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The HEAT-ALARM Project: Development of a Heat–Health Warning System in Greece †

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Abstract: Europe has been experiencing an increasing number of sweltering heat waves in recent years. This run of hot extremes induces a significant impact on the human environment, especially in terms of excess mortality, highlighting the urgent need for improved heat–health action planning. This is particularly true in countries situated in the eastern Mediterranean, which is considered a climate change hot spot. To increase preparedness and response to overheating risks, heat–health warning systems (HHWSs) are of vital importance. In this direction, the principal aim of the HEAT-ALARM research project is to provide a novel scientific and technological framework for the development of efficient HHWSs, employing Greece as a testbed. Going beyond the simple notion that outdoor meteorological conditions alone can adequately describe the heat–health nexus, a sophisticated human-biometeorological index, the modified physiologically equivalent temperature (mPET), is used. Advanced statistical models and tools are employed in order to establish a clear link between mPET and excess mortality at regional-unit administrative level. Moreover, urban climate factors produced by combining remote sensing and geographical information system techniques are incorporated into the HHWS via a state-of-the-art numerical weather prediction model. The latter includes a scheme that combines the parameterization and modeling of building effects and energy, respectively, in order to account for the urban indoor thermal conditions and the intra-urban differential heat exposure within the five highest populated cities of Greece (Athens, Thessaloniki, Patras, Heraklion and Larissa). Further, the human body's acclimatization ability is considered, as well as the physiological characteristics of different vulnerable groups of people, including the elderly, women and outdoor workers. The current paper describes the scientific background of HEAT-ALARM and provides preliminary results associated with the project's realization.

Keywords: extreme heat; human health; human-biometeorology; heat-related epidemiology; mPET; warning system

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1. Introduction

In the background of global climate change, the eastern Mediterranean region is facing an increased occurrence of intense and long-lasting heat waves [1]. Future climate projections also indicate that such extremes will be the norm for the eastern Mediterranean countries in the course of the 21st century [2]. In view of the above climatic trends, a critical public health concern emerges, as the increasing exposure of the population to extreme heat is associated with excess mortality [3,4]. Assisting society to cope with extreme heat requires early response systems, addressing the most vulnerable and considering the diversity of the human thermal perception within cities. In this direction, heat–health warning systems (HHWSs) have been found to significantly contribute to minimizing the negative health effects of overheating [5,6].

Within the above context, the HEAT-ALARM project aims to develop a novel HHWS for Greece, which is anticipated to act as the foundation for existing and/or new heat-health action plans in the country (Figure 1). Unlike previous efforts, HEAT-ALARM places humans at the center of the developed HHWS. As shown in Figure 1, the physiological characteristics of different vulnerable groups of people, including the elderly, women and outdoor workers, are considered, going beyond the simple notion that outdoor environmental conditions alone can adequately describe the heat–health nexus.

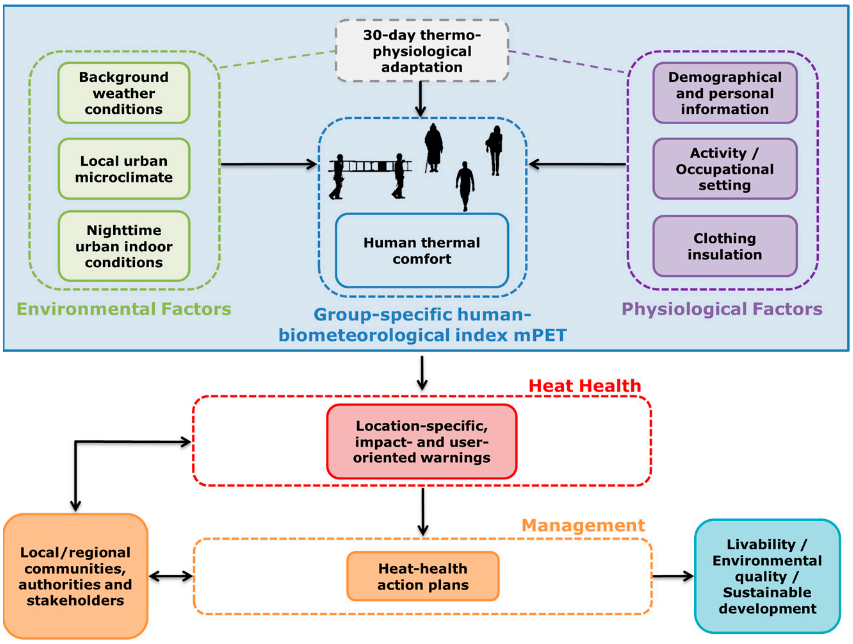

Figure 1. Conceptual framework of the HEAT-ALARM project.

Based on this conceptual framework, the specific objectives of HEAT-ALARM are as follows:

1. To conduct an up-to-date human-biometeorological and heat-related epidemiological study over Greece in order to link mortality to heat stress, expressed by a rational index, the modified physiologically equivalent temperature (mPET) [7];
2. To develop a prototype numerical weather prediction (NWP) system, capable of considering urban morphological factors, in order to account for the urban indoor temperatures and enhance the performance of the HHWS in terms of accurately predicting the intra-urban heat variations;
3. To define a scientifically documented protocol, based on a combination of indicators and factors associated with the human heat stress and urban thermal environment, for issuing location-specific, impact- and user-oriented heat warnings;
4. To engage with communities, authorities and stakeholders at local and regional level, in order to co-create a novel plan for fostering the communication and uptake of the heat–health warnings.

2. Thermo-Physiological Modeling and Epidemiological Analysis

Towards the realization of the project's HHWS, a country-wide heat–health study is conducted. This study is implemented for the most recent 30-year period (1991–2020), using reanalysis data, population and mortality data provided by the Hellenic Statistical Service (HSS), and the RayMan Pro model [8,9] for the human-biometeorological simulations. In particular, the meteorological forcing data for RayMan Pro are derived from the recently released Copernicus European Regional Reanalysis (CERRA) dataset [10]. Using the NUTS-3 (Nomenclature of Territorial Units for Statistics-3) classification, the country is divided into 72 regional units (RUs) or combinations thereof. The CERRA grid cells and population data within each RU are combined in order to compute population-weighted means of the derived reanalysis data. This approach allows for appraising the actual thermal environment experienced by the people. Concerning the mortality data, daily deaths due to all-natural causes for the period 1999–2018 are analyzed. The original data provided by HSS are aggregated at the above-described RU level, and they are grouped by sex (male; female), age (adult: <65; senior: ≥65) and outdoor occupation (skilled agricultural, forestry and fishery workers; elementary occupations [11]). Based on these groups, the RayMan Pro simulations are performed for two standard persons (male; female) in terms of age, height and weight for the general population (i.e., adults), performing light activity [5]. Age-, weight- and activity-dependent changes are introduced for the reference seniors [5], while the main modifications for the outdoor workforce are associated with the activity level. For all population subsets, the clothing insulation is automatically scaled based on the simulated thermal conditions [7], while short-term acclimatization effects are considered by adapting the mPET thermal stress classes based on the application of a 30-day Gaussian filter [5].

The above data are used to assess the human thermal bioclimate and its trends in the 72 defined RUs in Greece. Preliminary results show a marked increase in strong heat stress days in the RUs of Serres, Corinthia and Heraklion (Figure 2a–c). Concerning the latter RU, it is worth noting the lower number of days with maximum mPET greater than 35 °C, which indicates the beneficial effect of the Etesians (northern sector winds) in terms of reducing the thermal discomfort in Crete. Figure 2d also shows a flat trend in strong heat stress exposure for the Ioannina RU, highlighting the important regional differences in human thermal bioclimate in Greece.

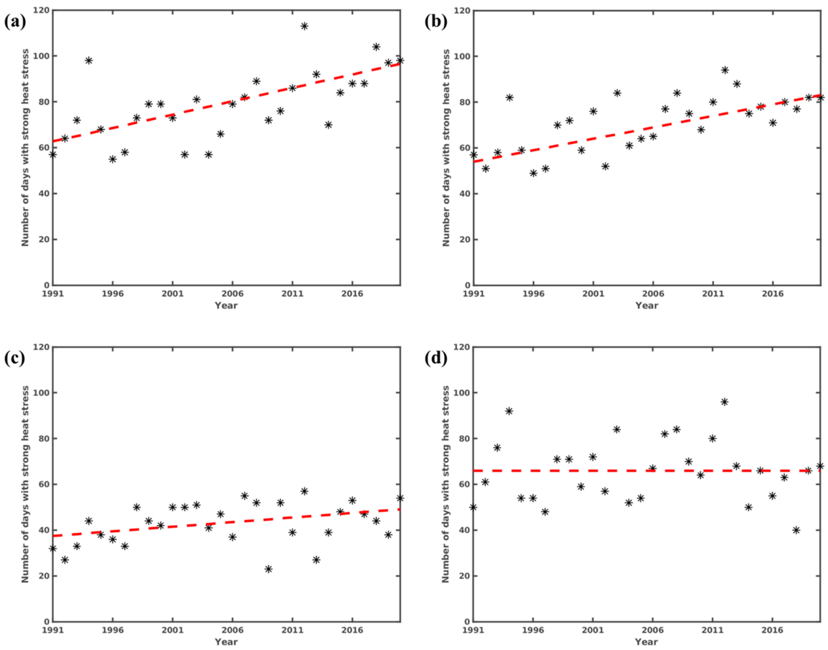

Figure 2. Annual number of days with strong heat stress (defined as days with maximum mPET greater than 35 °C) from 1991 to 2020 at the regional units of (**a**) Serres, (**b**) Corinthia, (**c**) Heraklion and (**d**) Ioannina. The red dashed lines correspond to the mPET trends calculated by applying the Theil-Sen estimator [12].

Further, the exposure–response relationship between heat stress and relative mortality at the RU level and for all population subsets under investigation is studied using generalized additive modeling and distributed lag non-linear models [3,4]. Eventually, the heat–health analysis will allow for defining location- and group-specific thresholds associated with increased mortality risks.

3. Numerical Simulations—Heat Health Warning System

The development of the HHWS's weather forecasting component is based on a state-of-the-art mesoscale NWP model, namely the Weather Research and Forecasting (WRF) model [13]. WRF is operationally implemented at high spatial resolution (2 km) over Greece by the METEO Unit at the National Observatory of Athens (NOA) [14]. This model configuration is extended during the HEAT-ALARM project by including fine-scale horizontal grid resolution (400 m) domains for the five highest populated cities in Greece (Athens, Thessaloniki, Patras, Heraklion and Larissa) and incorporating the advanced urban scheme BEP/BEM (building effect parameterization/building energy modeling) [15] in these domains. The application of WRF-BEP/BEM is supported by novel datasets of surface and urban canopy properties (SUCPs; e.g., surface's emissivity, buildings' height) that are produced for the targeted cities. A GIS-based approach is first adopted for classifying the study areas in local climate zones (LCZs) at the urban domains' spatial resolution (400 m) [16]. As an example, the derived LCZ maps for the cities of Athens and Larissa are given in Figure 3, showing that the central areas of both cities are dominated by compact built-up areas (LCZ 1–LCZ 3). Next, remote sensing techniques are exploited for defining the necessary SUCPs per LCZ [16]. The performance of the model will be thoroughly evaluated during its application in the summer of 2023, using observations that will be provided from the dense network of automated ground-based weather stations operated by the METEO Unit at NOA [17]. A first application of the above-described sophisticated urban modeling system has shown a robust performance in replicating the observed thermal environment and human bioclimate in the Athens urban area during both extreme heat and typical summer days [14].

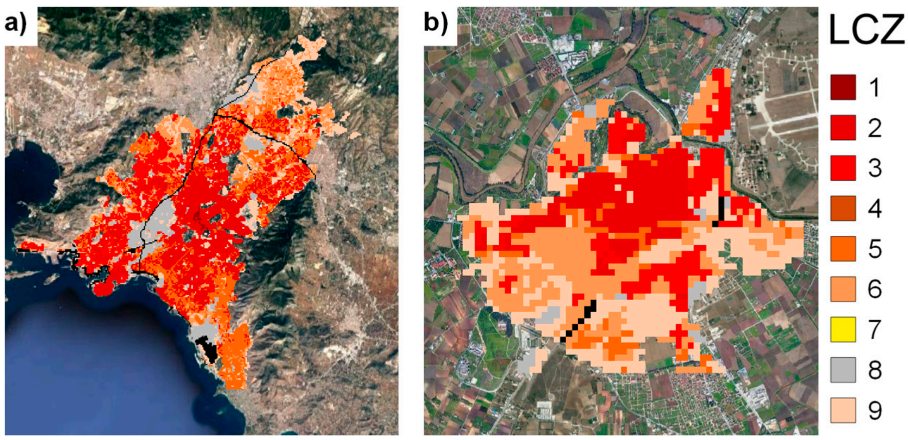

Figure 3. LCZ maps for (**a**) Athens and (**b**) Larissa.

The synthesis of the HHWS will follow the implementation of the heat–health study and the construction of the WRF-BEP/BEM-based NWP system. On a pre-operational basis, 3-day numerical weather forecasts, accounting for the differential effects of heat within the five highest populated cities in Greece, will provide the necessary input for the computation of mPET through the RayMan Pro model for all targeted population subsets at the RU level. Short-term acclimatization effects, as described in the previous section, will be considered for the mPET forecasts. Further, the indoor temperatures simulated by the NWP system for the eight nighttime hours in the targeted cities will allow for taking into account the nocturnal conditions inside urban dwellings. This is of vital importance, as the high nighttime urban temperatures have a more damaging impact on human health because they deprive urban residents of the sense of thermal relief [14]. Ultimately, an automated warning protocol will be set up considering the following: (a) the relationship between the computed mPET and mortality, (b) the human body's acclimatization ability, and (c) the urban climate and nocturnal indoor conditions. Health protection recommendations accompanying each heat warning level will be defined according to WHO (World Health Organization) heat prevention standards [18] and giving particular emphasis to high-risk locations and groups. Concerning the dissemination to various audiences (e.g., vulnerable groups and health authorities), a regional heat–health information plan (RHHIP) will be co-created with local and regional communities, authorities and stakeholders. RHHIP will establish a well-documented framework about what is communicated, by whom, when and by which means at the local and regional level.

4. Discussion and Concluding Remarks

Most of the previous efforts in assessing the impact of human thermal stress on mortality in Greece focused primarily on major metropolitan areas using solely meteorological-based thermal indices (e.g., [3,4]). HEAT-ALARM will provide a comprehensive heat- and health-related study for the first time at a nationwide scale using a rational heat stress index and taking into account variable socioeconomic groups. Further, the project will substantially contribute to highly resolved urban-scale weather forecasting by providing the necessary key input data in the five targeted cities and by validating a state-of-the-art NWP system that includes the sophisticated urban scheme BEP/BEM. Considering that such finely detailed data have been incorporated in modeling approaches only in Athens so far [14,16], this will be an important step towards the development of a national urban dataset for accurately simulating environmental risks in cities for various applications. It is important to note that the datasets comprising the mPET simulations, LCZs and SUCPs will be made publicly available in order to advance human -biometeorological and urban climate research in Greece, as well as in other countries since the applied methods are characterized by a high potential in replicability. The final outcome of the HEAT-ALARM project will be a flexible HHWS accompanied by a novel RHHIP for assisting heat prevention decision making and acting at the local and regional level. Flexibility refers to the ability to consider the physiological characteristics and acclimatization capacity of different groups of people and the differential heat impact within cities. This is of vital importance for addressing the most vulnerable [19,20], and it is currently missing from most HHWSs at European and international level [6,21].

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