The impact of climate change to occupational safety and health: future projections of thermal discomfort (humidex index) in the West Attica region

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Abstract. There is a growing concern on the implications of climate change on thermal stress, which in turn may affect workspace morale and performance, leading to lower productivity, or even posing a higher risk for employee’s health. In this paper, we study this aspect of climate change providing evidence on future projections of the Humidex Index (HI) for the West Attica Region, an overpopulated and industrialized area of Greece, which holds the World Meteorological Organization record for the highest temperature ever recorded in Europe. The current study is based on the use of the high resolution Weather Research and Forecasting (WRF) regional climate model to determine changes in the trends of extreme heat conditions under future scenarios analysis. Projections of future climate regional analysis for the mid-twenty-first century (2021-2045) indicate an increase in the yearly/daily values of maximum air temperatures (Tmax) and HI index values. In addition, the analysis reveal shorter return periods for the specific design thresholds of Tmax and of the HI index as associated with an increase in the number of events above thresholds for both RCPs 4.5 and 8.5 W/m² future scenarios. The anticipated (extreme) heat conditions expose the occupational safety and health (OSH) at high risk, and the paper provide suggestions for applied interventions in the direction of a safer working environment.

1. Introduction

Hot weather can cause thermal stress to employees when temperatures are too high for the human body. Thermal stress is a significant health and safety issue that differs from thermal comfort (which is an indicator of comfortability [1]), and has to be managed appropriately to prevent labour from devastating effect [2]. Normally, what happens when someone is exposed to hot environment is that the body adapts by sweating and increasing skin blood flow to prevent body temperature from rising. However, in extreme hot conditions of high temperature and high Relative Humidity (RH) the adaptation processes are not sufficient to cool down the body, and workers’ overall morale and work performance is reduced, resulting to lower concentration and productivity, or even leading to severe and fatal injuries from possible heat cramps, or heat exhaustion and/or physical activity heat stroke, which necessitate instant medical response [3].
Heat stress has been recognized as a critical problem in many industries that exhibit heavy workloads in the open air [4], and with the projected increase in temperatures as a result of climate change, the thermal discomfort is anticipated to further worsen for employees. A study by Campbell et al. indicated that future climate conditions might change the characteristics (frequency and intensity) of extreme heat events [5]. Towards this end, and a number of multi-model projections of future air temperatures and heat index values under nearly all climate change scenarios show continuing warming through 2100 [6,7], industries need to adapt methods and procedures against climate risks, so as to improve their resilience to climate change.

Taking into consideration that thermal discomfort and health impact analysis is significant in locations where this impact is projected to be most severe [5], and that extreme temperatures under the climate change context are expected to further increase, the study of the temperature, RH and HI index to estimate/assess the thermal discomfort as a result to the climate change at regional level is considered of high importance, especially for industrial activity in the West Attica region, which holds the World Meteorological Organization record for the highest temperature (48.0 °C, in 1977) ever recorded in Europe [8]. Engineering and industrial interventions should take into consideration the local conditions [9], hence, it is important to study the specific local characteristics, through a regional climate change assessment.

This study presented in this paper is focused on the above-mentioned region in Greece, which is an overpopulated and industrialized area. Following, Section 2 introduces a novel methodology for the calculation of the HI index, providing also information for the regional climate model and the climate parameters used. Section 3 presents the results of the WRF climate model analysis of the climate parameters used, and the HI index, the projections of future climate conditions, the return periods and the events above design thresholds for the industries sited at west region of Athens. In Section 4, we suggest further interventions, along with recommendations for future research that industry should consider in the development of specific plans for protecting the exposed labor and reducing health risks. Finally, conclusions are presented in Section 5.

2. Methodology
The assessment of thermal stress can be carried out easily by a single observer using long-established procedures and simple and inexpensive instruments [10]. Several indicators are suggested in the literature for the assessment of human thermal conditions. However, as Budd [11] comments, industry still uses a single indicator, the Wet-Bulb Globe Temperature (WBGT) index that has been used as an indicator of thermal stress in hot conditions [12], while the “cooling power index” [13] and the “Thom's discomfort index” [14] have been introduced to assess in a similar manner the outdoor environment.

In this paper, we adopt the thermal discomfort index Humidex (HI) to evaluate the comfort of the thermal environment of the broad Western Attica area, regarding working conditions. The HI is a temperature/humidity index that was first established and used in Canada [15], and it has also been used successfully in various studies in Italy [16,17] in a context of a noticed relationship between intense heat conditions and increase in deaths due to heat. Santée and Wallace [18] deduced that during extreme hot conditions one may find a strong correlation between the temperature of the human body obtained by the application of a thermal balance model and HI. In addition, Beccali at al. [19] argue that using HI, the expected consumption of household electrical energy for heating, mechanical ventilation, or cooling can be short-term predicted, while Giannopoulou et al [20] studied the impact of air temperature and RH on human thermal comfort over the broader region of Attica in Greece.

The present paper uses Advanced Weather Research and Forecasting atmospheric numerical model (v3.6.1) [21] simulations for two periods: 1980 to 2004, and 2021 to 2045. The WRF model has been enforced by EC-EARTH General Circulation Models (GCM) developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) [22], which has been dynamically downscaled to the region of Greece at a scale of 5×5 km² by Politi et al. [23,24]. The calculation of HI index is based on values of maximum air temperature ($T_{max}$) (in °C) and RH (as percentage). These data series were
extracted for the specific region of Attica at a scale of 5×5 km², and for the two afore-mentioned time periods, with respect to two Representative Concentration Pathways (RCPs: 4.5 and 8.5 W/m²). Thus, the continuous long and quality-controlled daily simulation data series, at a daily time resolution, have been prepared in such a way to also include the intensity and frequency of HI index that lie far in the tails of the Probability Distribution (PD) of climate variables. In addition, regional climate analysis with the use of WRF high resolution climate model was used to investigate the differences between future and past periods of daily and yearly values, the projected trends, the variability, the return period, and the events of the climate variables of $T_{\text{max}}$, RH and HI index that exceeded specific thresholds, beyond which they are considered dangerous for Occupational Safety and Health (OSH).

One may notice that the concept of return period is commonly used to carry information about the likelihood of rare and extreme events, while the probability of occurrence of an extreme consequence, or its return period, is based on a particular climate threshold. Thus, a return level with a return period of $T = 1/p$ years, is a high threshold $x(p)$ whose probability of exceedance is $p$ and defined by $p=1-FU(U)$ [25].

2.1. The Humidex Index (HI)

The HI index is a nominally dimensionless number (equivalent to degrees Celsius) based on the dew point. It is an index related to the air temperature and humidity, and defines how an average person senses climate conditions. The HI index was first determined by Masterton and Richardson [15] using the following equation:

$$HI = T + \frac{5}{9} \times (e - 10)\degree C$$

(1)

where, the pressure of water vapour is found by an alternative expression of the Clausius–Clapeyron equation, and then,

$$e = 6.112 \times \left(\frac{RH}{100}\right) \times 10^{[7.5\times T/(237.7+T)]}$$

(2)

According to the above equations, the HI values are always greater than the air temperature values, while the limits of HI index, with respect to the discomfort levels (as introduced by Masterton Richardson) are presented in Table 1.

| Zone                  | HI ($\degree C$) |
|-----------------------|------------------|
| Comfortable           | HI < 27          |
| Some discomfort        | 27 ≤ HI < 30     |
| Great discomfort       | 30 ≤ HI < 40     |
| Dangerous              | 40 ≤ HI < 55     |
| Very dangerous         | HI ≥ 55          |

Table 1. HI index: zones of comfort/discomfort [15].

3. Results and Discussion

This section provides projections of $T_{\text{max}}$, RH and HI index values for West Attica region, for the future period of 2021-2045, along with a comparison between past and future periods, as a result of climate change. The projections of future climate regional analysis indicate an increase in the yearly values of $T_{\text{max}}$ associated with increase in the HI index, in the mid-twenty-first century (2021-2045). Figure 1 represents how data has changed between past (EC-EARTH black line) and future period under the two RCPs (4.5 and 8.5 W/m²), over the 25 years period considered. The study of $T_{\text{max}}$ and HI index yearly values indicate a similar increasing trend over the two periods, which signifies the correlation between these two climate parameters.
In addition, the WRF model near term climatology changes of $T_{\text{max}}$ daily values for the same region are found to be in the percentage range of 13.3% and 12.6%, compared to mean climatology of the past, for RCP 4.5 and RCP 8.5 scenarios, respectively. Overall, analysis indicate percentage differences for the HI index daily values in the range of 5.2% and 5.5% for RCP 4.5 and RCP 8.5 scenarios respectively. Results are found to be consistent with other studies, demonstrating significantly larger values compared to the Greek mainland, in both for future scenarios [24,26].

Furthermore, for each yearly dataset of the climate parameters, daily values of the HI index were extracted for the past and future. Then, a continuous Probability Distribution (PD) was created based on the Extreme Value Theory (EVT) [25], and fitted to the 25 year metadata. These results are depicted in Figure 2, which presents the differences in the HI index between past and future. In addition, it demonstrates the expected changes of the HI index, indicating that climate change has the potential to either produce a shift in the PD curve, or a variation in its shape. The black line in Figure 2 shows the PD of the past, shifted to the yellow (RCP 4.5) and red (RCP 8.5) lines for the future. As the probability distribution becomes more flattened with higher HI values, it indicates a higher variability with increase in the extreme value of HI index. Overall, Figure 2 indicates that an increase in the frequency and in the probability of occurrence of higher HI index is anticipated to occur over the future.
HI > 40 is anticipated to increase over the future scenarios from 0.16%, up to 0.21% and 0.31%, under the RCPs 4.5 and 8.5. Based on these projections, one may conclude that “dangerous” conditions are expected to be marginally more frequent, and to occur only for a few days (from 15, to 19 and 28 for RCPs of 4.5 and 8.5, respectively), within the period of the 25 years, (see Table 2 and Figure 3).

Table 2. HI\textsubscript{max} index and zones of comfort/discomfort: past values and future projections.

| Zones of comfort/discomfort | Frequency (number of days) |
|-----------------------------|-----------------------------|
|                             | 1980-2004                   | 2021-2045                   |
| Comfortable (HI\textsubscript{max} < 27) | Past: 6327 | RCP 4.5: 5934 | RCP 8.5: 5884 |
| Some Discomfort (27 ≤ HI\textsubscript{max} < 30) | 1030 | 996 | 987 |
| Great Discomfort (30 ≤ HI\textsubscript{max} < 40) | 1759 | 2182 | 2232 |
| Dangerous (40 ≤ HI\textsubscript{max} < 55) | 15 | 19 | 28 |
| Very Dangerous (HI\textsubscript{max} ≥ 55) | 0 | 0 | 0 |

Figure 3. HI\textsubscript{max} index and zones of comfort/discomfort: past, and future projections.

Finally, the return period and the number of events above particular climate thresholds of the studied climate parameters (T\textsubscript{max}, RH and HI\textsubscript{max}) which impact OSH are calculated. As it was already indicated, the method for calculating return periods and the probability of exceeding a value is based on the Extreme Value Theory (EVT) [27]. Table 3 presents the change in the frequency of extremes (return period), and the number of events above particular climate thresholds which had already specified in literature to have impact on OSH [28]. Return period analysis indicates that the frequency of the studied climate threshold is, on average, likely to be exceeded, especially during higher temperatures (> 32 °C), thus the climate threshold to occur more frequently, stressing the health of employees. However, the human body face difficulties with heat buildup when air temperature exceeds 32 °C and 75% of RH [20]. The regional climate analysis indicate a decrease in the return period under RCP 8.5 and an increase in the number of events for climate threshold of 32 °C, regarding the climate parameter of T\textsubscript{max} from 802 events over the past period, to 1171 and 1113 over the two future scenarios. Moreover, the analysis of the future RCPs 4.5 and 8.5 W/m\textsuperscript{2} scenarios indicate an increase for the HI index above the specific climate threshold of 41°C, which is anticipated to be in the range of 88 and 109 respectively, and can result in moderate to high risks in OSH (possible stroke, heat cramps, or heat exhaustion), with prolonged exposure and/or physical activity. On the other hand, a decrease in the number of events above the design thresholds of 75% concerning the RH,
along with decrease and slight increase in the return period of the particular threshold, is anticipated to occur over the future scenarios respectively.

Table 3. Number and return period of events above climate threshold.

| Thresholds of climate parameters | T_max (32 °C) | RH (75%) | H_l_max (41 °C) |
|----------------------------------|--------------|----------|---------------|
| Events above threshold (#)      | Past RCP4.5 | Future RCP4.5 | Past RCP4.5 | Future RCP4.5 | Past RCP4.5 | Future RCP4.5 |
| Return period (years)           | 0.07 0.13 0.06 0.15 0.04 0.21 1.4 0.97 0.98 |

4. Recommendations for industry interventions

Employees working in industrial facilities under extreme air temperatures are highly exposed to thermally stressful situations, which can generate high risks of heat-related illnesses, while they may lead to an overall limitation of their productivity [4]. In general, the protection and safety of employees is determined by labor legislation, which presents differentiations to each individual country. Towards this end, a growing number of industries and organizations are already following specific measures to address sensitive health issues and health risks associated with extreme heat in the context of labor legislation. Given the anticipated increase temperature due to climate change, the impacts of heat stress for OSH and efficiency should be addressed, and the individual variations in the return period, scale, size and speed of extremes have to be thoroughly considered when evaluating the climate change impacts.

Towards this direction, industries have to implement adaptation measures to prevent and/or mitigate the adverse impacts of climate change on OSH. In this light, one may find a number of general measures which can be taken into account by governmental agencies and workers’ unions contribution concerning the development of health insurance, that protect employees from risk of heat stress [4]. Moreover, a variety of adaptation measures, both short-and long-term, can promote the heat adaptation practices [29]. For instance, extreme temperatures taking place more frequently require the development of early warning systems to protect employees, or suggest protective actions. In addition, the collaboration between the scientific community and industry to effectively tackle the problem of thermal exposure is of high importance. At the same time, the use of regional models and tools to process climate extremes considering future risks due to climate change, and not only risks based on climate extremes of the past [28,30], should be considered as an activity of added value. Climate adaptation approaches to combat heat impacts have to be introduced in industry’s more important sectors [4], implementing measures, such as:

- a decrease of the shift length and the work intensity, along with the replacement of heavy tasks and the use of electro mechanical equipment as much as possible [1],
- the development of a specialized work-rest schedules, and hiring adequate numbers of employees to equally distribute the task, according to the climate conditions [2],
- the use of appropriate personal protective equipment,
- the installation of cooling ventilation stations, where workers can take their breaks [1].

Finally, it is of high importance the implementation of preventive measures under the frame of a thermal stress prevention program, which include:

- a regular screening and monitoring process of the employees work in open air to prevent direct heat exposure,
- regular health monitoring and training of employees on the dangers of working in extreme conditions [2,31].
5. Conclusions
Climate change and extreme heat events have already put occupational safety and health, as well as the economic performance of industry at high risk. There is a growing concern on the implications of climate change on thermal stress, which affects both workplace morale and performance, leading to lower productivity, or even posing a higher risk for OSH. In the context of Western Attica Region, an overpopulated and industrialized area in Greece, the analysis presented in this paper indicate increases in the T\text{max} and HI daily values in the range of 5.2% and 5.5%, an increase in the number of events HI > 41°C threshold and decrease in the return period, for the future RCPs scenarios.

Clearly, the changing climate and the associated crisis require a change in the way we think about work design, from approaches which are based on past experience to those that are based on calculated projections of future climate conditions. Thus, industries are in need of applied methods and procedures against climate risks, so as to protect OSH. Towards this end, the present study highlights the need for improvement and/or re-design of the industry’s structures/infrastructures in order to take into account climate change and the corresponding anticipated (extreme) weather conditions (heat).

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