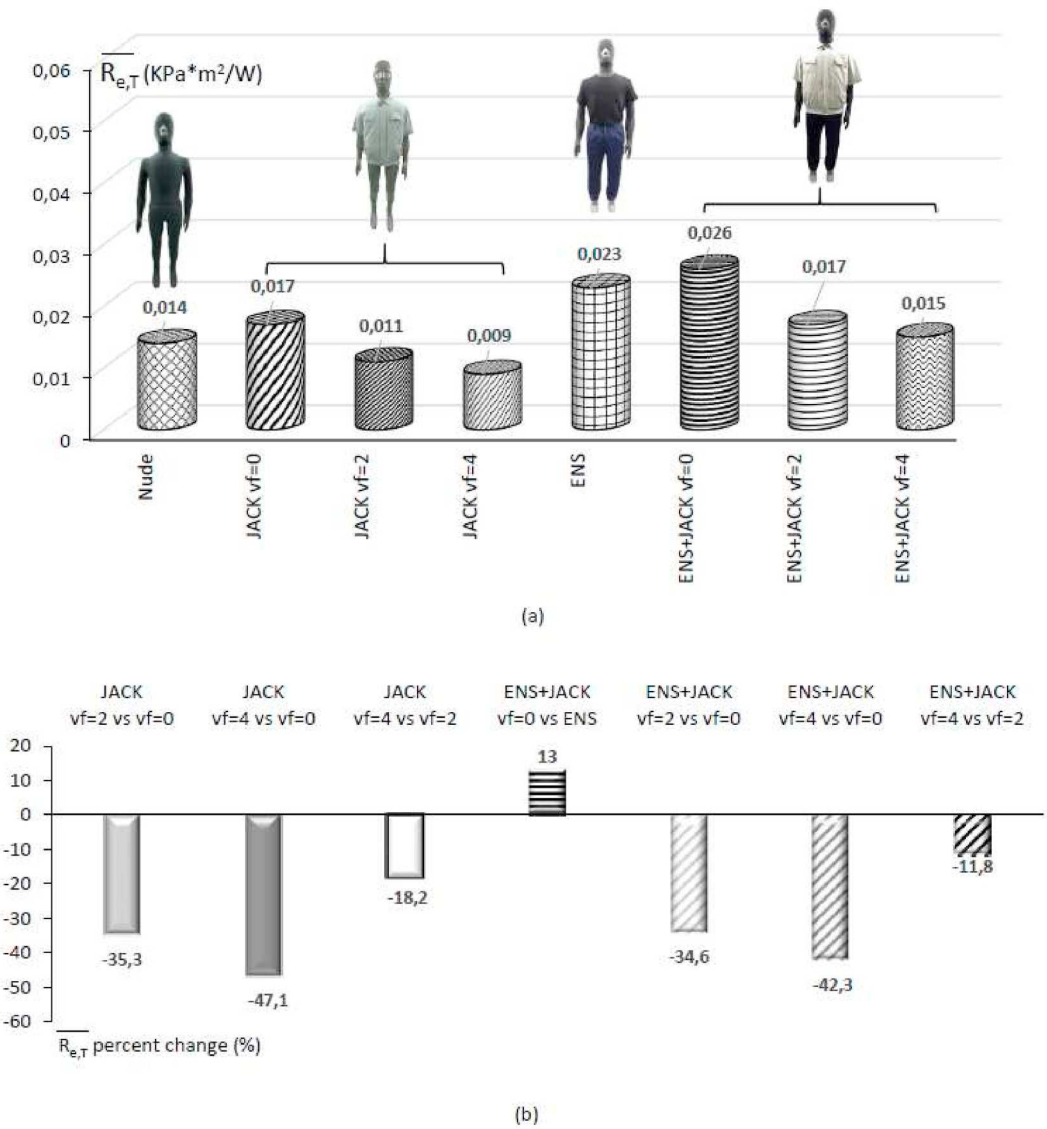

Fig. 4. (a) $\overline{R}_{e,T}$ values for the nude manikin and all the considered ensembles. (b) $\overline{R}_{e,T}$ percent change values.

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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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.

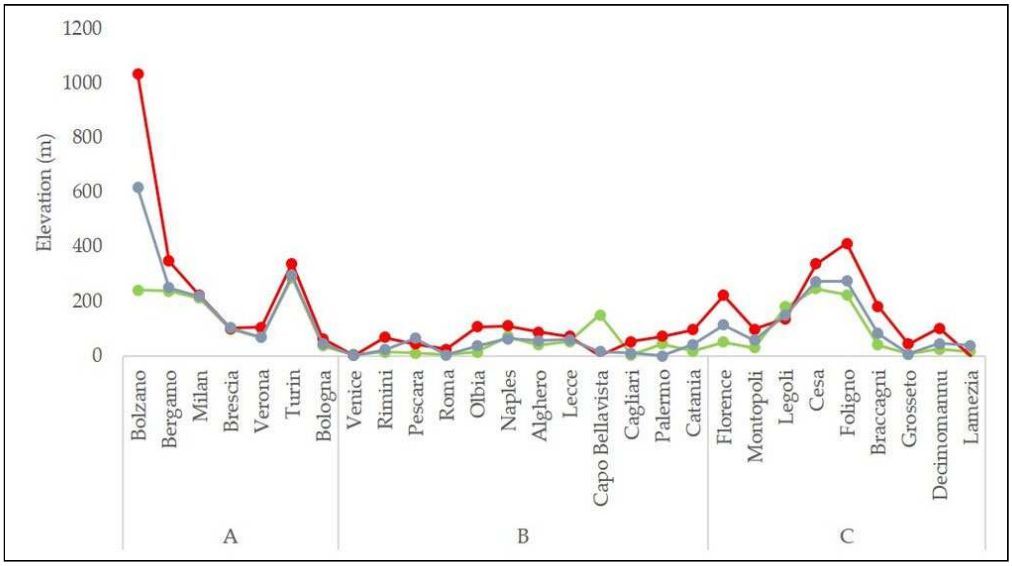

Figure 2. Elevation of the weather stations and the closest meteorological model grid points. Green line, weather station; Red line, BOL model; blue line, MOL model.

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).

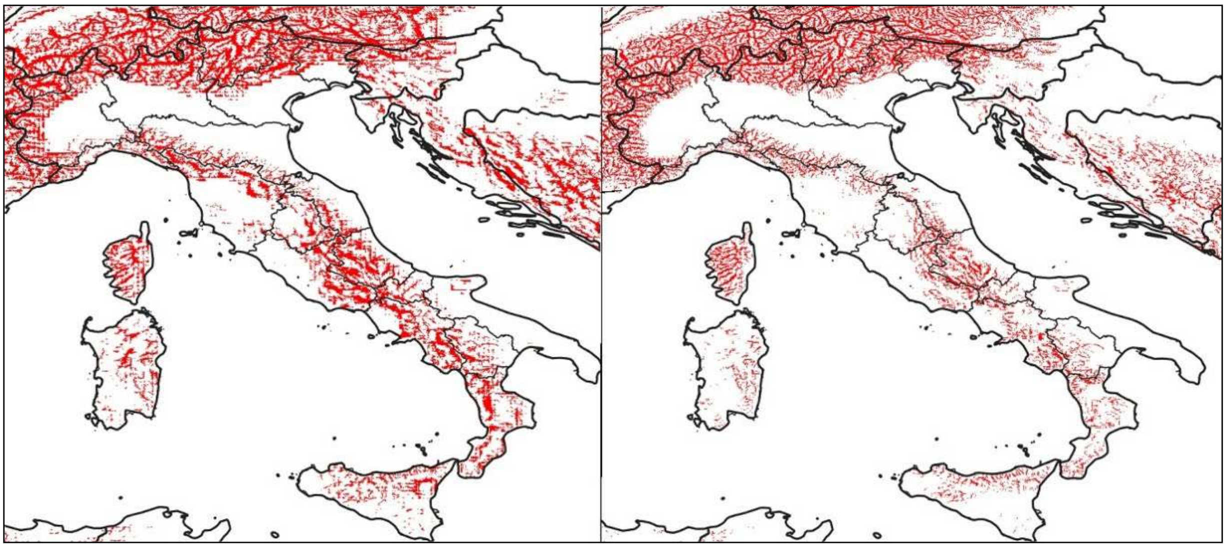

Figure 3. In red the areas of Italian peninsula where the models grid points (BOL on the left, MOL on the right) have an elevation higher than at least 200 m respect to that of a digital terrain model (DTM) with a spatial resolution of 90 m.

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]:

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

$$\text{WBGT RAL}(^{\circ}\text{C}) = 59.9 - 14.1 \log 10 \text{ MR} \quad (2)$$

$$\text{WBGT REL}(^{\circ}\text{C}) = 56.7 - 11.5 \log 10 \text{ MR} \quad (3)$$

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

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

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

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

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

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 RL $\geq$ 1.

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

- 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).

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

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

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

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

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

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

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

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

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

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

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

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

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

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.

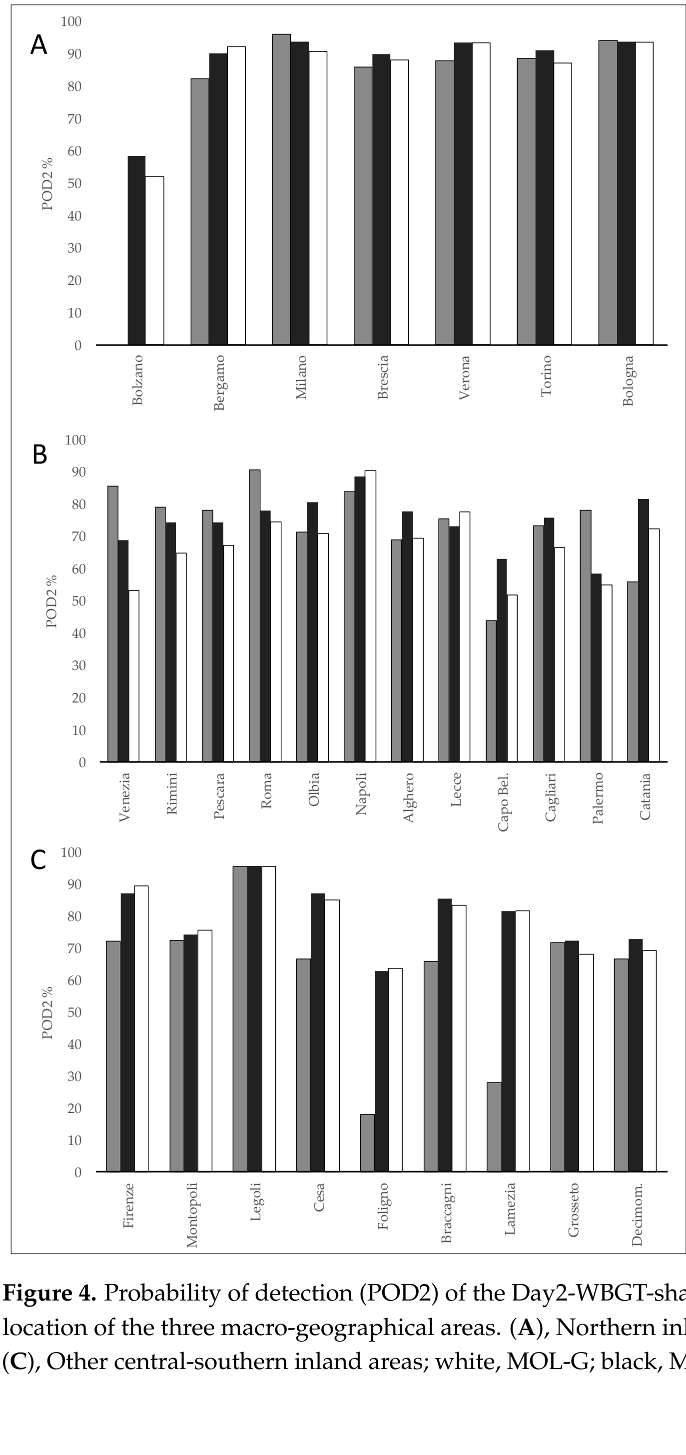

Figure 4. Probability of detection (POD2) of the Day2-WBGT-shade for the 12–18 time slot for each location of the three macro-geographical areas. (**A**), Northern inland plain areas; (**B**) Coastal areas; (**C**), Other central-southern inland areas; white, MOL-G; black, MOL-E; gray, BOL.

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" ($-0.8 < ME < 0$), 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.

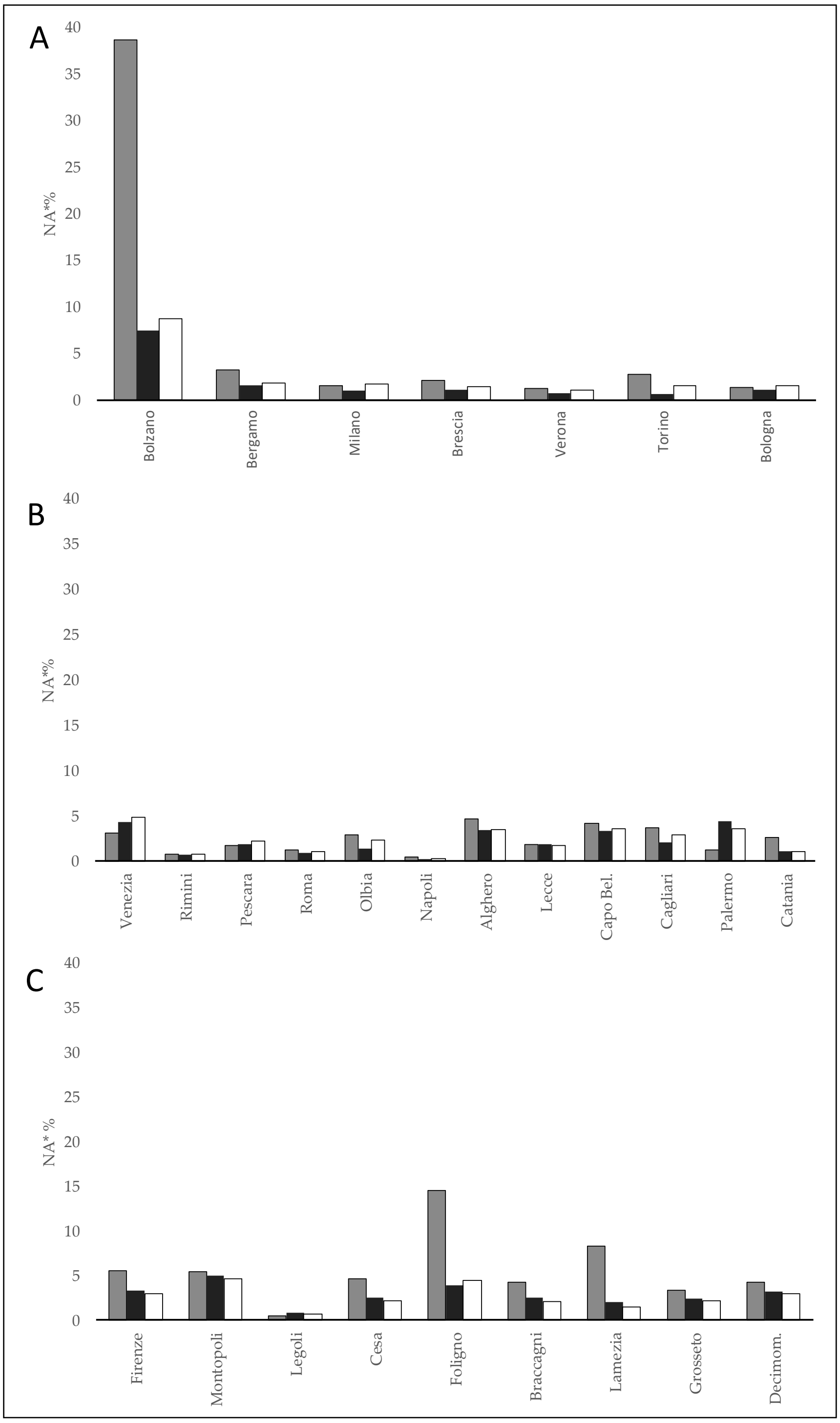

Figure 5. Normalized lack alarm (NA*) of the WBGT-shade for the 12–18 time band for each locality of the three macro-geographical areas. (**A**), Northern inland plain areas; (**B**), Coastal areas; (**C**), other central-southern inland areas; white, MOL-G; black, MOL-E; gray, BOL.

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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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.

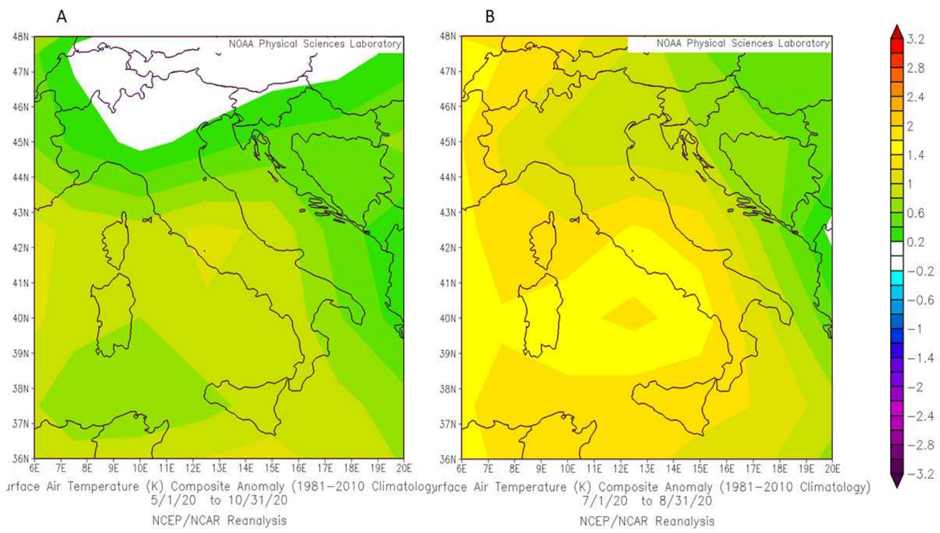

Figure 1. Air temperatures anomalies in Italy during the period May–October 2020 (**A**) and during the period July-August 2020 (**B**) compared to the climatology 1981–2010. Data obtained from https://psl.noaa.gov/cgi-bin/data/composites/printpage.pl, accessed on 6 April 2021.

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.

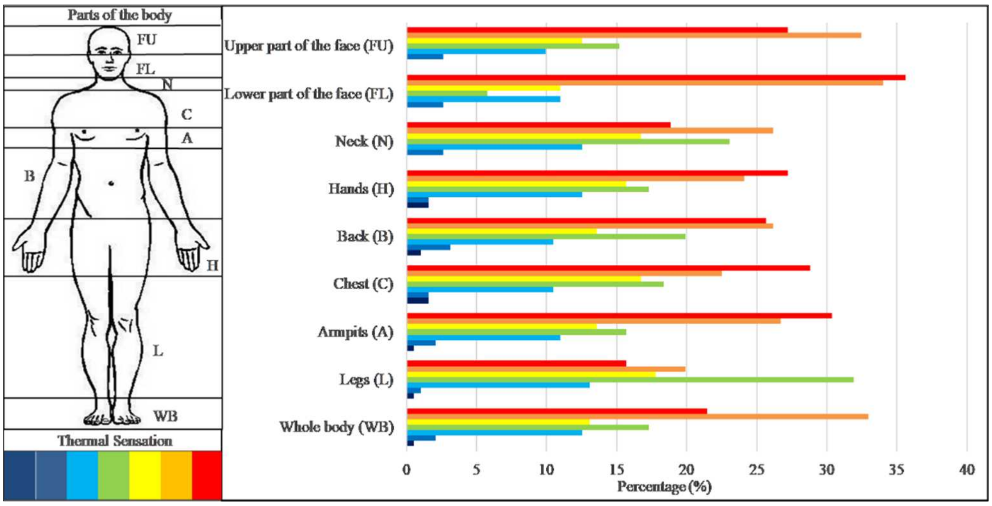

Figure 2. Thermal sensations declared by healthcare workers for each parts of the body covered by PPE during working time. Dark blue: Very cold; Blue: Cold; Light blue: Slightly cold; Green: Neutral; Yellow: Slightly hot; Orange: Hot; Red: Very hot.

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.

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

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.

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

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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Association between extreme ambient temperatures and general indistinct and work-related road crashes. A nationwide study in Italy

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A R T I C L E I N F O

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A B S T R A C T

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

Table 1 (*continued*)

Work-related road crashes	Cases (cases x1000 employees)	%
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

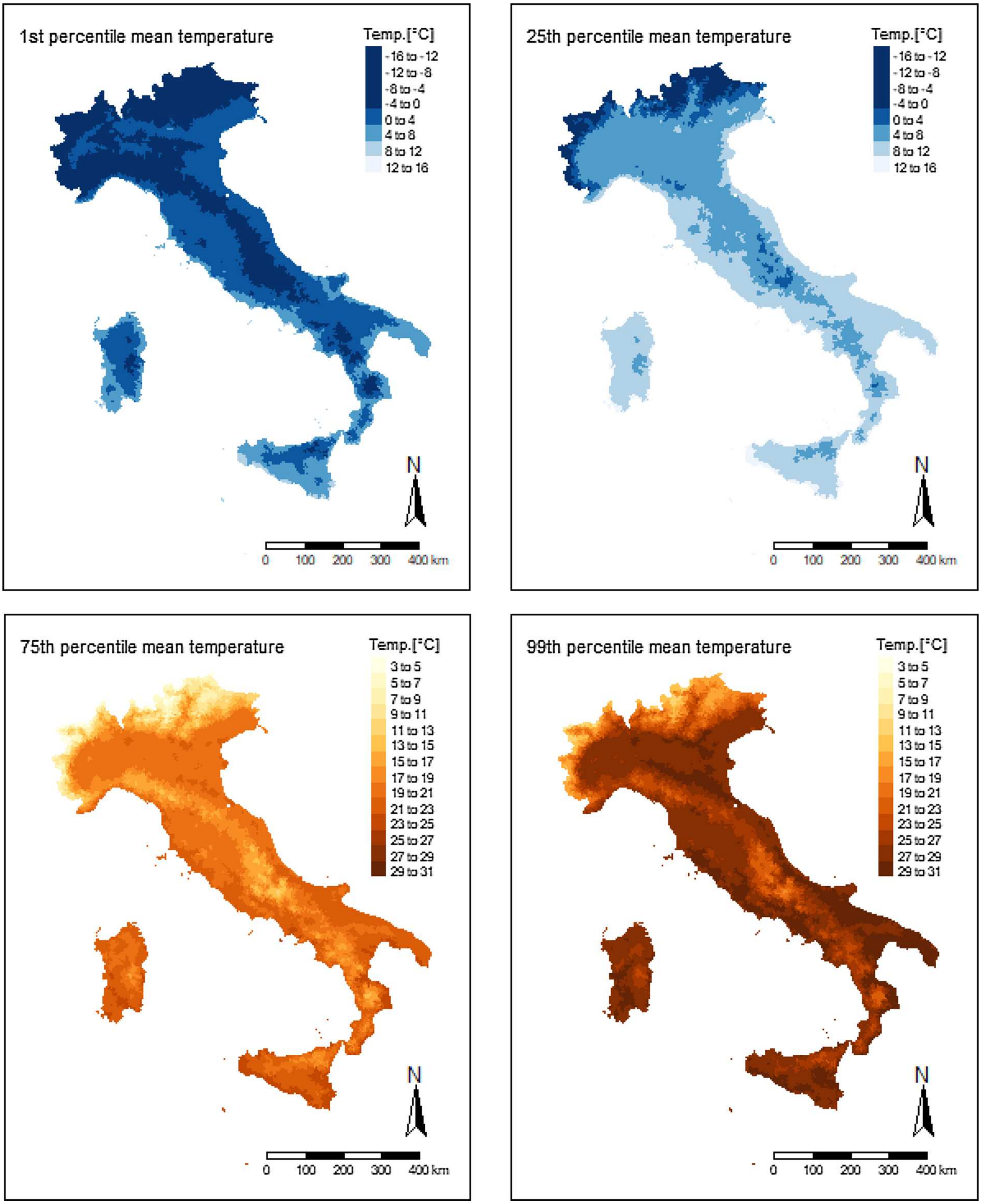

Fig. 1. Maps of 1st, 25th, 75th and 99th percentile of municipal temperature exposures based on results provided by the WRF meteorological model for years 2013–2015.

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 =

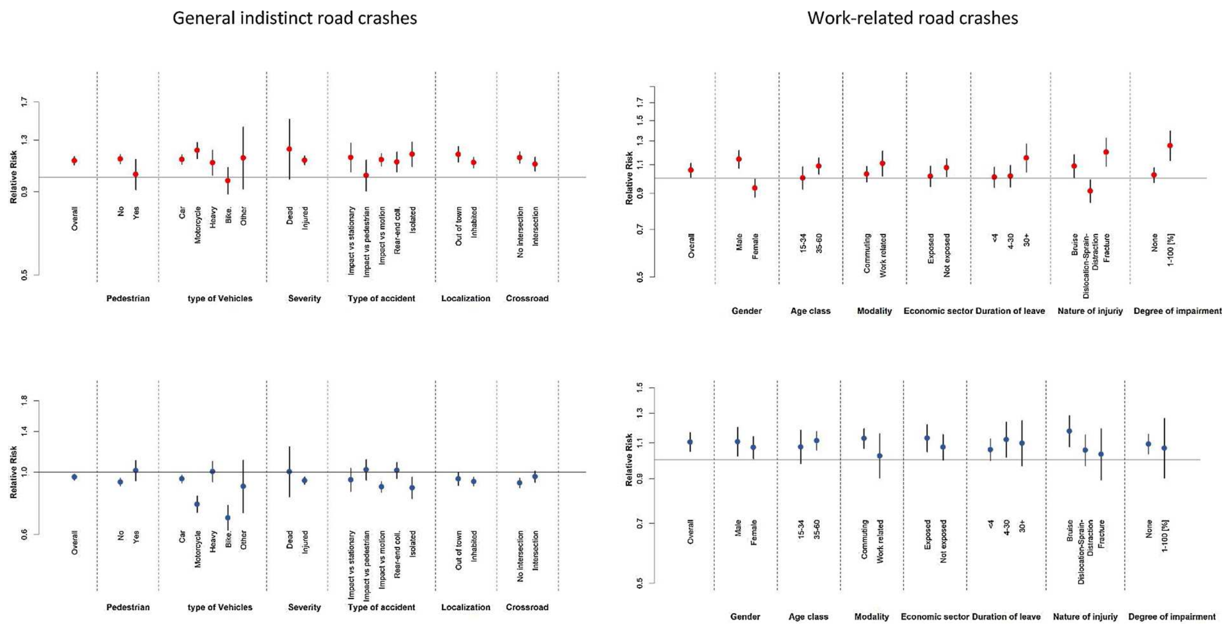

Fig. 2. Relative Risks by overall and effect modifiers for general indistinct (left) and work-related (right) road crashes, for hot (top) temperatures calculated for increments from 75th and 95th percentile and for cold (bottom) temperatures calculated for increments from 25th and 1st percentile.

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-related productivity loss: benefits derived by working in the shade or work-time shifting

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Abstract

Purpose – Agricultural workers represent an important part of the population exposed to high heat-related health and productivity risks. This study aims to estimate the heat-related productivity loss (PL) for moderate work activities in sun and shady areas and evaluating the economic cost locally in an Italian farm and generally in the whole province of Florence. Benefits deriving by working in the shade or work-time shifting were provided. Comparisons between PL estimated in Mediterranean (Florence, Italy) and subtropical (Guangzhou, China) areas were also carried out.

Design/methodology/approach – Meteorological data were collected during summers 2017–2018 through a station installed in a farm in the province of Florence and by two World Meteorological Organization

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(WMO)-certified meteorological stations located at the Florence and Guangzhou airports. These data were used to calculate the wet-bulb globe temperature and to estimate the hourly PL and the economic cost during the typical working time (from 8 a.m. to 5 p.m.) and by advancing of 1 h and 2 h the working time. Significant differences were calculated through nonparametric tests.

Findings – The hourly PL and the related economic cost significantly decreased ($p < 0.05$) by working in the shade and by work-time shifting. Higher PL values were observed in Guangzhou than in Florence. The decrease of PL observed by work-time shifting was greater in Florence than in Guangzhou.

Originality/value – Useful information to plan suitable heat-related prevention strategies to counteract the effects of heat in the workplace are provided. These findings are essential to quantify the beneficial effects due to the implementation of specific heat-related adaptation measures to counter the impending effects of climate change.

Keywords Climate change, Heat stress, WBGT, Black globe temperature, Bio-economy

Paper type Research paper

1. Introduction

Outdoor workers represent an important part of the population potentially at high risk of external heat exposure and related health effects for many easily understandable reasons. They have to work regardless of weather conditions, often involved in intense physical activities, even working for many hours to direct sun exposure (with no shade) or artificial radiant heat and, in several cases, wearing heavy personal protective clothing and equipment (Gao *et al.*, 2018) that limit the body heat loss. The advanced working age and the potential interaction between heat and chemical substances (i.e. pesticides and fertilizers) used in agricultural activities represent other important heat-related vulnerability factors. For these reasons, policy interventions and forward planning to protect workers from heat stress are urgently needed.

Today, the wet-bulb globe temperature (WBGT) index (Minard *et al.*, 1957) is the international reference among heat stress indices for workplace applications, and it is used as an international standard (NIOSH, 2016; ISO-7243, 2017).

In general, the combination of external heat exposure, additional heat sources in the workplace and internal heat production can cause heat strain that may result in clinical damages to organ functions, physiological changes and psychological changes (Kjellstrom *et al.*, 2016). This situation may lead to diminished occupational performance capacity through reducing working endurance, vision, coordination and concentration (Parsons, 2014), in this way reducing vigilance and potentially causing more mistakes while working, with a general performance degradation and a consequent increase of injuries (Binazzi *et al.*, 2019).

During extensive heat conditions, workers take more frequent and longer rests to prevent heat strain, which may cause significant reduction in labour productivity and individual economic output (Jackson and Rosenberg, 2010; Kjellstrom *et al.*, 2016). In a recent study (Day *et al.*, 2019), the authors reported that the heat-related PL is one of the most prominent "market impact" in studies on the economic effects of climate change. However, field studies that have tried to quantify the economic impact of heat stress based on worker's productivity are still very uncommon (Budhathoki and Zander, 2019; Vanos *et al.*, 2019), and there is no agreement among economists on which methods for estimations of these heat impacts would ensure reliability and validity for future projections (Kjellstrom *et al.*, 2019a).

The estimation of labour PL due to heat stress is currently possible by using the international ISO-7243 standard (NIOSH, 2016; ISO-7243, 2017) or the most recent risk function based on the few available epidemiological studies (Kjellstrom *et al.*, 2018).

Primary sectors of the economy are the occupational environments most affected by heat stress. Ensuring a reasonable standard of living for farm workers represents one of the general objectives for agricultural policy already set in the Treaty of Rome, signed in 1957 (Nilsson and Nilsson, 2005). Nevertheless, workers and their productivity are often overlooked in discussion about the heat effects (Kjellstrom *et al.*, 2016).

At European level, a great contribution on this topic is provided by the European project "Integrated inter-sector framework to increase the thermal resilience of European workers in the context of global warming" (HEAT-SHIELD) (https://www.heat-shield.eu/) that aims to develop solutions to protect the health and productivity in workplaces from excessive heat in the context of climate change. At international level, very important are the signals deriving from the study of heat stress conditions that are currently affecting workers living in countries located in tropical and subtropical areas. These countries are already experiencing severe and persistent heat stress conditions and that in the near future, due to climate change, may quickly affect also countries at temperate latitudes, which will require urgent and efficient adaptation measures. For this reason, some HEAT-SHIELD's partners are actively collaborating with Chinese colleagues studying the heat-related worker's health and productivity also in sub-tropical areas. At European level, the Italian HEAT-SHIELD's partners were involved during last summers in case studies collecting detailed micrometeorological data in some local farms with the aim of obtaining information on the effective heat stress conditions to which workers are exposed during typical working hours.

Italy is the third European country in terms of agriculture workforce, only after Romania and Poland (https://ec.europa.eu/agriculture/sites/agriculture/files/rural-area-economics/briefs/pdf/08_en.pdf). In 2017, almost 900,000 workers were employed in the Italian agricultural sector, which represents 3.8% of the national workforce and about 9% of the EU-28 agricultural workforce (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Farmers_in_the_EU_-_statistics). This labour force contributed about 2% to the gross value added produced by the Italian economy. The agricultural injury frequency in Italy in 2017 was about 5.5% (about 34,000 injuries) of the total national occupational injuries, and specific countermeasures preventing heat-related illness, such as worker breaks to access to cool potable water and to shade, wearing ventilated clothes and work-time shifting, are of primary necessity (Jackson and Rosenberg, 2010).

This study aims to estimate the potential hourly PL of workers for moderate (300 W) work activities in sun and shady areas assessed by using detailed micrometeorological data collected in the field during the summers 2017–2018, specifically in an Italian farm located in the province of Florence (Tuscany). The economic cost of the heat-related illness prevention through worker breaks under the situation in which the work-time recommendation is strictly followed was calculated. As this study is based on the hypotheses that the typical expected PL during the hottest season might be reduced by working in the shade or shifting the working time, these possible benefits were quantified. In addition, heat-related PL of workers were also estimated for the same periods by using data from two WMO-certified meteorological stations located at the Florence (Italy) and Guangzhou (China) airports, and PL comparisons between these two areas were provided. This type of investigation is potentially very useful because the Chinese subtropical location is already experiencing severe and persistent heat stress conditions during summer. For this reason, in-depth knowledge of the effect of heat stress on PL in the Chinese location can help to plan heat-related occupational prevention strategies also in Mediterranean areas to counteract the increasing heat stress forecasted in the next years due to the global warming.

2. Methods

2.1 Meteorological data and area of study

Local meteorological data were collected during summers (June 15 to September 15) 2017 and 2018 through a local meteorological station (HOBO U30 NRC) installed in a farm of wine and honey production in the province of Florence (Tuscany region, Central Italy) participating in case studies foreseen in the European HEAT-SHIELD project. Data on solar radiation (Wm^{-2}), barometric pressure (hPa), air temperature (°C), relative humidity (%), wind speed (ms^{-1}), wind direction (°) and black globe temperature (°C) were recorded at about 2 m above the ground during the whole study period with a time interval of 15 min. The black globe temperature was measured inside a 150 mm diameter black globe and validated by the comparison with a standard WBGT heat stress monitor instrument (Bruel and Kjaer, type 1,219).

For the same period and by using the NOAA Global Hourly Data Web platform of Climate Data Online (https://www.ncdc.noaa.gov/cdo-web/), hourly meteorological data of wind speed, air and dew point temperatures were collected from to WMO-certified meteorological stations located at the Florence (Italy) and Guangzhou (China) airports. The wind speed values measured at about 10 m were scaled up to 2 m according to the formula used in the study by Bröde *et al.* (2012). Solar radiation data were obtained by using daily solar radiation data downloaded by the Power Single Point Data Access web platform of NASA (https://power.larc.nasa.gov/data-access-viewer/) and then converted to hourly solar radiation by using the solar position and radiation calculator developed and maintained by the Washington State Department of Ecology (solrad.xls, version 1.0). This latter represents a translation of NOAA's JavaScript solar position calculator (http://www.srrb.noaa.gov/highlights/sunrise/azel.html).

Florence (lat. 43°46′17″N; long. 11°15′15″E, average altitude of 50 m a.s.l.) was included in this study because it is one of the warmest European cities under study within the HEAT-SHIELD project. According to the Köppen climate classification scheme (Rubel and Kottek, 2010), Florence is characterized by a borderline humid subtropical (Cfa) and Mediterranean (Csa) climate, with a moderate influence from the sea (the city is located 80 km from the Tyrrhenian Sea). Summers are hot, and the warmest months are July and August: mean monthly temperature of about 24 °C and a monthly mean dew point of about 17 °C (monthly mean values of relative humidity about 65%).

The Chinese city region of Guangzhou (one of the biggest Chinese cities) was selected because it is located in a subtropical area (23°12'N, 113°29'E, 72 m) with higher monthly mean air and dew point temperatures that easily create stressful sultry conditions during summer months. Guangzhou is located in a subtropical monsoon climate region (Köppen Cfa) usually experiencing long summers with high temperatures also associated with very high humidity levels. In particular, the warmest months are July and August, with monthly mean temperatures above 28 °C and a mean dew point temperature slightly above 24 °C (monthly mean values of relative humidity close to 80%). Close to Guangzhou city, there are also major farming areas similar to the situation in Florence.

2.2 Heat stress index calculation

Heat stress conditions accounting for sun exposure and full shade situations were calculated in the locations under study by the WBGT index. WBGT was originally developed by US military ergonomists in the 1950s (Minard *et al.*, 1957) and is currently widely used and internationally recognized (NIOSH, 2016; ISO-7243, 2017) as a method for assessing heat stress conditions in occupational fields. WBGT considers the combination of several important microclimate variables, such as the natural wet-bulb temperature (T_{nwb}, °C), the black globe temperature (T_g, °C) and the dry-bulb temperature (T_a, °C), in this way estimating heat stress exposure in the sun and in the shade. The WBGT_sun (in conditions of direct short-wave radiation) equation was used (Eqn 1) because most of the work activities carried out in the farm involved in this study were outdoors.

$$\text{WBGT\_sun}(°C) = 0.7T_{\text{nwb}} + 0.2T_g + 0.1T_a \tag{1}$$

However, with the aim to understand the possible contribution that would be made working in shadow conditions, the WBGT_shade (no direct short-wave radiation) was also calculated (Eqn 2).

$$\text{WBGT\_shade}(°C) = 0.7T_{\text{nwb}} + 0.3T_g \tag{2}$$

As seen from Eqns 1 and 2, T_{nwb} is the largest component (70%) of WBGT. T_{nwb} is a combination of air temperature and humidity, but it is also influenced by heat radiation and wind speed. T_{nwb} was calculated by the Liljegren method (Liljegren *et al.*, 2008), implemented in the heat stress calculation tool provided by the Climate Chip (Climate Change Health Impact and Prevention) Web platform (http://www.climatechip.org/). Today, WBGT represents the most commonly used heat stress index for workplace applications (Kjellstrom *et al.*, 2016; Takakura *et al.*, 2017) because it also includes recommendation for intrahourly rest/work cycles at different metabolic rates clearly specified by ACGIH (2015) and the international standard (ISO-7243, 2017).

2.3 Productivity loss (PL) estimation

The hourly PL due to heat stress was estimated for workers involved in moderate work activities (300 W) exposed in the sun and in the shade by using two risk functions: (1) based on ISO-7243 (NIOSH, 2016; ISO-7243, 2017); (2) based on epidemiological data (Kjellstrom *et al.*, 2018).

The ISO-7243 (2017) indicates, for various work intensity levels, the WBGT thresholds above which a worker should reduce her/his metabolic rate by performing several minutes of rest within an hour's work in order to avoid that the core body temperature rises above 38 °C. This situation avoids risks to the worker's health but also creates PL. In this study, the ISO-7243 risk function for moderate work activities (300 W) was used. These calculated breaks assume that the worker and their employers implement the ISO recommendations.

The other risk function was developed by Kjellstrom *et al.* (2018) reviewing the few epidemiological data sets currently available (Wyndham, 1969; Sahu *et al.*, 2013) for moderate work activities (metabolic rate of 300 W).

The shape of both risk functions (Figure 1) followed a cumulative normal distribution (Eqn 3).

$$\mathrm{PL}(\%), y = 0.5\left[1 + \mathrm{erf}\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right] \tag{3}$$

where μ and s represent the mean and standard deviation, respectively, of the associated normal distribution.

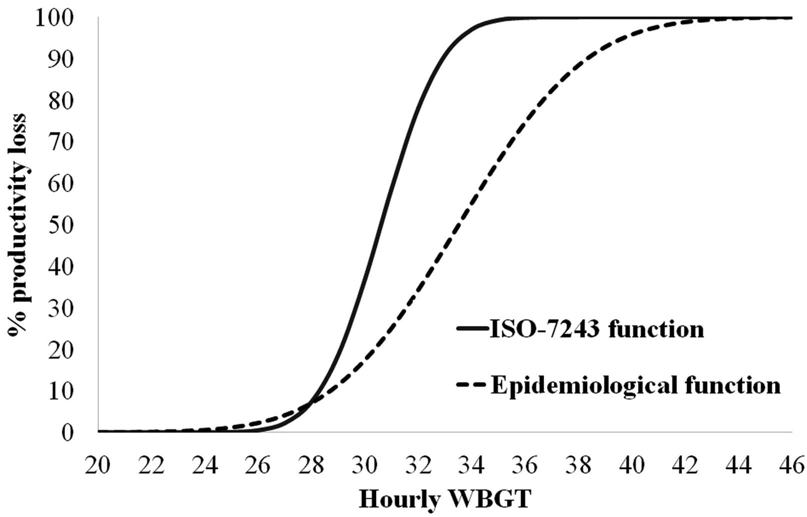

Figure 1. Estimated exposure-response relationships for reduced hourly work capacity (labour productivity) in jobs at 300 W intensity based on international standard (ISO-7243 function) and epidemiological data (Epidemiological function).

These risk functions directly convert a WBGT value in a percentage of PL (*y* is a value ranging from 0 to 100%) estimated considering that a worker reduces the work intensity with increasing heat stress, avoiding clinical problems (Kjellstrom *et al.*, 2018).

The daily mean PL was estimated accounting for workers exposed in the sun and in the shade by using meteorological data collected in the localities under study in three working times (WTs):

(1) $WT_{8–17}$: from 8 a.m. to 5 p.m. (with 1 h break from 12 a.m. to 1 p.m.) that represents the typical daily working hours of workers employed in the farm participating in the HEAT-SHIELD case study;

(2) $WT_{7–16}$: from 7 a.m. to 4 p.m. (with 1 h break from 12 a.m. to 1 p.m.);

(3) $WT_{6–15}$: from 6 a.m. to 3 p.m. (with 1 h break from 11 a.m. to 12 a.m.).

2.4 Economic cost estimation

The economic cost estimation was carried out on a local scale considering the exact number of agricultural workers involved in the farm (selected to participate in case studies of the HEAT-SHIELD project) located in a rural area of the province of Florence and on a larger scale estimating the annual work unit (AWU) involved in the wine sector in the whole province of Florence.

The Florence farm involved in this study included 18 workers engaged in outdoor activities addressed to viticulture and committed for 5 days a week (from Monday to Friday). After the administration of a self-assessment questionnaire on the impact heat on worker's activities, almost 80% of these workers (14 workers) declared that the heat, and especially the heat wave, has an impact resulting in a perceived PL. In particular, a perceived PL of about 10% declared by 7 workers; PL between 10 and 30% stated by 6 workers; even more than 30% declared by 1 worker.

According to the local territorial collective labour agreement for permanent employers (effective from May 1st, 2017), 14 workers were classified as "common workers", with a gross monthly salary of €1,305.90 (daily salary of €50.2), and 4 were classified as "qualified workers", with a gross monthly salary of €1,459.14 (daily salary of €56.1). Then, the economic cost due to PL of workers was calculated by multiplying the daily salary of all workers by the PL estimated by the risk functions (Eqn 4).

$$\text{Economic cost}(€) = \text{Workers salary}(€) x \text{PL}(\%) \tag{4}$$

Taking an example, considering a day with a 5% heat-related PL and the daily salary of 14 common workers (€50.2 × 14 workers × 5%) and the 4 qualified workers (€56.1 × 4 workers × 5%), the estimated daily economic cost would be €46.4.

Therefore, the economic impact estimated in this study is the economic cost of heat-related illness prevention through worker breaks under the situation in which the work-time recommendation is strictly followed. The quantitative economic estimation used in this study was similar to that already published in a previous case study carried out in Canada (Vanos *et al.*, 2019).

With the aim of extending the economic cost estimation to the whole province of Florence, the AWU indicator, already used in previous bioeconomic studies on agriculture (Spička and Smutka, 2014; Mantino, 2017; Nowak *et al.*, 2019) was calculated. As defined by the European Commission (https://ec.europa.eu/knowledge4policy/glossary/annual-work-unit_en), 1 AWU corresponds to the work performed by one person who is occupied on an agricultural holding on a full-time basis (about 1,800 h). In this study, AWU was calculated by using the number of hectares of vineyards in the province of Florence (just over 16,000 hectares in 2017) obtained by consulting the statistical database on agriculture of the Tuscany Region (https://www.regione.toscana.it/statistiche/pubblicazioni-statistiche/agricoltura) and the annual work (number of hours) necessary to manage 1 hectare of vineyard (270 h per hectare) obtained by consulting the hectare culture tables which allow to determine the required labour needs per hectare in the various crops (Decree of March 5, 2001, of the Italian Department of Agriculture and Forestry published on GURS N. 39 of August 3, 2001: Determination of the work requirement needed per hectare of crop). The economic cost estimation for the whole province of Florence was then obtained multiplying the AWU by the PL (hours of work lost during the summers) and by the hourly salary of a common agricultural worker.

2.5 Statistical analyses

Descriptive statistics of measured meteorological variables and WBGT during the three different working times ($WT_{8–17}$, $WT_{7–16}$, $WT_{6–15}$) were provided for the local Italian farm and the two WMO-certified meteorological stations located at the airports of Florence (Italy) and Guangzhou (China).

Hourly PL values for workers exposed in the sun and in the shade during the three different daily working times and the related economic costs were estimated during the whole summer period at the Italian farm. With the aim to increase the sample size, the economic cost was also estimated for the whole province of Florence. Significant differences between PL in the sun and shady areas and among different working times were calculated through the nonparametric Mann–Whitney and Kruskal–Wallis tests.

For the same period, similar analyses were also carried out assuming heat stress exposure of workers based on microclimate conditions recorded at the Italian (Florence) and Chinese (Guangzhou) airport meteorological stations. In this way, PL differences between the two cities were shown, and the possible benefits deriving by working in shady conditions or shifting the working time were quantified.

The computations were carried out by using the IBM SPSS Statistics, version 25.0.

3. Results

3.1 Productivity loss and economic cost estimation

Based on microclimatic and heat stress conditions (Table 1) monitored at the farm during the typical working time ($WT_{8–17}$) and the two modified working times ($WT_{7–16}$ and $WT_{6–15}$), the average values of most microclimate variables significantly decreased going from $WT_{8–17}$ to $WT_{6–15}$. The only exception was the relative humidity that instead revealed an opposite behaviour, thus showing significant increases progressively anticipating the working time. Even the average values of WBGT_sun and WBGT_shade revealed significant decreases by anticipating the working time of 1 h and above all 2 h: WBGT_sun and WBGT_shade decreased by about 10% and 8%, respectively, going from the typical working time ($WT_{8–17}$) to $WT_{6–15}$.

The PL in the shade was significantly lower (more than 80% lower) than the PL in the sun (Figures 2 and 3). The highest PL values were estimated with the ISO-7243 function.

Table 1. Hourly average microclimate variables and WBGT values in the sun (WBGT_sun) and in the shade (WBGT_shade) monitored at the farm during the summer 2017–2018 at different working times (WT_{8-17}, WT_{7-16} and WT_{6-15})

Variables	$WT_{8–17}$	$WT_{7–16}$	$WT_{6–15}$	p
T_a (°C)	27.0 (±5.6)	25.4 (±6.1)	23.8 (±6.3)	<0.001
RH (%)	51.6 (±20)	57 (±21.5)	61.9 (±22)	<0.001
V (ms^{-1})	1.0 (±0.9)	0.9 (±0.9)	0.8 (±0.8)	<0.001
T_g (°C)	36.6 (±8.3)	33.9 (±9.8)	31.1 (±10.8)	<0.001
WBGT_sun (°C)	24.7 (±3.7)	23.5 (±4.5)	22.2 (±5.1)	<0.001
WBGT_shade (°C)	21.8 (±3.1)	20.9 (±3.6)	20.0 (±3.9)	<0.001

Note(s): In round brackets, the standard deviation is indicated. Significant variations among the three different working times is calculated through the non-parametric Kruskal–Wallis test

In addition, higher statistically significant PL values were observed during the typical working time ($WT_{8–17}$) rather than PL observed by 1 h ($WT_{7–16}$) or 2 h ($WT_{6–15}$) work-time shifting (Figures 2 and 3). In particular, PL in the sun decreased by 18% if the workers started working 1 h earlier (starting to work at 7 a.m.) and even by 33% if they shifted the working time by 2 h (starting at 6 a.m.) respect to the typical working time (starting at 8 a.m.).

The hourly economic cost (considering the 18 workers involved in the Florentine farm) due to the PL in the sun during the typical working time ranged between €5.7 (PL based on the epidemiological function) and €8.0 (PL based on the ISO-7243 function). This impact was significantly reduced by anticipating of 1 h and especially 2 h the working time. In this latter case, the hourly economic cost ranged between €3.8 and €5.4 for PL calculated based on the epidemiological and the ISO-7243 function, respectively. The hourly economic cost due to the PL of workers engaged in shady conditions was significantly lower than the PL in the sun: it was always lower than €1.0 and even lower than €0.5 during WT_{6-15} regardless of the PL function used.

The total heat-related economic costs (the sum of both summers 2017 and 2018) in the farm estimated during $WT_{8–17}$ by using the epidemiological function ranged between about €6,000 for the 18 workers exposed to the sun (the economic cost could be even higher if PL

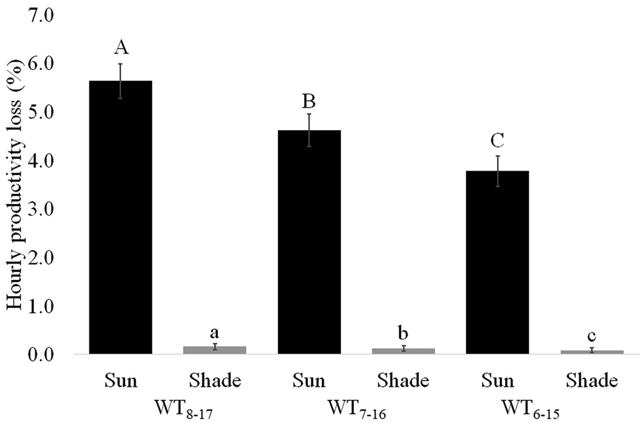

Figure 2.
Hourly productivity loss estimated by the ISO-7243 function in the sun and in the shade during different working times in an Italian farm (summers 2017 and 2018). Different letters indicate statistically significant differences ($p < 0.05$) between working times.

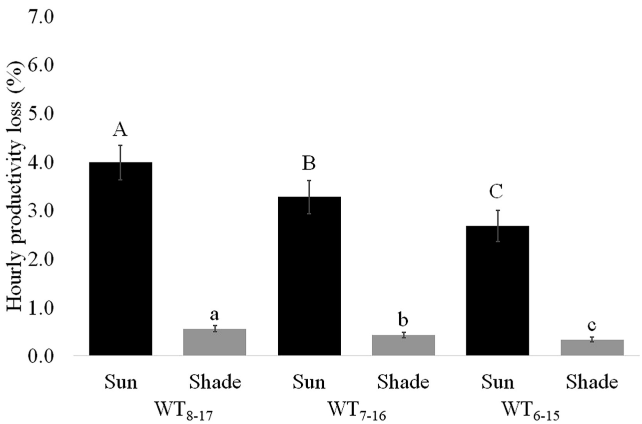

Figure 3.
Hourly productivity loss estimated by the epidemiological function in the sun and in the shade during different working times in an Italian farm (summers 2017 and 2018). Different letters indicate statistically significant differences ($p< 0.05$) between working times.

estimated with the ISO-7243 function was considered) and about €830 for workers working in shady conditions (Figure 4).

The economic cost estimation for the whole province of Florence revealed a labour input (in terms of persons working fulltime) of about 2,500 workers involved in the wine sector and the estimated total (the sum of both summers 2017 and 2018) heat-related economic cost ranged between about €800,000 for workers exposed to the sun during $WT_{8–17}$ and about €542,000 during $WT_{6–15}$ (a reduction of about 33%). The economic cost was significantly ($p < 0.01$) lower for workers working in the shade (about €113,000 for $WT_{8–17}$ vs. about €68,000 for $WT_{6–15}$).

3.2 Productivity loss differences based on meteorological data recorded at the Florence and Guangzhou airports

The hourly PL estimated during the typical working time ($WT_{8–17}$) by using the Florence airport meteorological data was lower than the PL estimated by using the local farm meteorological data (Figure 5). This result depends above all on significantly lower humidity levels at the airport (about 40% at the airport vs. about 50% at the farm) and higher wind intensities (about 2 ms^{-1} at the airport vs. about 1 ms^{-1} at the farm) than those observed at the farm, although the average air temperature at the city airport (28.4 °C ± 4.6) was about 1.4 °C higher than the rural one recorded at the farm, The relationships between the Italian (Florence) and Chinese (Guangzhou) PL estimated in the sun and in the shade calculated by using the airport meteorological data (Table 2) revealed substantial higher values in Guangzhou compared to Florence. The PL values estimated in the sun in Guangzhou were 7.3, 8.2 and 8.3 times higher than the PL values estimated in Florence when $WT_{8–17}$, $WT_{7–16}$ and $WT_{6–15}$ were considered, respectively. These relationships were even greater when PL values estimated in shady conditions were considered (Table 2).

The hourly PL for workers exposed to the sun in the Chinese location was always higher than 15%, even changing the working time (Table 2): the average WBGT value always remains next to 29 °C even anticipating working time by 2 h. The hourly PL in the sun decreased by 2.2% in Guangzhou and 12% in Florence if the workers started working 1 h earlier ($WT_{7–16}$) and even by 9.3% in Guangzhou and 20.2% in Florence if they shifted the working time by 2 h ($WT_{6–15}$), respect to the typical working time ($WT_{8–17}$).

On the other hand, the situation improves considerably in both cities if working in the shade was considered. In this case, in fact, the hourly PL in all working times ranged between

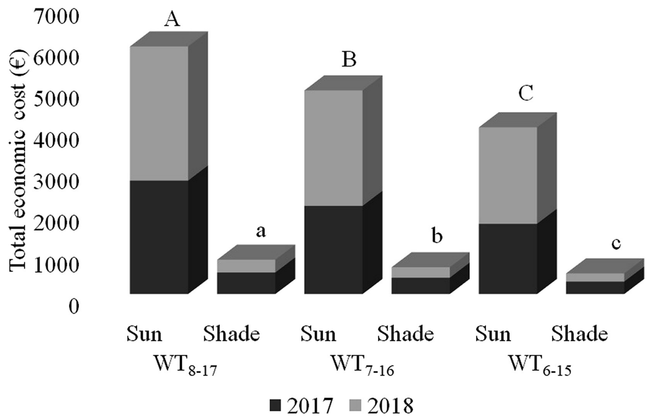

Figure 4.
Total heat-related economic costs in an Italian farm based on the productivity loss calculated based on the epidemiological function during summers 2017 and 2018. Different letters indicate statistically significant differences ($p < 0.05$) between working times.

7% and 6% in Guangzhou (little more than 60% reduction compared to working in the sun) and it was lower than 0.5% in Florence (little more than 80% reduction compared to working in the sun).

4. Discussion

This study is a concrete example of how even simple precautions, e.g. work in the shade or work-time shifting, represent effective adaptation strategies to reduce the typical PL of outdoor agricultural workers due to the increasing heat stress and consequently the economic cost during the summer season. The main findings of this study can be summarized as follows:

(1) The hourly PL and the related economic cost of agricultural workers decreased significantly by working in shady conditions and by work-time shifting, showing improvement effects especially by anticipating the typical working time by 2 h (start working at 6 a.m.).

(2) Hourly PL values estimated in all working times by using the Florence airport meteorological data were lower than that estimated by using the local farm meteorological data.

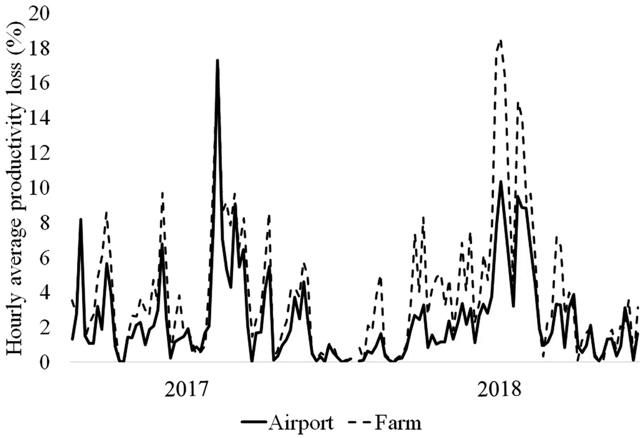

Figure 5. Hourly productivity loss in the sun estimated during the typical working time ($WT_{8\text{-}17}$) by using the epidemiological function based on meteorological data recorded in Italy (Tuscany) at the city-airport (continuous line) and the rural-farm (dashed line) during summers 2017 and 2018.

Table 2. Hourly productivity loss (%) calculated with the epidemiological function for workers exposed to the sun and working in shady areas in Florence (Italy) and Guangzhou (China) during the summers of 2017 and 2018

Working times	Productivity loss (%) for workers exposed to the sun [mean WBGT ± SD]		Productivity loss (%) for workers in shady areas [mean WBGT ± SD]	
	Florence	Guangzhou	Florence	Guangzhou
$WT_{8–17}$	2.4% (2.2–2.6) [24.2 °C ± 3.1]	17.4% (16.8–18.0) [29.5 °C ± 2.1]	0.4% (0.4–0.4) [21.8 °C ± 2.4]	6.8% (6.6–7.0) [27.5 °C ± 1.4]
$WT_{7–16}$	2.1% (1.9–2.3) [23.4 °C ± 3.6]	17.0% (16.4–17.7) [29.4 °C ±2.1]	0.3% (0.3–0.4) [21.3 °C ±2.7]	6.4% (6.2–6.6) [27.4 °C ± 1.4]
$WT_{6–15}$	1.9% (1.7–2.1) [22.4 °C ± 4.3]	15.8% (15.1–16.5) [29.0 °C ± 2.4]	0.3% (0.2–0.3) [20.6 °C ± 3]	5.9% (5.7–6.1) [27.2 °C ± 1.5]
p-value	<0.001	<0.001	<0.001	<0.001

Note(s): Confidence intervals are indicated in round brackets. Hourly mean WBGT ± the standard deviation are indicated in square brackets

(3) Significantly higher PL values were observed in the Chinese subtropical area than that estimated in Florence.

(4) The decrease of PL observed by work-time shifting (anticipating the typical working time) was greater in Florence than in Guangzhou.

The fundamental assumption of this work is based on the fact that when heat stress conditions occur, workers adapt their behaviour by taking longer and more frequent breaks (for resting and drinking); they generally slow down their work activities with the aim to maintain the core body temperature in safe limits. This assumption is even more robust increasing the intensity and the duration of the physical activity, consequently rising the metabolic heat production inside the body with higher risk of heat-related illness. This situation translates into a reduction of the effective working time causing a general PL and a consequent economic cost.

Studies that have tried to quantify the heat effect on workers' productivity and to estimate the economic impact are still very few (Roson and Van der Mensbrugghe, 2012; Chinnadurai *et al.*, 2016; Kjellstrom, 2016; Takakura *et al.*, 2017; Budhathoki and Zander, 2019; Vanos *et al.*, 2019). However, the exposure to heat stress is expected to increase significantly in the next years because of climate change (Mora *et al.*, 2017) also in areas where the worker population is not used to fighting this phenomenon (Kjellstrom *et al.*, 2018). In addition, as described in a recent report of the International Labour Organization (Kjellstrom *et al.*, 2019b), the cost to the world economy due to decreased labour productivity (especially due to the incessant increase in heat) is expected to be greater than that caused by any other major disruption related to climate change. For this reason, effective adaptation measures to the heat stress and the implementation of control measures in the workplaces are urgently needed to protect worker's health and economic losses (Chinnadurai *et al.*, 2016; Takakura *et al.*, 2017; Meegahapola and Prabodanie, 2018; Day *et al.*, 2019). Taking breaks in shady or cooled areas during working time according to specific heat stress conditions and physical efforts represent a fundamental heat-related adaptation method recommended by the International Organization for Standardization (ISO-7243, 2017) and other governmental agencies (ACGIH, 2015; NIOSH, 2016).

A recent study (Takakura *et al.*, 2017) provided a comprehensive assessment of the economic cost of heat-related illness prevention through worker breaks in the workplace. In particular, the authors calculated the heat-related worker breaks depending on the WBGT and the intensity of physical activity as reported in international standards (NIOSH, 2016; ISO-7243, 2017); however, our study revealed that the heat-related PL for moderate work activity could be more limited if a risk function based on epidemiological data is applied. This aspect is of great importance because the most accurate estimation of the heat-related PL should be based on epidemiological evidences.

However, because of the great difficulty in collecting quantitative information on PL directly in field work situations, only a few studies are available and the most detailed was carried out by Sahu *et al.* (2013) who estimated that approximately 5% of the work output at 26 °C in the first hour was lost for each °C of WBGT increase. This is one of the main limitations of our study where calculations are applied uniformly over the entire study population without considering any physical and or physiological variations, age factors and any morbidities that might play a significant role in work capacity of the workers. It is also necessary to consider that the overall costs estimation of the heat-related PL of workers involved in the wine sector for the whole province of Florence was calculated accounting for the AWU method who considers a full-time job. However, in the agricultural sector, and also in the wine sector, most are seasonal workers and for this reason, their number may change during the year. In addition, the qualitative aspect, which certainly represents another useful information for a more accurate estimate of the heat-stress-related cost, has not been analysed. The working quality depends, for example, by the timing when different work mansions are carried out, the use of personal protective equipment and work tools to carry out certain tasks, or worker's acclimatization. It is known that the heat stress has direct effects on the physical performance (mainly because of dehydration) as well as on cognitive functions (Cheung *et al.*, 2016; Piil *et al.*, 2018), therefore reducing the quality of the work done and increasing the risk of accidents in the workplace. For these reasons, future studies on PL and cost estimations should also focus on the qualitative aspect. The latter will also be one of the goals of an Italian project of the National Institute for Insurance against Accidents at Work, whose acronym is "WORKLIMATE", that is about to start and that will focus on the social cost of accidents at work and on heat-related adaptation strategies for workers also accounting for qualitative information.

However, based on the currently available data, this study provides a good and useful example of quantitative estimate of the potential hourly PL of workers involved in moderate work activities in sun and shady areas in relation to thermal stress and that can be validated when field data will be available.

The work of Takakura *et al.* (2017) suggested that shifting working time is also an effective adaptation measure to reduce the economic cost of heat-related illness prevention through worker breaks, and the authors concluded that future studies should quantitatively investigate the effectiveness of these adaptation measures in relation to outdoor work. A subsequent interesting study carried out by the same authors (Takakura *et al.*, 2018) also quantified on a global scale (grid cell of 0.5° x 0.5° resolution) the working time shift in hours that will be required in the future (based on climatic scenarios) to offset the labour capacity reduction. The authors partially confirmed the effectiveness of shifting working time also stating that climate change mitigation actions remain indispensable to counteract the increasing heat. However, this last study still had the limitation that it does not consider the hourly labour capacity calculation based on a more realistic epidemiological function (Kjellstrom *et al.*, 2018). In addition, for the purposes of the work itself, these studies (Takakura *et al.*, 2017, 2018) calculated the labour capacity for grid cell at low resolution (about 50 km resolution) and therefore useful for having a global picture but less representative of the real local situation. In fact, in this type of studies, some bias in the estimation of the WBGT could occur. Our study responds precisely to this last requirement providing accurate microclimatic monitoring at a local farm scale with the aim to obtain detailed and reliable quantitative information on the effectiveness of a specific heat-related adaptation strategy (the work-time shifting) useful for limiting the heat-related PL and the consequent economic cost. The present study also revealed the importance to estimate PL on the basis of local microclimate data: important PL differences can also be observed using microclimatic data recorded in areas not far from each other but located in different environmental contexts (i.e. peri-urban or rural areas). Our findings even revealed that the estimated PL during working hours was higher in a rural area (farm), characterized by high humidity rates and less ventilation, compared to a peri-urban area (where the airport is located), although the latter had shown an average air temperature higher than the rural area. Studies in outdoor environments, where especially the solar radiation might play a strong contribution in determining heat stress for outdoor workers, great attention should be addressed to the measure of T_g. In general, the outdoor monitoring of this parameter is carried out for study purposes and very limited time periods (some hours of monitoring). In our study, T_g was monitored outdoors at the farm every hour continuously for two summers (2017–2018). This represents a strength point because it allows the availability of a relatively long time series of T_g values directly measured in work field (also potentially useful for validation of T_g values estimated from global low-resolution models) and not its estimation obtained through modelling approaches by using other variables and which can favour bias in the WBGT calculation. In this way, the accurate estimation at the farm of the outdoor heat-related PL during different daily working times revealed significant PL reductions by shifting the working time (starting earlier in the morning) and working in shady areas. In particular, the "typical" heat-related PL in the sun and the consequent economic cost calculated over the entire study period could have been reduced up to 33% by starting to work 2 h before (starting at 6 a.m.) the typical working time. This result support the conceptual framework provided by Day *et al.* (2019) useful to help decision makers identify suitable climate-related adaptation options to counteract the effects of heat. These authors stated that behavioural measures such as changing working hours to avoid the hottest parts of the day, together with regular drink breaks, might be effective and often cheaper than technical solutions in dealing with temperature peaks especially for outdoor workers. However, our findings also revealed that this behavioural solution reduces the problem of the heat-related PL but does not allow a complete resolution of this phenomenon because an hourly PL in the sun ranging from 2.7% to 3.8% (depending on the PL function adopted) during the summer period is shown even starting to work early in the morning. This result is in agreement with the recent work of Takakura *et al.* (2018) that confirmed the effectiveness of shifting working time (starting earlier in the morning) as an adaptation measure for reducing, but not completely eliminate, the problem of the labour capacity reduction due to climate change. For this reason, they highlighted the importance of climate-change mitigation to minimize the impact of heat. In particular, the authors stated that outdoor workers in many parts of the globe should start working before sunrise if they want to substantially contain the labour capacity reduction. However, shift work alters the usual living patterns of the worker and result in some degree of sleep deprivation whose effects in living patterns on heat tolerance are mostly undocumented (NIOSH, 2016), and for this reason, the shift of working time should be reasonably contained. In addition, it must also be considered that changing working time may be constrained by cultural factors (Day *et al.*, 2019). Nevertheless, in Tuscany, many farms usually change their working time during the summer generally starting the early morning hours and in any case by interrupting the intense work activities during the early afternoon. At Italian latitude, starting to work at 6 a.m. means starting after sunrise during June and July but also start working before sunrise during August and above all September.

However, our study has also shown that another adaptation measure, such as favouring work in shady areas, can significantly improve the situation, bringing the hourly PL for the Italian location on very low values, largely below 1%. Therefore, improving the effectiveness of the rest periods by making the workers rest in shady and well-ventilated areas or still using mobile shading structures (even simply large umbrellas or gazebos with wheels) represent solutions that could significantly reduce the heat-related PL and the consequent economic impact preserving the worker's health. In addition to the preventive measures previously described, other strategies can also be adopted with the aim to protect worker's health and to reduce PL. Together with governments, both employers and workers should be involved in the design and implementation of the best mitigation and adaptation policies (i.e. reorganization of production processes, how to adjust working hours, how to distribute the various work activities throughout the day, technological improvements, etc.), in this way ensuring compliance with health and safety standards and finding practical solutions to enable workers to cope with high temperatures and allowing employers avoiding or limiting PL (Kjellstrom, 2019b). A recent technical report developed in the framework of the HEAT-SHIELD project (Technical Report 12 - D4.1 Final Report (WP4) available at: https://www.heat-shield.eu/technical-reports) described and updated, based on the recent scientific knowledges, the various solutions and strategies to mitigate or minimize negative effects of excessive heat exposure in the agricultural sector. In particular, it is advisable that agricultural firms (independently from the firm size) consider/develop an appropriate heat response plan useful for both employers and employees. The report describes in detail the hydration options, characteristic of breaks, timing of work, cooling interventions during breaks and works and clothing strategies that should be brought to the attention of agricultural workers through their employers with the aim of protecting the worker from the dangers of the heat and preserving productivity. More field studies are needed to investigate the role of these and other factors in PL reduction, also supporting our results. A useful adaptation strategy is the recently developed multilingual European "HEAT-SHIELD occupational warning system" platform (https://heatshield.zonalab.it/). This forecast system contains customized information for workers (based on the physical demands of the job as well as on workers' physical, clothing and behavioural characteristics and on the work environment), includes short-term (5-day forecasts) recommendations related to how much hydrate (water intake) and rest (work breaks) useful to help heat adaptation for workers and also provides long-term heat-risk forecasts (up to about one month) for planning/organizing work activities useful for employers, organizations and operators in charge of safeguarding health and productivity in various occupational areas (Morabito *et al.*, 2019). Because of the increasingly evident effects of climate change that find the highest expression in global warming, more and more attention will have to be addressed to implement effective heat-related adaptation strategies to reduce (or at least to contain) the expected PL in many occupational sectors. As reported by a recent work (Kjellstrom *et al.*, 2018), the severe heat stress conditions and the consequent substantial reduction of work capacity and labour productivity that are currently affecting for long time-periods some tropical and subtropical areas, will soon affect wide areas of the world, including southern parts of Europe. The comparisons between PL values estimated in Chinese subtropical and Italian Mediterranean cities shown in our study revealed how important is this investigation in various geographical areas of the planet that may require suitably different strategies to counteract the effects of heat in the workplace based on local microclimatic characteristics. For example, our study has shown that in Guangzhou, it is much better to prefer work in the shade than to anticipate working time because thermal stress remains unchanged even anticipating work-time: the average values of WBGT always remain close to 29 °C. In addition, in-depth knowledge of the effect of heat stress on PL in other geographical areas that are already experiencing detrimental heat stress conditions (taking into consideration the substantial differences in terms of sunrise/sunset time, the solar angle and the diurnal WBGT variation) might help to plan heat-related occupational prevention strategies in other areas, such as Mediterranean cities, to counteract the increasing heat stress forecasted in the next years due to global warming. The Mediterranean area, together with other European areas, is considered one of the most prominent "Hot-Spots" in future climate change projections (Giorgi and Lionello, 2008), also confirmed by the Fifth Assessment Report of the IPCC (IPCC, 2014). Based on the Climate Chip Web platform, thermal stress conditions predicted in Florence for the period 2071–2099 will be in several months similar to those currently observed in Guangzhou (period 2011–2014) (Figure 6). In particular, Florence will experience maximum monthly WBGT values higher than 28 °C in July and August by the end of this century with significant impacts on hourly PL as Guangzhou is already experiencing.

Consequently, Italy would also experience severe losses in agricultural production, due to physical factors, such as the increased temperature and reduced water availability (Galeotti and Roson, 2012), but also due to factors related to the health of agricultural workers who, exposed to conditions of heat stress for increasingly persistent periods, will see their productive efficiency at work significantly reduced. This aspect is of great importance in the wine sector of Tuscany: wine cultivation represents one of the pillars of agriculture in this region, with important effects on the local economy. Unfortunately, the share of agriculture of the total GDP decreased in Italy since 2000 (it was 2.6% of GDP) reaching 1.9% in 2017 (https://data.worldbank.org/indicator/NV.AGR.TOTL.ZS?locations=IT&view=chart).

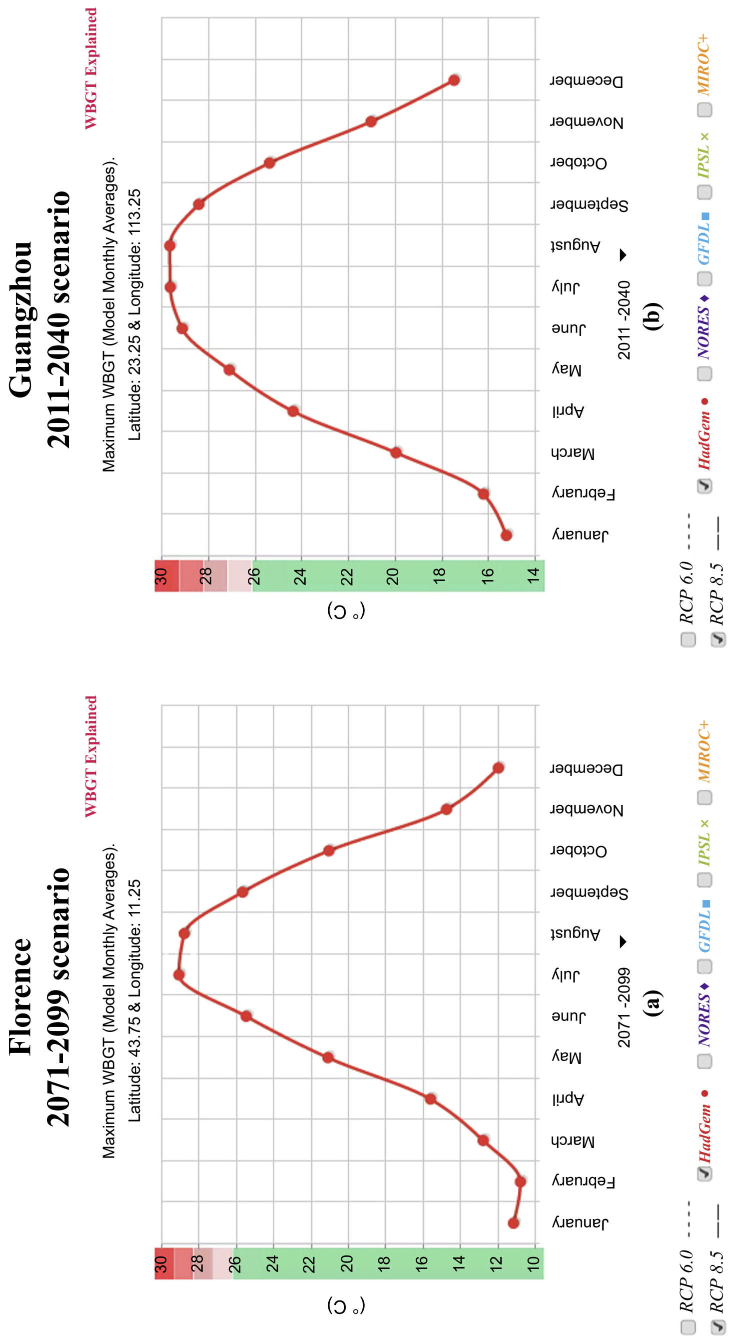

Figure 6.
Maximum monthly WBGT predicted based on the UK Met Office model HadGEM2-es (HadGem) and RCP 8.5 for the period 2071-2099 in Florence (a) and for the period 2011-2040 in Guangzhou (b) (source ClimateCHIP website: http://www.climatechip.org/).

Considering only the situation in central Italy (the area where the farm involved in our study was located), the estimate of the GDP in the agricultural sector referring to 2017 has shown a marked decline compared to 2016 (−8.4%) (https://www.istat.it/it/archivio/217603). This reduction (especially observed in the wine sector) is certainly due to the adverse weather conditions that characterized much of 2017 (e.g. the dry summer). In particular, the summer of 2017 was yet another summer with temperatures decidedly above average in the province of Florence and with widespread heat stress conditions for workers. The 2017 was one of the harvests most affected by the climate change of the last few years, both in terms of quality and quantity, with a strong reduction in wine production in Tuscany: 1 million hectolitres less than the previous year (1 million 600 thousand hectolitres), with a decrease of 38% based on the Tuscany Region report relating wines in Tuscany in 2017 (https://www.toscana-notizie.it/-/scheda-il-rapporto-sui-vini-in-toscana-nel-2017).

As the effect of heat stress on labour productivity is considered a key economic impact of climate change, which could affect national output and workers' income (Day *et al.*, 2019), a better management of the agricultural workforce through behavioural measures (i.e. work-time shifting) during the summer period would certainly represent a strong point to limit the economic cost. These adaptation strategies, together with mitigation actions, are strongly recommended and urgently needed especially for outdoor workers committed to work in increasingly intense and persistent heat stress conditions which will affect wide geographical areas in the coming years.

5. Conclusions

This study confirms the hypothesis that the typical expected heat-related PL of outdoor agricultural workers engaged in a moderate activity (300 W) might be reduced during the hottest season by easy adaptation actions, such as working in shady conditions and by the work-time shifting. However, these strategies are improvement but not decisive actions to reduce the heat effect. In fact, PL still occurs even anticipating the working time of a couple of hours (starting to work early in the morning, around sunrise), although with significantly lower PL values than that estimated during the typical working time (from 8 a.m. to 5 p.m.).

The choice of the risk function to be used for estimating the heat-related PL, and the consequent economic cost, significantly influences the results: PL can be more limited if a risk function based on epidemiological data rather than the ISO-standard is used. Future studies will also have to consider the estimation of PL for workers engaged in activities with different intensity of effort.

Studies related to field monitoring and allowing the collection of detailed data aimed at quantifying the beneficial effects due to the implementation of specific adaptation measures for limiting the heat-related PL and the consequent economic cost are urgently need. In addition, the study of heat-related PL in various geographical areas of the planet and above all those that are already experiencing severe and persistent heat stress conditions can provide important indications to put into practice the best policy intervention and forward planning to counter the impending effects of climate change in Mediterranean areas.

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Heat warning and public and workers' health at the time of COVID-19 pandemic

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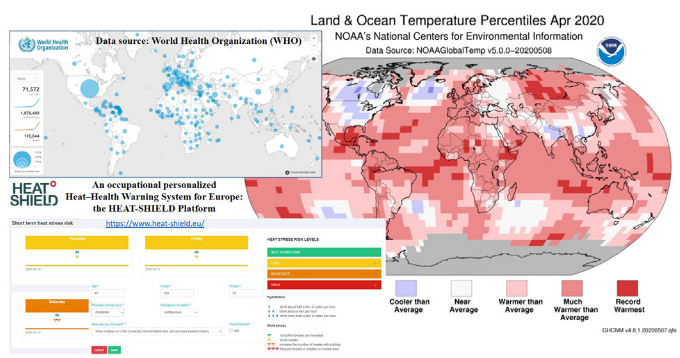
HIGHLIGHTS

- 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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ABSTRACT

The humanity is currently facing the COVID-19 pandemic challenge, the largest global health emergency after the Second World War. During summer months, many countries in the northern hemisphere will also have to counteract an imminent seasonal phenomenon, the management of extreme heat events. The novelty this year concerns that the world population will have to deal with a new situation that foresees the application of specific measures, including adjunctive personal protective equipment (i.e. facemasks and gloves), in order to reduce the potential transmission of the SARS-CoV-2 virus. These measures should help to decrease the risk of the infection transmission but will also represent an aggravating factor to counteract the heat effects on the population health both at occupational and environmental level. The use of a specific heat health warning system with personalized information based on individual, behavioural and environmental characteristics represents a necessary strategy to help a fast adaptation of the population at a time where the priority is to live avoiding SARS-CoV-2 infection.

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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

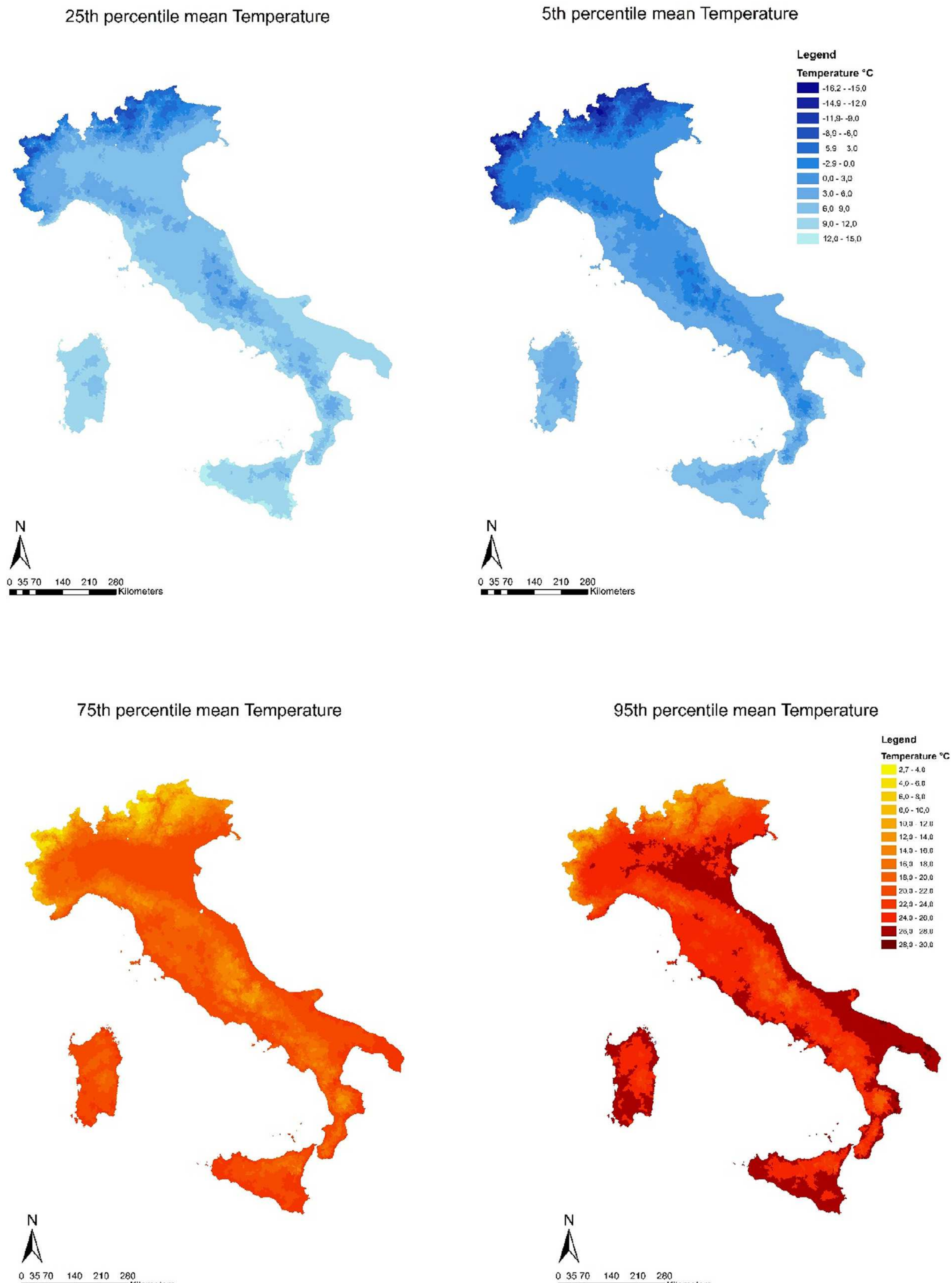

Fig. 1. Maps of 5th, 25th, 75th and 95th mean daily temperatures for each municipality in Italy during years 2006–2010.

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

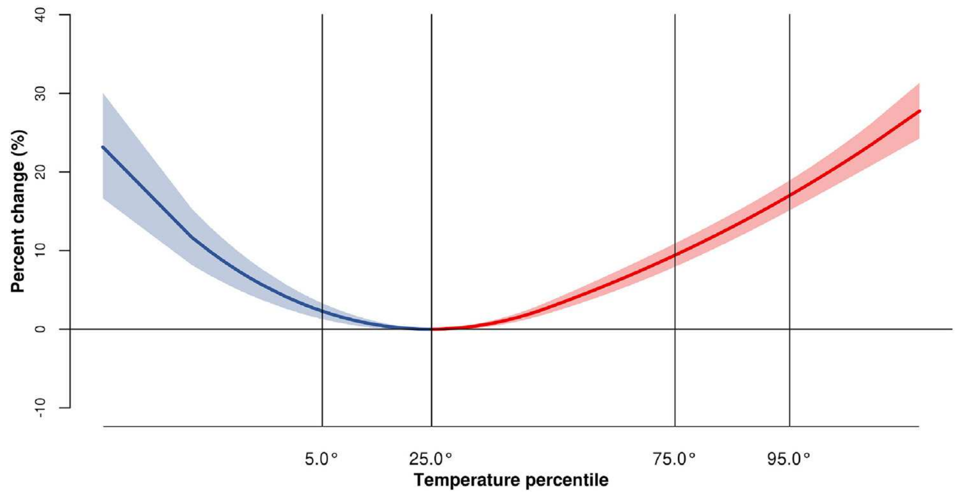

Fig. 2. Dose-response relationship. Percent change in work related injuries by temperature percentile. Blue and red areas correspond to cold and hot temperature effects. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

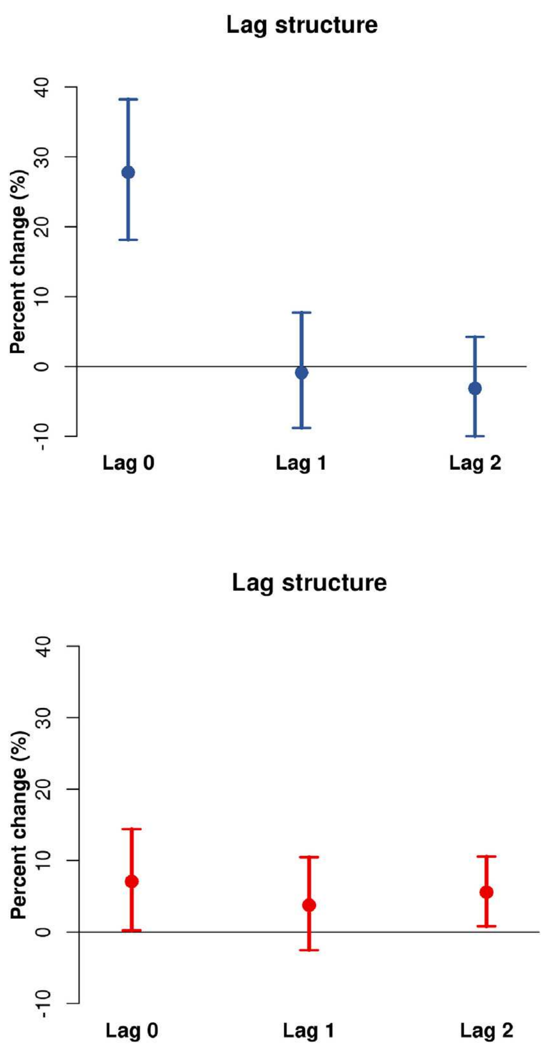

Fig. 3. Lag specific effects for the overall cumulative exposure-response relationship between outdoor temperature and occupational injuries for cold effects (a) and heat effects (b). Italy, 2006–2010.

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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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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An Occupational Heat–Health Warning System for Europe: The HEAT-SHIELD Platform

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Abstract: Existing heat–health warning systems focus on warning vulnerable groups in order to reduce mortality. However, human health and performance are affected at much lower environmental heat strain levels than those directly associated with higher mortality. Moreover, workers are at elevated health risks when exposed to prolonged heat. This study describes the multilingual "HEAT-SHIELD occupational warning system" platform (https://heatshield.zonalab.it/) operating for Europe and developed within the framework of the HEAT-SHIELD project. This system is based on probabilistic medium-range forecasts calibrated on approximately 1800 meteorological stations in Europe and provides the ensemble forecast of the daily maximum heat stress. The platform provides a non-customized output represented by a map showing the weekly maximum probability of exceeding a specific heat stress condition, for each of the four upcoming weeks. Customized output allows the forecast of the personalized local heat-stress-risk based on workers' physical, clothing and behavioral characteristics and the work environment (outdoors in the sun or shade), also taking into account heat acclimatization. Personal daily heat stress risk levels and behavioral suggestions (hydration and work breaks recommended) to be taken into consideration in the short term (5 days) are provided together with long-term heat risk forecasts (up to 46 days), all which are useful for planning work activities. The HEAT-SHIELD platform provides adaptation strategies for "managing" the impact of global warming.

Keywords: worker; customized forecast; Wet-Bulb Globe Temperature (WBGT); risk level; heat adaptation; work breaks; hydration; European Center for Medium Range Weather Forecasts (ECMWF); global warming

1. Introduction

Meteorological observations worldwide reveal significant increases of heat-stress conditions and future climatological scenarios report that we should expect far worse situations even in the most optimistic projections [1,2]. Workers, and above all outdoor manual workers, represent an important part of the population potentially vulnerable to heat stress [3–5]. In particular, work that involves high levels of physical exertion—such as heavy lifting and manual labor carried out for example by farmers, construction workers, fire-fighters, miners, soldiers, and manufacturing workers operating near artificial heat sources—are particularly affected since individuals tire faster and metabolize heat less effectively under exertion [3,4,6]. Workers are often exposed for many hours to direct solar radiation or artificial radiant heat, and in several cases wearing personal protective clothing and equipment that significantly aggravate heat stress by limiting body heat loss. An advanced working age or the potential interaction between heat and chemical substances (i.e., pesticides and fertilizers), used i.e., in agricultural activities, represent other important heat-related vulnerability factors. For economic reasons, workers may need to work during hot weather conditions, which impose an occupational heat stress; it is a public health issue. However, appropriate adaptation strategies could help to avoid heat-related health problems, and also limit the typical productivity loss that occurs during the warmer period of the year [7,8]. Although workers contribute enormously to economic growth, they are often overlooked in discussions about the effects of heat [9,10], and specific heat warning systems for occupational purposes are actually unavailable internationally.

An accurate and timely heat–health warning system (HHWS) represents one of the core elements nested in a wider Heat–Health Action Plan, which encompasses and directs all preventive measures to be taken to protect the population from the effects of environmental heat exposure [9,11]. At present, HHWSs aim at protecting the general population or people considered most vulnerable, such as the elderly population [12,13], even if in recent studies [10,14] young workers were found to be as vulnerable and at increasing risk of occupational injuries with high temperatures. Various metrics to define the effects of heat on health have been developed [9,15,16], based on different thermal (i.e., single-metric based on air temperature or heat stress index; heat budget models; air mass-based synoptic climatological approaches) and health indicators (generally mortality data, but also morbidity indicators could be used if available). In this way, different heat threshold levels based on epidemiological (i.e., city-specific heat-related mortality thresholds) or climatological (i.e., specific percentiles of the local distribution of minimum and maximum temperatures) evidences, or even based on heat stress levels assessed through specific thermal stress indices, have been developed and are currently used to issue heat warnings in HHWSs [9,17]. Concerning the occupational sector, a HHWS should be more focused on heat stress than mortality events or other health indicators addressed to the general population. This is because heat stress for workers represents a public health concern [5] and worker health and performance are affected at much lower environmental heat strain levels than those directly associated with higher mortality. When working in the heat, skin blood flow and sweat rate increase to allow for heat dissipation to the surrounding environment (thermoregulatory adjustments), thus increasing risk of heat-related injuries, kidney diseases and generally, physiological strain leading to dehydration [18,19]. A recent study [20] 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 higher heart rate associated with dehydration signifies an overall elevation of cardiovascular strain [21]. Dehydration may have an even larger impact on performance in cognitive occupational settings where people are exposed for prolonged periods to high heat stress levels and fail to prevent hypo-hydration [20]. Surely, a good adaptation to heat can help to prevent many negative consequences, even if it has recently been highlighted that heat acclimation may not be sufficient to protect against hyperthermia when complex tasks are performed [22]. Thus, the availability of timely heat stress warnings calibrated on specific work activities and accounting for the clothing worn would make it possible to reduce heat-related performance losses, especially in the case of prolonged heat exposure.

Due to the different needs of the occupational sector compared to the general population, a HHWS for occupational purposes should have some main characteristics. In particular:

- It should be personalized; that is, based on the physical demands of the job as well as on workers' physical, clothing, and behavioral characteristics and on the work environment;
- it should include short-term suggestions useful to help heat adaptation for workers;

- it should contain long-term heat risk information for planning/organizing work, which is useful for employers, organizations, and operators in charge of safeguarding health and productivity in various occupational areas.

To achieve this goal, a meteorological forecasting model for different lead times (with forecasts up to about one month) is necessary, as well as the use of a thermal stress indicator able to provide detailed information in various situations. Then, the metric used should account for the level of physical activity performed by a worker, which will obviously be influenced by personal physical characteristics (e.g., weight and height), the clothing worn, and the working environment, differentiating between a worker exposed to solar radiation, or other heat sources, and a person working in the shade.

At the international level, there is presently no example of a HHWS specifically targeting workers and capable of meeting the main characteristics listed above. At European level, an important contribution on this topic has been provided by the European project "Integrated inter-sector framework to increase the thermal resilience of European workers in the context of global warming" (HEAT-SHIELD) [23] that aims to develop solutions to protect the health and productivity in workplaces from excessive heat in the context of climate change. In 2017, a first prototype of an occupational HHWS for entire Europe for a timeframe of four upcoming weeks was developed within the frame of HEAT-SHIELD. In 2018, an online open access service (website platform) was officially launched to help industry and society anticipate threats by heat stress to workers' health and productivity.

The aim of this paper is to present and describe the characteristics of the website platform "HEAT-SHIELD occupational warning system" [24], currently operating for the entire Europe and representing one of the main outcomes of HEAT-SHIELD.

2. Materials and Methods

In this section, descriptions of the weather forecast model and the heat stress indicator used to develop the website platform are provided, together with the main outputs of the HEAT-SHIELD platform and a forecast verification analysis.

2.1. The Weather Forecast Model

The HEAT-SHIELD platform was developed on the basis of the monthly ensemble forecasts of the European Center for Medium Range Weather Forecasts (ECMWF) [25]. The forecast ensemble consists of 51 members, with the control being the member with initial conditions corresponding to the best estimate of the operational analysis. All members (and the control simulation) represent equally probable atmospheric situations. This operational forecast model provides monthly numerical weather forecasts twice a week, initialized on Monday and Thursday at 0 UTC, and are referred to as ECMWF extended range predictions (ENS-EXT). The current ENS-EXT system has a horizontal resolution of $0.2° \times 0.2°$ (lat × lon, ~18 km mesh size) for the first 15 days and $0.4° \times 0.4°$ (~36 km) from days 16 to 46. Daily forecast values of temperature, humidity, radiation, and wind speed are bilinearly interpolated onto the desired coordinates.

Due to the coarse spatial resolution and systematic model biases of the ensemble forecast model, it is certainly not suitable for providing detailed information related to the heat warning for workers. Location-specific forecasts rather than gridded forecast products were developed through downscaling and bias correction procedures, namely empirical quantile mapping (hereafter EQM) [26]. This method establishes a quantile-dependent correction function between the observed and simulated distributions [27–29]. EQM was first calibrated with paired forecasts and observations from the past 20 years in a lead-time dependent manner [30]. Secondly, the EQM corrections were applied to the actual forecasts. The correction procedure was performed separately to each of the input variables of the heat stress index. In this way, location-specific forecasts were provided for sites where sufficiently long observation records (20 years) of the relevant meteorological variables exist. For this reason, several meteorological datasets were combined in order to get a representative and dense enough, ground-based observational dataset over the entire Europe (Figure 1):

1. The European Climate Assessment and Dataset project (ECA & D) [31] was the primary source for the observational dataset. There is, however, a limited number of stations with non-standard parameters such as humidity and wind (see green points in Figure 1). Thus, the following datasets were used to complete the full set of stations.
2. Dataset of the Global Surface Summary of the Day (GSOD, see blue points in Figure 1) from the National Oceanic Atmospheric Administration (NOAA). Stations exceeding more than 20% of missing values in ECA & D and GSOD in the period between 1996 and 2016 were removed from the dataset.
3. The Swiss national observing system SwissMetNet (SMN, see red points in Figure 1) [32].
4. A couple of stations from HEAT-SHIELD case studies were included in the set of stations: Data from one station in Celje (Slovenia), near the Odelo d.o.o. manufacturing plant [33], provided by the Slovenian Environment Agency (ARSO), and from one station in Arezzo (Tuscany, Italy) provided by Regional Service of Tuscany (CFR).

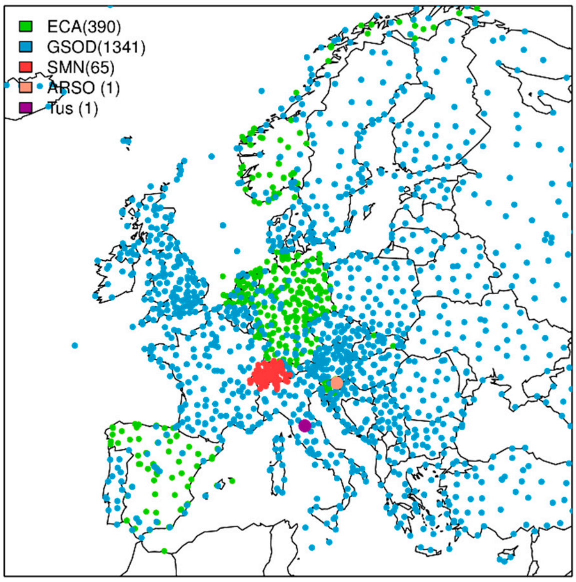

Figure 1. European stations which comprise the observational dataset of the HEAT-SHIELD platform, from ECA & D (green), GSOD (blue), SMN (red), ARSO (pink) and Tuscany (purple).

The resulting observational dataset contains daily measurements of air temperature, dew point temperature, and wind speed from 1798 meteorological stations across Europe and covering a period of 20 years (from 1998 to 2017 for summer 2018 forecasts). As only few of these stations also provide radiation measurements, satellite data for the same period as the other variables were used as best estimates for radiation observations. Specifically, the surface incoming solar radiation product from EUMETSAT's Satellite Application Facility on Climate Monitoring (CM SAF) [34] was used. The reader is referred to Casanueva et al. [2] for more details on the observational datasets.

2.2. Heat Stress Indicator

Based on the target group of the HEAT-SHIELD platform, i.e., workers engaged in outdoor activities exposed in the sun and in the shade, the Wet-Bulb Globe Temperature (WBGT) index was used as the primary heat strain indicator because it can be calculated (estimated) from standard weather and climate model data as well as measured locally at workplaces.

WBGT was originally developed by U.S. military ergonomists in the 1950s [35] and is currently widely used and internationally recognized [19,36] as a method for assessing heat stress conditions specifically in military [37], occupational and sports fields [38–40]. WBGT (unit = °C) considers the combination of the natural wet bulb temperature (dependent on humidity, air temperature and wind speed), the black globe temperature (dependent on radiation and wind speed) and the air temperature for estimating heat-stress in the sun ($WBGT_{sun}$, in conditions of direct short-wave radiation) and in the shade ($WBGT_{shade}$, no direct short-wave radiation). The natural wet bulb temperature simulates the cooling of the body via sweat evaporation, while the black globe temperature simulates the heat absorption from short- and long-wave radiations (from the sun, the soil or artificial heat sources in the workplace). These two variables are influenced by both the air temperature and the wind speed. For example, low wind speeds considerably affect black globe temperatures and significant higher values occur with no wind. WBGT shows a large dependence on wind speed when the wind is low and only minor WBGT increases occur above 1 m/s [41].

Based on reference WBGT values, recommendations in term of work–rest cycles and water intake depending on specific work activities are provided by several international organizations. In particular, the International Organization for Standardization (ISO) [36] uses WBGT thresholds to recommend work–rest limits for workers involved in different physical activities and wearing specific clothing in hot environments, in order to avoid a core body temperature exceeding 38 °C [41]. The core body temperature of all humans is maintained close to 37 °C. While some increase in the core temperature beyond this latter threshold may be acceptable, an increase above 39 °C creates health risks [42] that vary from person to person. These variations depend on ethnic group, age, gender, duration of heat exposure and degree of acclimatization; in this way also generating geographical variations [41,43].

At this stage, 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.

Following the recommendations for calculating workplace WBGT from meteorological data provided by Lemke and Kjellstrom [41], we applied the WBGT implementations of Bernard and Pourmoghani [44] and Liljegren et al. [45] 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 $WBGT_{sun}$ and $WBGT_{shade}$ formulas starting from well-established meteorological variables (air temperature, humidity, wind speed, and solar radiation) provided by the weather forecast model.

The ECMWF model outputs used for the daily WBGT predictions are daily maximum temperature, daily average dew point temperature, and daily average near-surface wind speed. As daily maximum global radiation is not available as a forecast output, we derived this parameter from quantile mapping of daily mean radiation against the observed daily maximum radiation as part of the bias correction. Using these bias-corrected daily values of maximum temperature and radiation, and average humidity and wind, daily maximum $WBGT_{sun}$ and $WBGT_{shade}$ were computed by using the R package HeatStress [46], in this way providing the forecast of the maximum heat stress for each specific day.

2.3. HEAT-SHIELD Platform Outputs

2.3.1. Non-Customized HEAT-SHIELD Platform Outputs

The primary forecast outputs are daily ensembles of the maximum WBGT (both in the sun and in the shade) for each of the 1798 locations. From these WBGT ensembles, probabilities of exceeding any WBGT threshold of interest can be computed, thus allowing to address specific user needs on particular WBGT thresholds. As forecast uncertainty increases with lead time, it is appropriate to use aggregated quantities when attempting to do longer term predictions. Averaging in time or space is a basic way to focus on the more predictable larger-scale components of the atmosphere and allows for extending skill to longer lead times, albeit at coarser (spatial/temporal) resolution [47]. This can be accounted for by creating forecast products displaying the predictions aggregated over several days (aggregated over seven days, from Monday to Sunday) rather than daily information.

In particular, for each of the four upcoming weeks, a map showing the maximum daily probability of exceeding a specific heat stress condition (WBGT above a specific threshold) scheduled for the week is provided. With the aim to provide an overall picture over Europe, a single WBGT threshold was chosen to assess the heat stress situation potentially detrimental in several outdoor occupational sectors across the continent. The choice was made by using one of the WBGT thresholds described by the ISO standard [36] for which it is required to increase the work breaks with the aim of avoiding that the core body temperature exceeds 38 °C. Trying not to be too alarmist, and taking into account the experience of the HEAT-SHIELD partners and user feedback, a threshold of 27 °C for $WBGT_{sun}$ was exemplary chosen for the weekly operational forecast. For WBGT values above this threshold, the ISO 7243 [36] recommends increasing work breaks for workers engaged in jobs that require a very high or high physical effort depending on whether the workers are acclimatized or not to heat respectively. This information is, however, very general and should be used above all to motivate the user to register on the HEAT-SHIELD platform to obtain customized information based on individual characteristics.

2.3.2. Customized HEAT-SHIELD Platform Outputs

User customized outputs are derived by the personalization of the metabolic rate used for the calculation of the customized recommended alert and exposure limits (RALs and RELs for unacclimatized and acclimatized workers, respectively) as well as correcting the WBGT forecast for insulating effects from clothing and personal protective equipment (PPE) worn by workers. The final output is the customized daily heat risk level forecasted for a specific day.

In detail, the personalized metabolic rate (MR) is assessed on the basis of the body surface area (BSA) and the activity level (ISOlevel). BSA is calculated knowing both the user's height and the weight (Equation (1)) [48]

$$BSA\left(m^2\right) = weight\ (kg)^{0.425} \times height\ (m)^{0.725} \times 0.20247 \tag{1}$$

Other methods for calculating BSA based on more recent formulas are also available [49,50]. However, the Du Bois and Du Bois formula [48] still represents a standard method widely applied in most medical cases [50,51] and several studies have revealed its strikingly high accuracy [52–54].

The ISOlevel is a number measured on a scale from 1 to 5 indicating the user's activity level (1 being resting, 5 very high metabolic rate) based on the classification of levels of metabolic rate according to the kind of activity from ISO 8996 [55].

The personalized MR was calculated based on the Equation (2) that represents a slight modification of the reference table of classification of metabolic rate by category as reported in the ISO 8996 [55].

$$MR\ (W) = BSA \times ISOlevel \times 50 \tag{2}$$

The MR assessed is then used to calculate the customized RALs (Equation (3) for unacclimatized workers) and RELs (Equation (4) for acclimatized workers) according to the criteria for a recommended standard of the National Institute for Occupational Safety and Health (NIOSH) [19].

$$RAL\ (°C - WBGT) = 59.9 - 14.1\ log_{10}\ MR \tag{3}$$

$$REL\ (°C - WBGT) = 56.7 - 11.5\ log_{10}\ MR \tag{4}$$

Both RAL and REL were developed to protect most healthy workers exposed to environmental and metabolic heat from developing adverse heat-related health effects (i.e., maintain thermal equilibrium): Workers exposed to environmental and metabolic heat below the appropriate NIOSH RALs or RELs will be protected from developing adverse health effects. Healthy workers are those physically and medically fit for the level of activity required by their jobs and wearing the conventional one-layer work clothing ensemble consisting of not more than long-sleeved work shirts and trousers (or equivalent) [19]. When the clothing worn differs substantially from the conventional one-layer work clothing (i.e., more than one layer and/or greater air and vapor impermeability), the rate and amount of heat exchange between the skin and the ambient air will be significantly altered by convection, conduction, radiation, and sweat evaporation. Therefore, the forecasted WBGT is corrected to an effective WBGT ($WBGT_{eff}$) by adding the Clothing Adjustment Value (CAV) as described in ISO 7243 [36].

The final output is the customized heat-related occupational risk level forecasted for a specific day obtained from the percentage ratio between the $WBGT_{eff}$ and the customized RAL or REL (Equation (5)).

$$Risk\ level\ (\%) = \frac{WBGT_{eff}}{RAL\ (or\ REL)} \times 100 \tag{5}$$

The HEAT-SHIELD platform risk levels are described in Table 1.

Any user who is initially registered on the HEAT-SHIELD platform is considered an "unacclimatized worker" to heat stress conditions and, for this reason, the RAL is initially used in the calculation of the customized heat risk level. However, after 5 days with at least moderate heat stress risk level (Table 1) forecasted in the short term (the first 5 days of forecasting the heat stress risk of the HEAT-SHIELD platform) during the warm season, the worker is considered "acclimatized" and the REL (higher WBGT limits than RAL) is used for the heat stress risk level calculation. Based on some stakeholder meetings organized as part of the HEAT-SHIELD project, one of the main feedback obtained was that workers are often not able to define whether they are adapted to heat. For this reason, we decided to adopt a simple empirical approach which, based on the available scientific literature, allowed us to consider when a worker can be considered acclimatized to heat. According to previous studies [56–58], about 1 to 2 weeks of daily heat exposure are needed to gain adaptation that reduces physiological strain and helps to improve physical work capabilities under a hot environment. Other studies have shown that about 75% of the physiologic adjustments occur within the first 4–6 days of heat exposure [59,60] and a recent study [61] revealed that 5 days of exposure to heat sessions were enough to acclimatize to heat workers involved in hot-climate countries. The 5-day threshold with critical heat stress conditions (in our case with at least a moderate risk level) was therefore used to define when a worker can be considered acclimatized to heat within a warm season.

Recommendations for intra-hourly work breaks and water consumption (hydration) at different metabolic rates described in Table 1 were developed based on the available knowledge from the scientific literature and on the indications reported by the American Conference of Governmental Industrial Hygienists [58], the NIOSH [19], and the ISO 7243 [36].

Further details on the heat stress risk-level-based recommendations are also available:

- Not significant: No special precautions are required and no further breaks than usual are needed.
- Low: You should be able to maintain normal activities. You may experience heat strain (generally low) and increased sweating. Consider clothing adjustment and drink more than normal.
- Moderate: Your water needs will be high. Increase the number of breaks (include small breaks with cooling) and drink frequently. Remember to rehydrate after work/exercise: Be aware that thirst is usually not a sufficient indicator when sweating is high. If this risk level is forecasted during the first summer days, pay extra attention to increase drinking and keep a good hydration status (drink/rehydrate with your meals) outside working hours. Consider adjusting the timing of activities (heavy physical tasks) to the cooler period of the day.
- High: This level is associated with severe heat stress. It is strongly suggested to adjust work—use active cooling, schedule frequent breaks in shadowed or cool areas where you can hydrate. Additional drinking is required (water needs may be more than 1 L/h). If possible, after consulting your doctor, add mineral salts to your meals. Consider adjusting the timing of activities (moderate–heavy physical tasks) to the cooler period of the day.

Table 1. The characteristics of the HEAT-SHIELD platform risk levels.

HEAT-SHIELD Platform Risk Levels and Color Codes	WBGT Levels		Work Breaks	Water Consumption (Hydration)	HEAT-SHIELD Recommendations
	Unacclimatized	Acclimatized			
Not significant RL ≤ 80%	<22.5 L_{MR} <20.0 M_{MR} <18.5 H_{MR} <17.5 VH_{MR}	<25.0 L_{MR} <23.0 M_{MR} <21.5 H_{MR} <20.5 VH_{MR}		L_{MR} from M_{MR} to VH_{MR}	No special precautions are required: Maintain normal working and hydration procedures.
Low 80% < RL < 100%	22.5 L_{MR} 20.0 M_{MR} 18.5 H_{MR} 17.5 VH_{MR}	25.0 L_{MR} 23.0 M_{MR} 21.5 H_{MR} 20.5 VH_{MR}		L_{MR} and M_{MR} H_{MR} and VH_{MR}	Pre-alarm (attention): Pay attention to frequent drinking and plan small breaks.
Moderate 100% ≤ RL < 120%	28.5 L_{MR} 25.0 M_{MR} 23.0 H_{MR} 22.0 VH_{MR}	31.0 L_{MR} 28.5 M_{MR} 27.0 H_{MR} 25.5 VH_{MR}		L_{MR} and M_{MR} H_{MR} and VH_{MR}	Alarm: Drink frequently and increase the number of breaks with cooling.
High RL ≥ 120%	>33.5 L_{MR} >29.5 M_{MR} >27.5 H_{MR} >25.5 VH_{MR}	>36.5 L_{MR} >33.5 M_{MR} >31.5 H_{MR} >30.5 VH_{MR}		L_{MR} and M_{MR} H_{MR} and VH_{MR}	Emergency: Drink often, even more than 1 L/h and schedule frequent breaks in shadowed or cool area.

L_{MR}, M_{MR}, H_{MR} and VH_{MR} represent low (180 W), moderate (300 W), high (415 W), and very high (520 W) metabolic rates (MR), respectively. Green heart: No further breaks than usual are required; Yellow heart: Plan small breaks; Two orange hearts: Increase the number of breaks; Three red hearts: Frequent breaks. One drop: Drink about half a liter of water per hour; Two drops: Drink about a liter per hour; Three drops: Drink more than a liter of water per hour.

2.3.3. Forecast Verification

With the aim to monitor and improve the forecast quality (the ability of a model to correctly predict an event, that is the degree of agreement between the forecasts and the corresponding observations), the forecasts during summer 2018 were verified against observations. For this purpose, a thorough comparison of the daily WBGT forecasts against the corresponding observed values at the 1798 representative meteorological stations used for downscaling and bias correction procedures was carried out. The probabilistic component of ensemble forecasts requires diverse metrics to characterize their quality in terms of accuracy, reliability association, and discrimination [30,62]. In this work, the continuous ranked probability score (CRPS) was used to assess the accuracy of the forecasts [63]. This metric is widely used in forecast verification and represents the ensemble version of the mean absolute error. It is sensitive to the bias in the ensemble mean and to the over- or under-dispersion of the ensemble (i.e., it also penalizes ensembles with large spread even when having a good ensemble mean prediction). The score can be expressed as a skill score (SS) relative to a reference forecast (CRPSS). A positive CRPSS indicates a better performance of the forecast compared to the reference (perfect score of 1), CRPSS = 0 means that the forecast is as good as the reference and negative scores indicate lower skill than the reference. In this work, the CRPSS of the bias-corrected forecasts is obtained considering two possible reference datasets: (1) Raw forecasts (non-bias-corrected) and (2) observations from the past 20 years (which mimic a 20-member ensemble, hereafter climatological forecasts). The former shows potential added value of the bias-corrected forecasts with respect to the uncorrected forecasts, whereas the latter represents the skill of the forecasts with respect to a naive forecast based on climatological observations. Daily CRPS values were averaged into weekly values (week 1 spans from day 5 to day 11, week 2 from day 12 to day 18, week 3 from day 19 to day 25, week 4 from day 26 to day 32). Final CRPSSs were obtained from the weekly CRPS, for each European location. The verification was conducted considering forecasts which span from April to September 2018, i.e., 40 forecasts.

3. Results

Besides the general information on the HEAT-SHIELD project, the home page of the multilingual website platform "HEAT-SHIELD occupational warning system" (Figure 2) [24] contains the non-customized heat stress forecasts and a link "use web version" to access the registration to get customized forecasts.

3.1. HEAT-SHIELD Platform Interface and Outputs

The map of the weekly maximum probability of exceeding the daily $WBGT_{sun}$ threshold of 27 °C, available for each of the four weeks, is the non-customized heat stress forecast output and is generalized information accessible to everyone without any registration. This information is provided for all 1798 locations (represented by points) for which the forecast is available at European level and is shown by a point-related chromatic scale varying between green (the lowest probability of occurring) and dark red (the highest probability) (Figure 2). Figure 2 shows a clear gradient with high probabilities of $WBGT_{sun} > 27$ °C in southern Europe, medium probabilities in several central European countries and very low probabilities in the North. This spatial distribution results from the typical climatological conditions of air temperature, with a south-north (latitudinal) gradient.

To access the personalized forecast heat stress alert system, including the suggested rest/hydration advices, a registration is required (Figure 3) by clicking on "USE WEB VERSION".

The registration process consists, in a first step, of providing an e-mail address (Figure 4), necessary to receive an alert message automatically in the event of a moderate (or high) heat risk level in one of the first 5-day forecasts (the first 5 days of forecasting the heat stress risk of the HEAT-SHIELD platform), and a password to access the user profile at any time and change it if necessary. Subsequently, the user must provide a series of information including the most important for the purposes of calculating the customized heat stress:

- Height (cm) and weight (kg);
- The location, which must be chosen by the user after indicating the exact address for which the forecast is need and double clicking on the available shield (one of the 1798 stations) nearest and with similar altitude to the location of interest;
- The physical activity level (low, moderate, high, and very high);
- The work environment (outdoors in the sun or shade);
- The type of clothing or PPE worn during work.

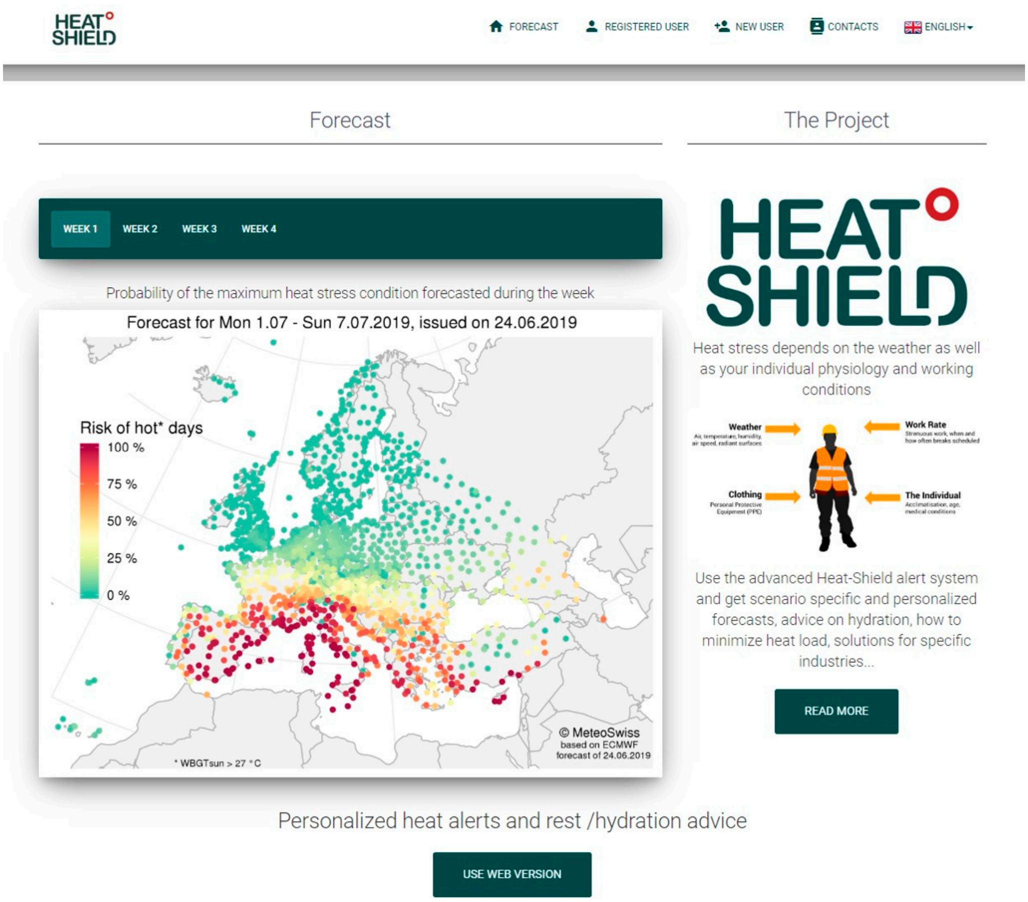

Figure 2. Home page of the HEAT-SHIELD occupational warning system [24].

Figure 3. Registration page to access the personalized HEAT-SHIELD occupational warning system outputs.

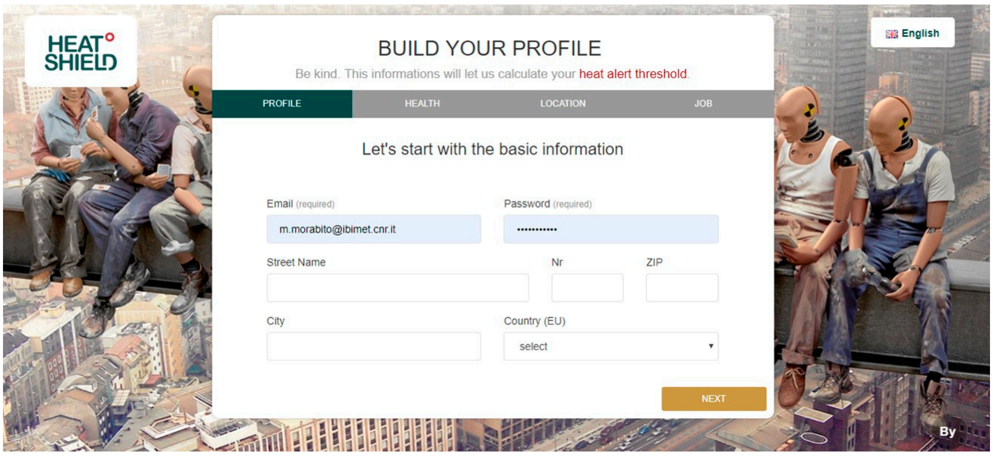

Figure 4. Registration page to create your own profile of personalized heat stress warnings.

The registration process can be done by a user identified as a worker or a stakeholder (i.e., employer, competent doctor, or other operators in charge of safeguarding workers' health). In the latter case, the difference consists in the possibility to select a "standard" worker in terms of height and weight.

Once the registration is completed, the user can access his/her personal forecast page containing the forecasts of the heat stress risk and behavioral suggestions (in relation to hydration and work breaks recommended) to be taken in the short term, that is for the first 5 days (Figure 5).

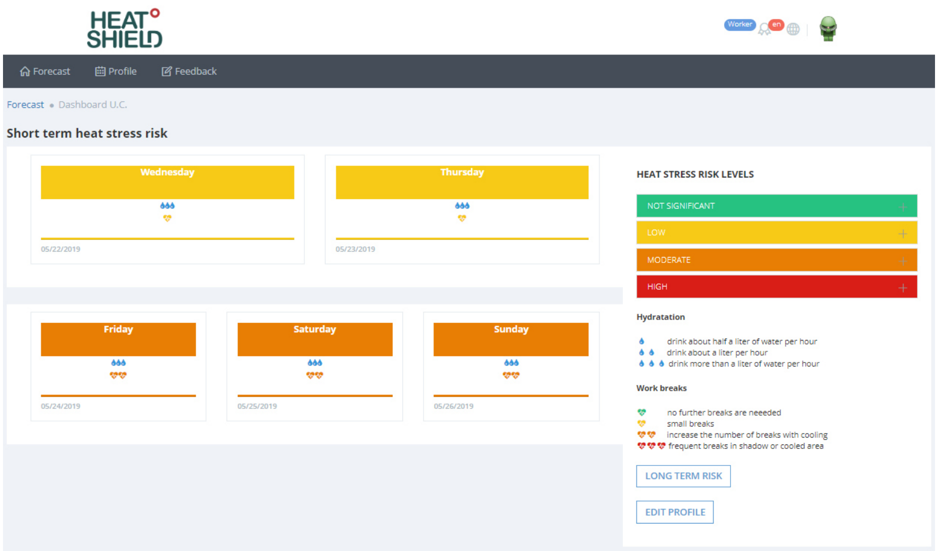

Figure 5. Worker's heat stress risk and behavioral suggestions to be taken in the short term (the first 5 days of forecasting the heat stress risk of the HEAT-SHIELD platform) available in the own profile of the personalized heat stress warning.

The short-term warning forecast is updated daily. If at least one day with a moderate (or high) heat stress risk level is expected in the short term (within the first 5-day forecasts), a warning message is automatically sent to the e-mail address provided by the user during the registration process (Figure 6).

In addition, the worker's heat stress risk is also available in the long term (by clicking on "LONG TERM RISK") by means of a colored calendar (Figure 7), from the 6th to the 46th day, updated twice a week, on Tuesday and Friday. In this case, the information is mainly aimed at providing useful information for planning work activities in the long term.

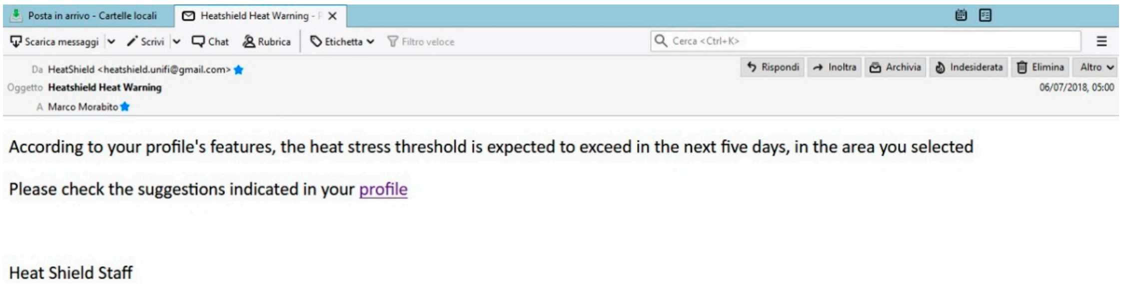

Figure 6. The HEAT-SHIELD warning sent to the user's e-mail when at least one day with a moderate (or high) heat stress risk level is expected in the short term (the first 5-day forecasts of the HEAT-SHIELD platform).

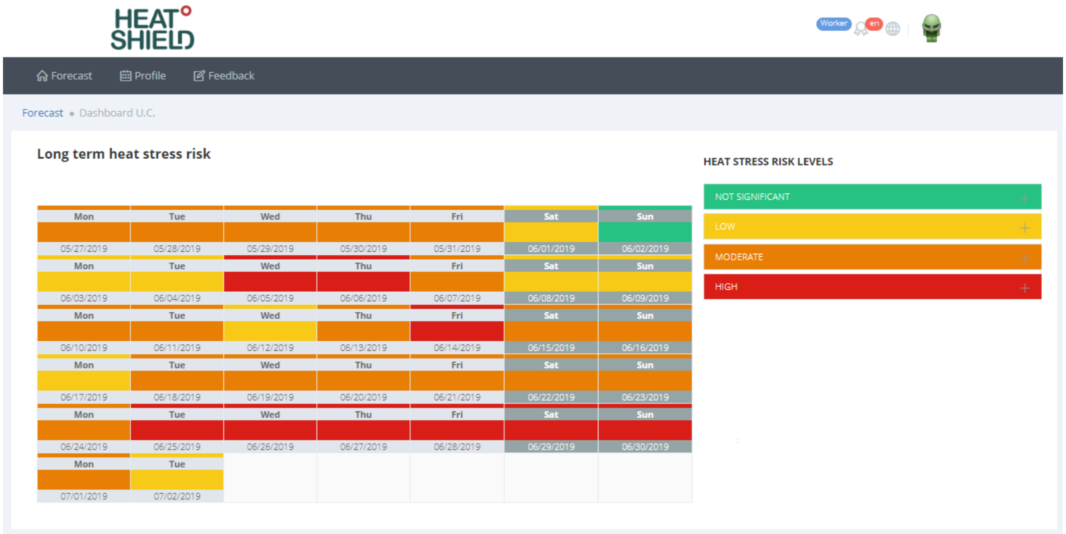

Figure 7. Worker's heat stress risk in the long term (from the 6th to the 46th day forecasted) available in the own profile of the personalized heat stress warning.

It is also possible to modify the user's profile by clicking on "EDIT PROFILE" (e.g., changing the physical characteristics, the work effort, the workplace condition, or the clothing worn) and immediately obtaining new short- and long-term heat stress risk forecasts based on the new input data.

By accessing the "Profile" page, the user can also create multiple profiles for workers with different characteristics or engaged working in different geographical areas and therefore with different forecasts (Figure 8).

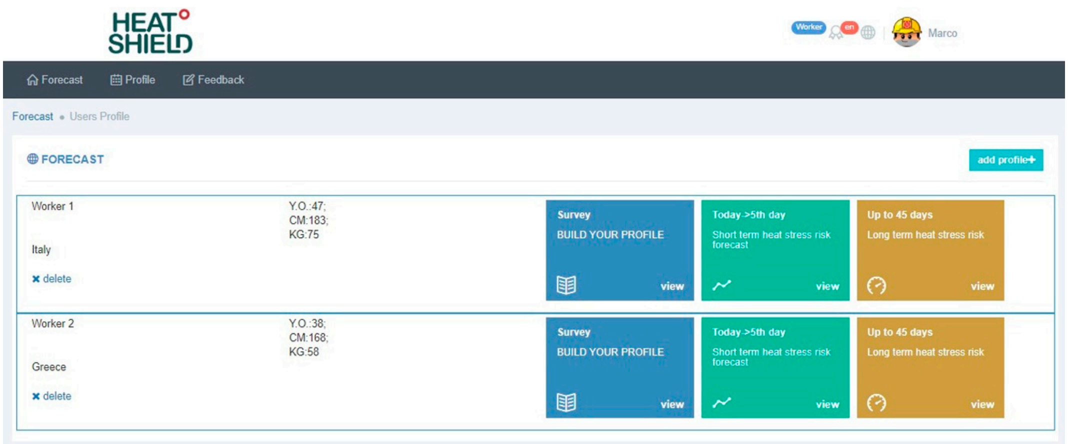

Figure 8. Page showing different worker's profiles.

Finally, by accessing the "Feedback" page, the user can also send feedback messages on various topics concerning the HEAT-SHIELD platform and report any errors.

3.2. WBGT Forecast Verification

The CRPSS is used to account for the skill of the forecasts used by the HEAT-SHIELD platform (Section 2.3.3). Figure 9a,c shows the spatial distribution of the CRPSS of $WBGT_{shade}$ in week 2 (days 12 to 18). There is a clear added value of the bias-corrected forecasts with respect to the raw counterparts (positive CRPSS in Figure 9a). This added value appears mainly in regions with complex topography or at some coastal regions (Figure 9a) and remains at all lead times (Figure 9b), illustrating the capability of EQM to downscale the coarse model output to location-specific information. The bias-corrected forecasts are more skillful than climatology up to 12–18 days at most sites (Figure 9d), especially in Central and Northern Europe (Figure 9c). The CRPSS of $WBGT_{sun}$ vs. climatology is very similar to that of $WBGT_{shade}$ (not shown), both in terms of spatial pattern and skill decrease with lead time. For 19–25 days ahead, forecasts can only marginally add value to climatological forecasts, and beyond 25 days, forecasts are as skillful as climatology (Figure 9d). Note that a location-specific climatological forecast of WBGT also represents valuable information (i.e., location- and season-specific climatological risk of heat stress) and the HEAT-SHIELD platform therefore provides meaningful information throughout the full forecast range.

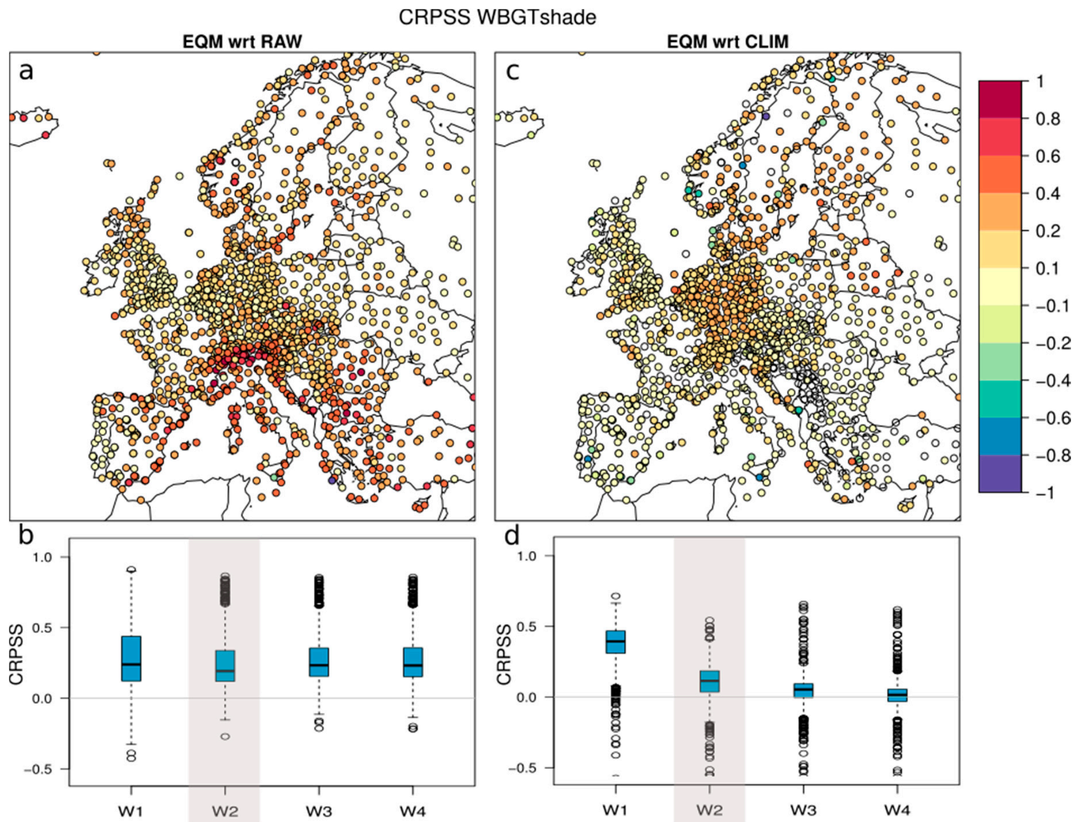

Figure 9. (**a**,**c**) Maps of skill score (SS) relative to a reference forecast (CRPSS) of $WBGT_{shade}$ at lead times 12–18 days (Week 2 (W2), see details in Section 2.3.3), with respect to the raw forecasts (empirical quantile mapping (EQM) with respect to RAW) and to the climatology forecast (EQM with respect to CLIM). (**b**,**d**) Weekly CRPSS of $WBGT_{shade}$. Each box represents the CRPSS values across European stations. The box for W2 (12–18 days) corresponds to the values displayed in the maps above.

4. Discussion

The HEAT-SHIELD platform [24] developed within the frame of the European Project HEAT-SHIELD and described in this study represents the first step to fill the lack of international heat warning systems specifically addressed to occupational sectors. This website platform was officially launched in 2018 and is currently operating for about 1800 European localities. It represents the first international example of personalized short- and long-term heat risk forecasts with useful heat-related adaptation information for workers and stakeholders in charge of safeguarding workers' health and productivity.

The main characteristics of the HEAT-SHIELD platform are listed below and make this heat warning system original and unique:

- the HEAT-SHIELD platform is multilingual.
- The local-heat-stress-risk forecast is "customized" based on:
    - the worker's physical characteristics (specifically height and weight),
    - the physical activity level,
    - the clothing or PPE worn during work,
    - the work environment (outdoors in the sun or shade),
    - also taking into account whether the worker is acclimatized or not to the heat.
- The short-term heat risk forecast (5-day forecasts) includes behavioral recommendations related to how much hydration (water intake) and rest (work breaks) during the worst (in term of heat stress) hour of the day.
- Long-term heat risk forecasts are available up to just over one month (46 days).

Currently the website platform is available in six languages (English, Italian, Slovenian, French, Portuguese and German) and will be further implemented in other languages. This characteristic is of great importance especially in the occupational field because most European countries are typically multicultural. It is indeed known that foreign workers may have a real difficulty in understanding the local language with consequent important repercussions on the perception of the heat risk in the workplace [64,65]. As reported in a recent review on the existing HHWSs in Europe [17], one of the main communication limits of these systems is that the warnings are generally issued in the local language of each country in addition to (in very few countries) English.

The non-customized heat stress forecast output (the maps of the weekly maximum probability of exceeding the daily $WBGT_{sun}$ threshold of 27 °C) is simplified, generalized information valid for the whole Europe and accessible to everyone without any registration information. However, this information has the limitation of highlighting the potential heat risk mainly in southern Europe, displaying a clear latitudinal gradient typically resembling the air temperature gradient. The scientific literature [66–68] has shown that local populations are acclimatized to their local climate and respond to heat stress differently. A solution to try to solve this limitation would be to collect data on the perception of heat stress in the occupational sectors in various geographical areas with different climatic characteristics. In this way, the WBGT thresholds might be recalibrated accounting for geographical adaptation. The main aim of the very general information provided by the non-customized outputs is to motivate the user to register on the HEAT-SHIELD platform to obtain personalized information on heat stress risk calculated by using a tailored WBGT threshold based on individual worker characteristics and the workplace environment. The personalization of the forecast certainly represents an ambitious challenge to improve the generic information already available and provided by the main meteorological services and that need to correctly interpret each personal situation. This customized approach is essential in occupational settings due to the high variability of environmental conditions and job/task activities, which results in a strong heterogeneity of the thermal stress exposure with direct repercussions on workers' health and productivity. However, it must also be considered that, in common practice, workers accustomed to carry out specific work tasks repetitively, might make a self-evaluation in a way that underestimates the work effort and therefore the heat-related job risk perception. This situation might include some bias and distort the efficiency of the strategies to counteract heat stress. Distortion might also depend on socio-cultural aspects, such as the dietary habits that underlie the maintenance of a good level of hydration and nutrition. For example, people of Muslim origin are at greater heat-related health risk during the Ramadan period [69,70]. On the other hand, a natural reaction to heat of a worker is to reduce their physical activity, that is a self-pacing or autonomous adaptation which reduces the body's internal heat production but also the hourly work capacity [71–73].

A strength of the developed website platform relates to its ability to provide hydration and work/break schedule recommendations in the short term. Taking breaks in shady or cool areas as well as suggestions on hydration (water consumption) during working time according to specific heat stress conditions and physical efforts represents a fundamental heat-related adaptation method recommended by the ISO [36] and other governmental agencies [19,58]. Moreover, the platform also includes e-mail alerts that represent important adaptation strategies to timely counteract heat stress conditions and safeguard the workers' health and productivity.

The HEAT-SHIELD platform is a potentially very useful tool because heat stress is significantly increasing in many geographical areas worldwide, with strong effects also in European cities [74]. In addition, heat stress is expected to increase significantly in the next years because of climate change [1,2] also in areas where the worker population is not used to fighting this phenomenon [75], such as central-northern European countries.

At the moment, the HEAT-SHIELD platform is the only example of a website platform providing such a comprehensive collection of information. Nevertheless, there are already a few interesting smartphone applications in place that inform workers about precautions against outdoor heat stress. These include the OSHA NIOSH Heat Safety Tool [76] and the ClimApp [77] device currently in an advanced stage of development by several HEAT-SHIELD partners. These applications are, however, not able to provide long-term forecasting information that is particularly useful for planning issues. Precisely for this reason, the HEAT-SHIELD website platform is based on the extended range ensemble forecasts of the ECMWF that enables customized heat stress risk up to over a month. In this way, useful information for employers, organizations and operators in charge of safeguarding health and productivity in various occupational areas are provided, calibrated with greater precision, the interventions to be taken according to the subjective characteristics of the worker and other situations in which the workers are involved. A further interesting feature of the HEAT-SHIELD platform is the possibility for real-time verification of the heat stress risk situation by modifying some characteristics, for example, by varying the work environment (e.g., working in the shade) or the clothing worn, in this way planning the best actions to counteract the effects of the heat in the long term. Certainly, there is a need of further validation including the worker's health component linked to the information provided by the HEAT-SHIELD platform. This might be done by processing the subjective information collected by the self-administered questionnaire developed within the frame of the HEAT-SHIELD project. They have already been used in several European countries for gathering evidences on workers' risk perception of heat stress in the workplace and potential productivity losses due to extreme heat. For example, based on a preliminary investigation [78] carried out during the summer months of 2017 and 2018 on some workers engaged in Italy in construction and agriculture sectors, results revealed agreements between the ISO-standard WBGT thresholds associated with specific work efforts and the worker's thermal stress perceptions for high WBGT values (WBGT > 30 °C). Conversely no agreements were observed for lower WBGT values. In the latter case, workers declared a heat stress level (from low to more often moderate heat stress) even if the ISO-standard WBGT threshold for that activity level does not recommend critical heat-stress conditions. For this reason, if data collected also in other countries during the summer of 2019 and the following summers confirm these preliminary results, the recalibration of the ISO-standard WBGT thresholds may be desirable, also including lower critical values which, however, may represent a health problem. Furthermore, through the case studies planned as part of the HEAT-SHIELD project, other health/physiological data of workers are being collected that could be of great help for a worker's health validation in relation to heat stress in workplaces.

Since the HEAT-SHIELD project started (January 2016), some stakeholder meetings presenting the HEAT-SHIELD platform have already been organized during the years of 2018 and 2019 in several European countries, and other meetings are scheduled in different countries by the end of the project (December 2020). One of the main objectives of these meetings, in which employers, workers, worker safety representatives, prevention, protection service managers and competent doctors took part, was to obtain immediate feedback on the HEAT-SHIELD platform. Initial user feedback suggest that there is potential for further improvements, with new procedures/suggestions aimed to provide increasingly detailed information useful for worker's heat-related health prevention and reducing productivity loss. Trying to maximize employers' involvement in the use of the HEAT-SHIELD platform is a priority since they are considered key elements among all stakeholders. In particular, employers are the main actors for regulating work activities (i.e., defining of the length of work shifts and relative work breaks, identifying of the days and working hours in which to carry out certain work activities, defining of the number of workers involved in specific work tasks, etc.) and are responsible for the workers' health, without ever losing sight of the economic aspect linked to work productivity.

Field studies carried out also in the field of the HEAT-SHIELD project [14,20,22,65,79–81] aimed at evaluating the responses of workers exposed to heat stress conditions during different work activities will be particularly useful for identifying the best heat-related adaptation strategies helpful to manage this hazard situation. For now, only recommendations on water consumption and work/rest breaks clearly described in reports provided by international organizations working on this topic are provided. However, other recommendations (i.e., the recommended clothing, or others) obtained by using other thermal-stress indicators, subjective information (i.e., age or gender), and detailed infographics related to specific occupational sectors, could also be integrated and included in an operational way in the HEAT-SHIELD platform to counteract the effects of heat. A more complex issue, on the other hand, concerns the possibility of personalizing the heat risk level based on pre-existing diseases or specific pharmacological treatments. Currently, information on the customized heat risk refers to a healthy worker and not where specific drugs are used; the situation should always and exclusively be evaluated by an occupational health physician.

In the near future, it will also be desirable to develop a system for monitoring work injuries to be updated in real time, to report heat-related injuries in order to activate timely emergency response interventions. In the current version, the website platform does not include heat stress thresholds based on the relationships between WBGT and injuries because only very few studies have investigated this relationship [82]. In addition, the use of meteorological data for occupational heat stress assessment is actually limited because weather stations do not traditionally and directly measure some important climate factors useful for WBGT calculation [83,84]. For this reason, results are not as obvious as those identified between several thermal indicators and some categories of the general population (e.g., the elderly) [85–87]. In fact, in this latter case, city-specific thermal stress thresholds were identified, and in several cases, these thresholds were implemented in HHWSs addressed to the general population or the elderly [17].

The current website platform relies on a probabilistic forecast model, which has the advantage of allowing long-term forecasts. It has, however, also some limitations such as the temporal resolution (it only provides a daily value). In particular, the intra-daily hourly heat stress risk forecast (i.e., morning, afternoon, evening, night) is not provided and the information is only available for a limited number of European localities (about 1800). For this reason, we are already working to implement the heat stress risk forecast in the short term for specific regions by using high-resolution (i.e., spatial resolution of 3–7 km) deterministic meteorological models. In this way, detailed information on an hourly basis will be obtained and personalized heat stress risk will be available for various times of the day in which workers can be engaged. Furthermore, by exploiting the high spatial resolution of deterministic meteorological models, the information will be extended to all locations without the need to perform downscaling operations at the meteorological station level.

5. Conclusions

The HEAT-SHIELD platform [24] is the customized occupational heat-related warning system developed within the framework of the European HEAT-SHIELD project as the first operational website platform providing short- and long-term heat warning to safeguard workers' health and productivity on a continental scale. This platform represents a useful adaptation strategy aimed at protecting workers, a population category particularly exposed to the effects of climate change. The usefulness of this type of adaptation strategies is linked to the fact that, based on future climate change scenarios, more and more workers operating on ever-wider geographical areas affected by heat-stress hazard conditions will be exposed for longer periods of time during the year to the effects of global warming.

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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 ($\chi^2 = 17.1$, $p = 0.001$) but reported less impact from heat on productivity ($\chi^2 = 10.6$; $p = 0.014$) 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).

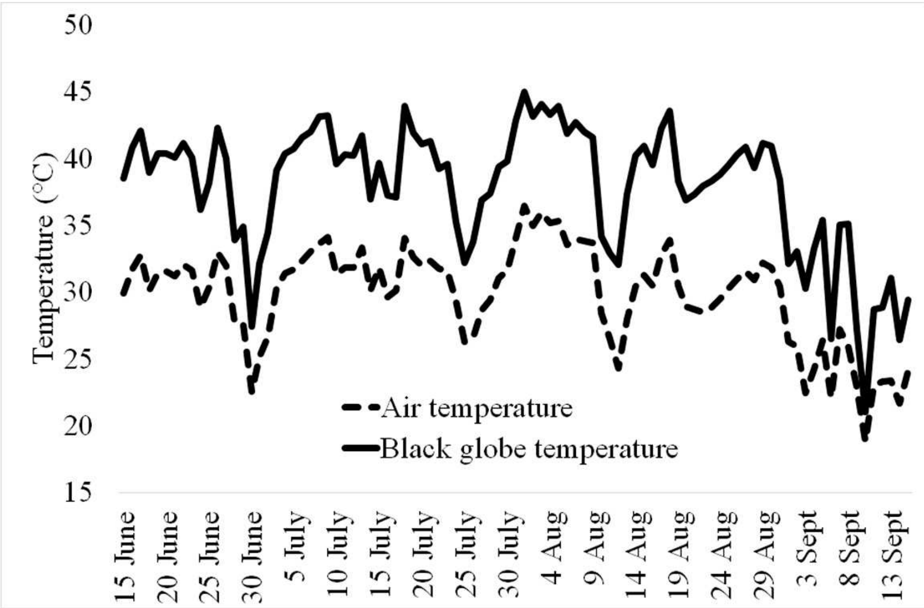

Figure 1. Air temperature (continuous line) and black globe temperature (dashed line) measured during the working time of the day (8:00 a.m.–5:00 p.m.) in the three work sites involved in the study during the summer 2017.

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.

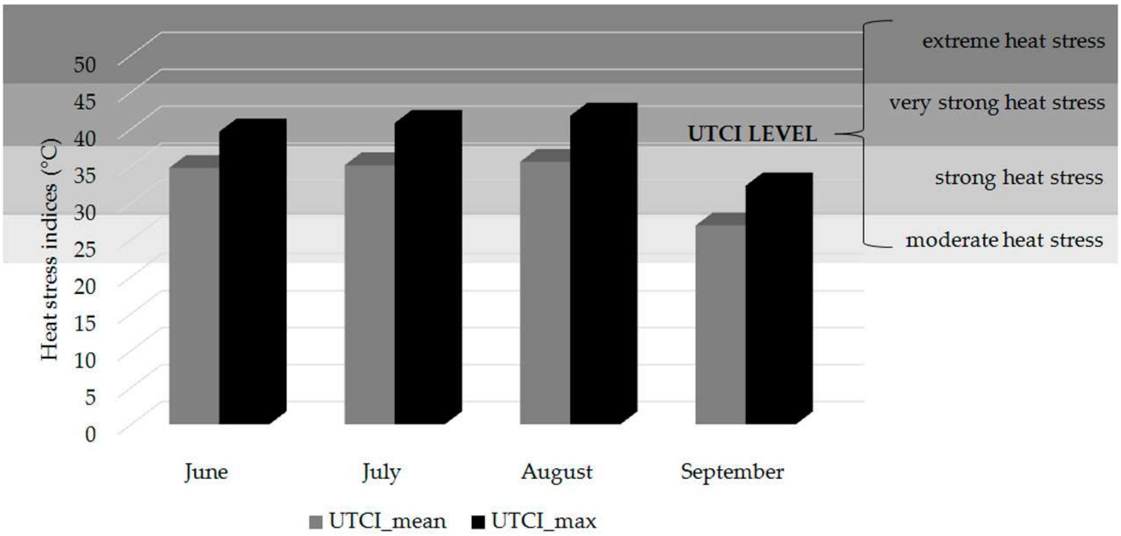

Figure 2. Mean and Maximum Universal Thermal Climate Index (UTCI) index for each month during the working time at the three work sites involved in the study (summer 2017) and the recommended rest according to the WBGT ISO standard for a worker that perform an activity that requires an effort of 300 watt. 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).

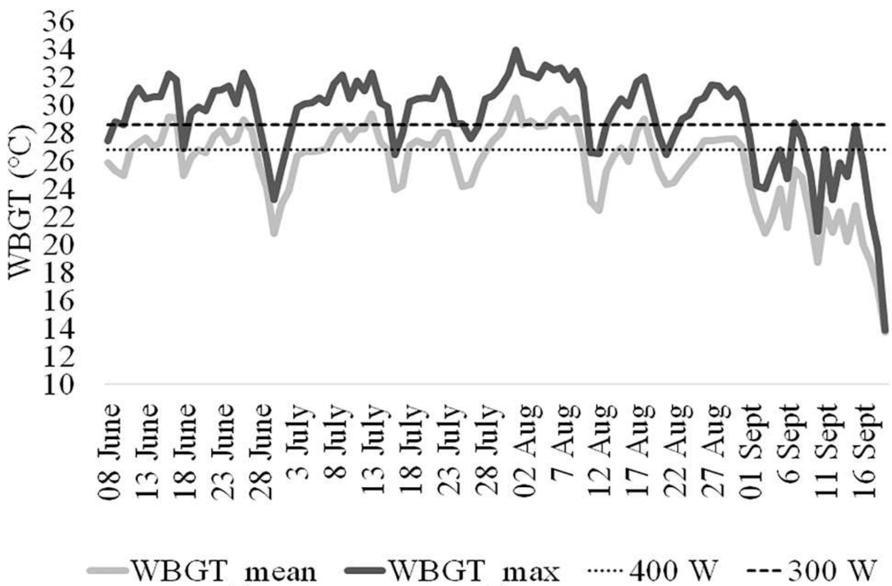

Figure 3. Mean and maximum daily Wet-Bulb Globe Temperature (WBGT) index during the working time of the day at the three work sites involved in the study, summer 2017. The dashed lines represent the WBGT ISO standard thresholds respectively for a high (400 W) and a moderate (300 W) work effort as declared 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 (χ^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]	$\chi^{2\ b}$	*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 (χ^2 = 13.9; p = 0.008), as well as the perception of the decline in productivity (χ^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 (χ^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 (χ^2 = 39.58; p = <0.001). There is no statistically significant association between nationality in receiving advises when heat waves are in progress (χ^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

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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.

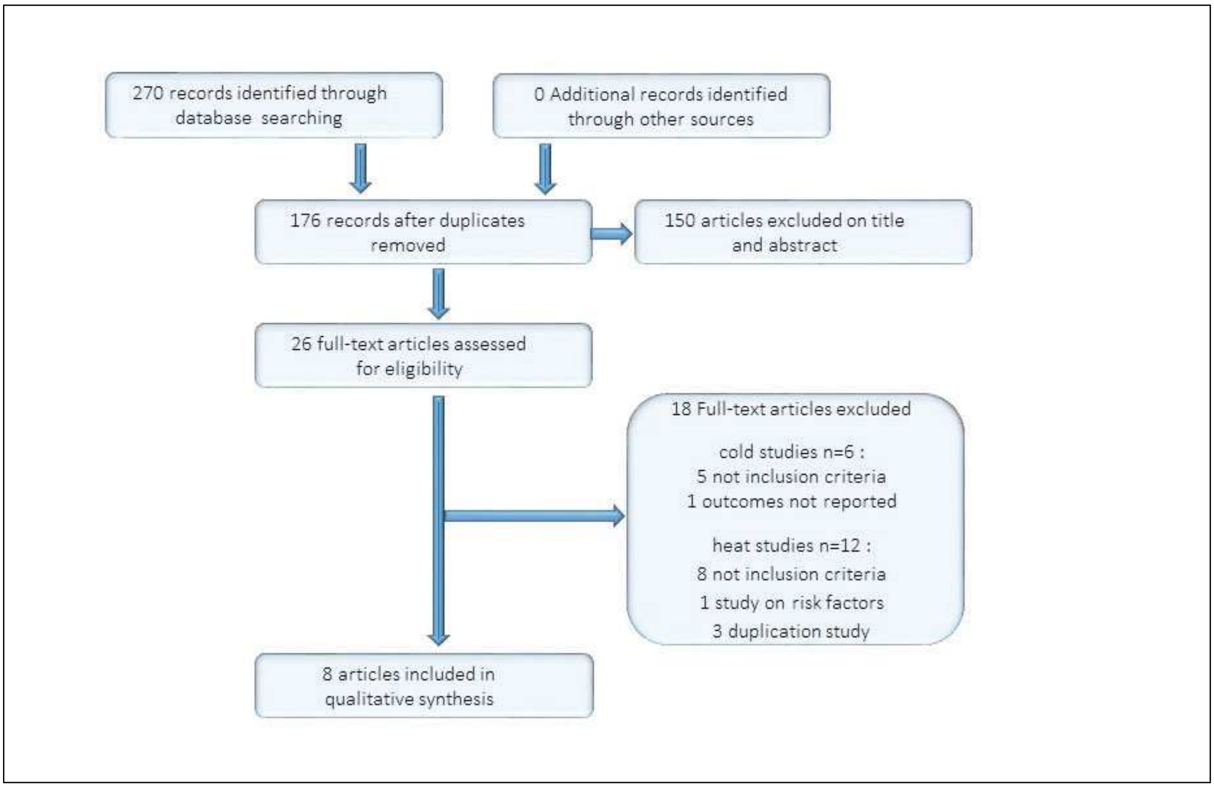

Figure 1
Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) flow diagram.

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.

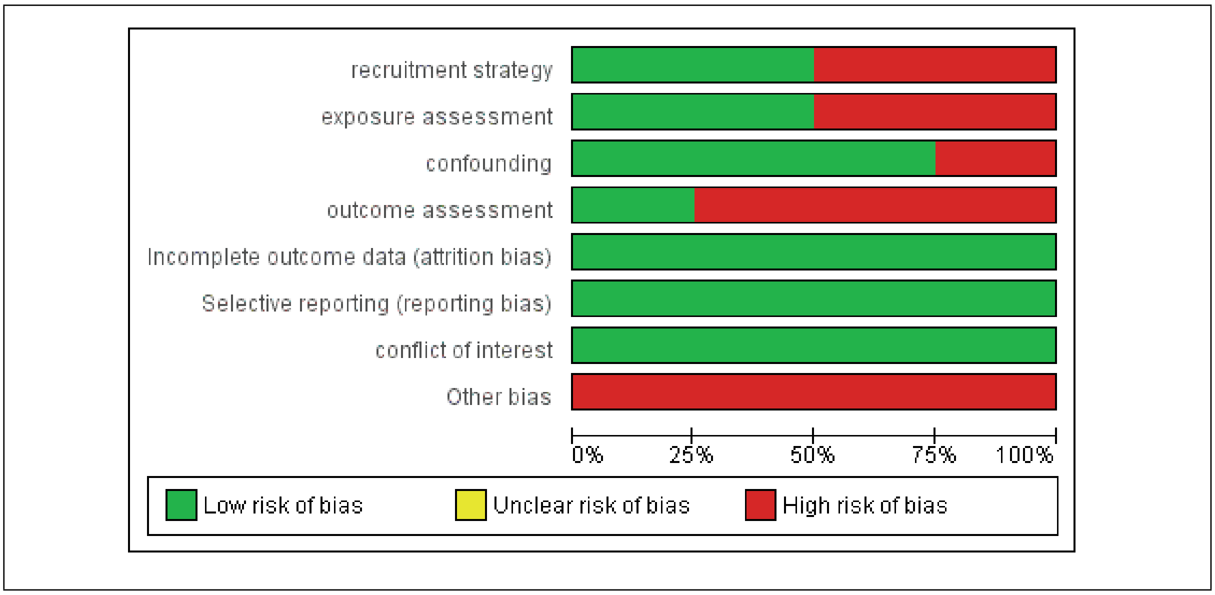

Figure 2
Risk of bias graph: review authors' judgements about each risk of bias item presented as percentages across all included studies.

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

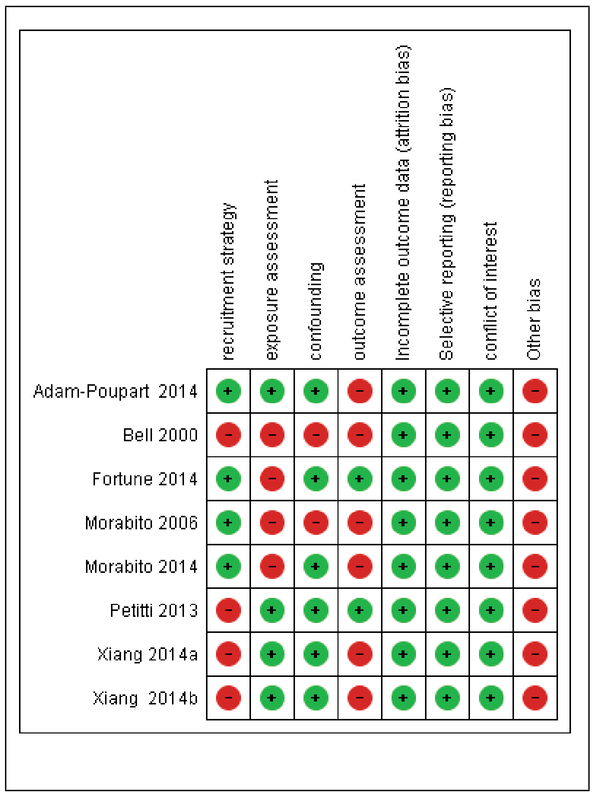

Figure 3
Risk of bias summary: review authors' judgements about each risk of bias item for each included study.

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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