International Journal of Biometeorology
https://doi.org/10.1007/s00484-018-1525-3

Operational forecasting of human-biometeorological conditions

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Received: 23 November 2017 / Accepted: 2 March 2018

Abstract
This paper presents the development of an operational forecasting service focusing on human-biometeorological conditions. The service is based on the coupling of numerical weather prediction models with an advanced human-biometeorological model. Human thermal perception and stress forecasts are issued on a daily basis for Greece, in both point and gridded format. A user-friendly presentation approach is adopted for communicating the forecasts to the public via the worldwide web. The development of the presented service highlights the feasibility of replacing standard meteorological parameters and/or indices used in operational weather forecasting activities for assessing the thermal environment. This is of particular significance for providing effective, human-biometeorology-oriented, warnings for both heat waves and cold outbreaks.

Keywords Modified physiologically equivalent temperature · Numerical weather prediction · Weather forecast · RayMan · BOLAM · WRF · Greece

Introduction

Standard meteorological variables and simple composite indices are traditionally used in operational weather forecasting activities for assessing the thermal environment. From a human-biometeorological perspective, this approach neglects the physical and physiological basics, diminishing the value of the relevant assessments and leading to misrepresentations of the thermal environment (Matzarakis and Amelung 2008; McGregor 2011). To provide a comprehensive characterization of the thermal component of the environment, a complete human heat budget model needs to be taken into account (Fanger 1970; Landsberg 1972; Driscoll 1992; Parsons 2003).

Considering the progress that has been made in past decades with respect to the development and evaluation of human heat budget models (Vanos et al. 2010), it is surprising that simplistic and crude indices are still extensively used. For instance, apparent temperature has been widely used for investigating heat-related mortality (e.g., D'Ippolit et al. 2010), while the more popular wet bulb globe temperature has been employed in several studies focusing on the assessment of outdoor heat stress conditions (e.g., Gaspar and Quintela 2009), evaluation of the effectiveness of heat mitigation strategies (e.g., Yamagata et al. 2008), and monitoring of heat exposure (e.g., Noweir and Bafail 2008). It appears that such indices remain attractive due to the limited data that are required for their computation, which, in turn, facilitates their incorporation into literally any weather forecasting service. Yet, they fail to satisfy the fundamental condition that for each index value, there should be a unique outcome with respect to strain, regardless of the atmospheric stress (Błazejczyk et al. 2011).

This paper presents the development of an operational forecasting service for thermal perception and stress in Greece, based on a thermo-physiologically founded index. The service is founded on the offline coupling between two numerical weather prediction (NWP) models, running operationally at the National Observatory of Athens (Greece), with a comprehensive and extensively validated human-biometeorological model. The key aim of the service is to provide information and advice on thermal conditions in a practical way that can be easily understood by the public. To our best knowledge, the

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Published online: 12 March 2018

presented service is the first one of its kind, at least in the region of the southeast Mediterranean.

Methodology and prototype results

The thermal perception and stress forecasting service is founded on the offline coupling of two NWP models, namely BOLAM (Lagouvardos et al. 2003) and WRF (Skamarock et al. 2008) with the human-biometeorological RayMan Pro model, version 2.3 (Matzarakis et al. 2007, 2010). Briefly, the NWP models provide the forcing data for RayMan, that is air temperature and humidity, wind speed (reduced to 1.1 m, which approximates the weighting height of the human body), global radiation, and surface temperature. RayMan then computes the modified physiologically equivalent temperature (mPET; Chen and Matzarakis 2017), which is the comfort-based index used for assessing thermal perception and stress conditions. The mPET-based human-biometeorological assessment is carried out after Matzarakis et al. (1999) for a standard European 35-year-old male, 1.75 m tall, weighing 75 kg, and having a metabolic heat production rate of 80 W (light activity). An adaptive clothing model, based on air temperature, is used for parameterizing clothing insulation. More details on mPET and its calculation using the RayMan model can be found in Chen and Matzarakis (2017) and Matzarakis et al. (2007, 2010).

Special procedures were developed to allow for the coupling of the Unix-based NWP models and the Windows-based RayMan model in an operational context. These procedures are summarized in Fig. 1, which shows the flow chart of the developed service. First, the raw NWP data are pre-processed. The pre-processing is carried out with NCAR Command Language (NCL, 2017) on the UNIX server and includes (a) the extraction of forcing variables, (b) the grid-to-point interpolation of variables using a supervised nearest neighbor approach (applied only in the case of BOLAM), (c) a quality control check, and (d) the generation of the RayMan input files in the required plain text format. The produced RayMan forcing data files are then transferred to the Windows server via a SSH File Transfer Protocol (SFTP) interface. At the Windows server, the Task Scheduler utility program is employed for launching a script written in Visual Basic (VB). This script is used for checking whether the RayMan input data have become available and, if yes, launching the model. It then carries out the entire model setup (e.g., selection of input files and paths and specification of parameters) in a fully automated way, similarly to what a user would normally do by clicking and typing. Following the completion of the RayMan execution, output data are transferred back to the UNIX server, again via SFTP. The last step includes calling two NCL scripts for post-processing and visualizing/publishing the computed human-biometeorological data. In particular, the BOLAM/RayMan data are exported as time series, in plain ASCII format for a predefined set of points of interest (section "Point forecasts"), while the WRF/RayMan data are stored in gridded format (section "Gridded forecasts").

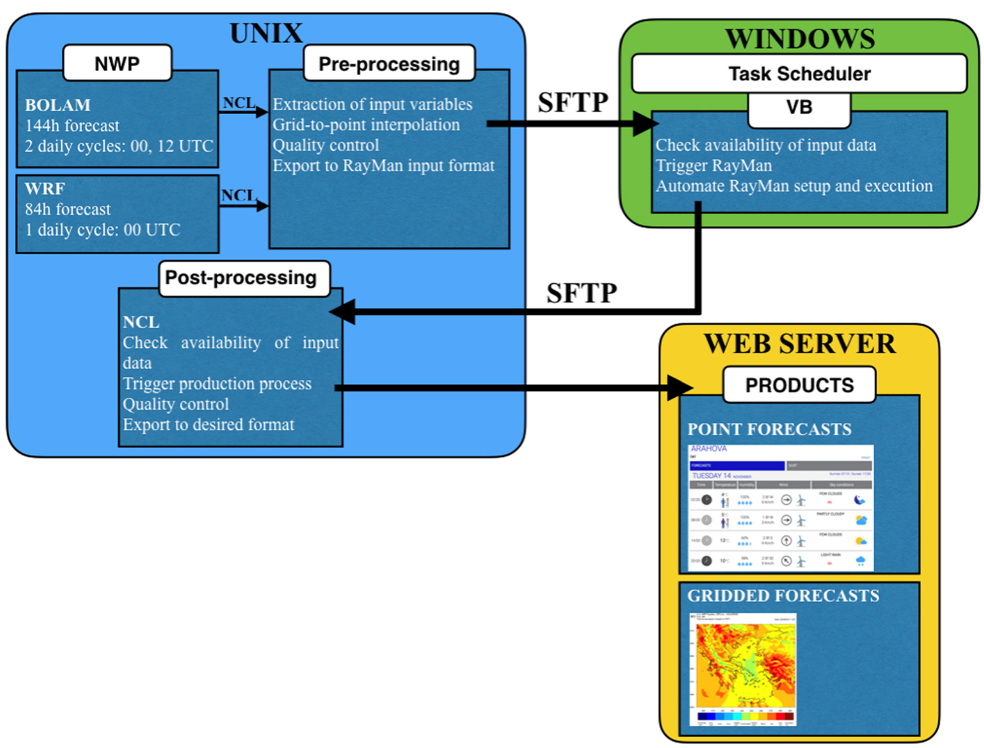

Figure 1 Flow chart of the coupled meteorological/human-biometeorological forecasting service

Point forecasts

Daily forecasts for thermal perception and stress conditions, based on the BOLAM/RayMan modeling system, are provided for 500 major cities and towns of Greece, including tourist destinations. The forecasts are updated twice per day, in the morning and in the evening, and are communicated to the public through the website http://www.meteo.gr, which is the most popular weather-related website in Greece and in the top five of most visited websites. All forecasts are available in two languages, Greek and English.

Figure 2a illustrates an example of forecast provided for a popular mountainous destination in south Greece, with the explanatory text that is available in the help section of the website shown in Fig. 2b. As shown in Fig. 2a, the human-biometeorological information is embedded within the typical temperature forecast. Simple, user-friendly icons are used to facilitate the communication of the information to the public. The icons depict a human body embedded in a square that is colored differently, depending on the forecasted thermal perception and stress (Fig. 2b). For the purposes of the public forecasts, six levels of thermal perception and stress are implemented, ranging from very cold (extreme cold stress) to very hot (extreme heat stress).

Gridded forecasts

Maps depicting the forecasted spatial distribution of thermal perception over Greece, based on the WRF/RayMan modeling system, are also produced on a daily basis. The maps are updated once per day, early in the morning, extend to a forecast horizon of 3 days, and are published on a dedicated webpage (http://meteo.gr/meteomaps/index.cfm).

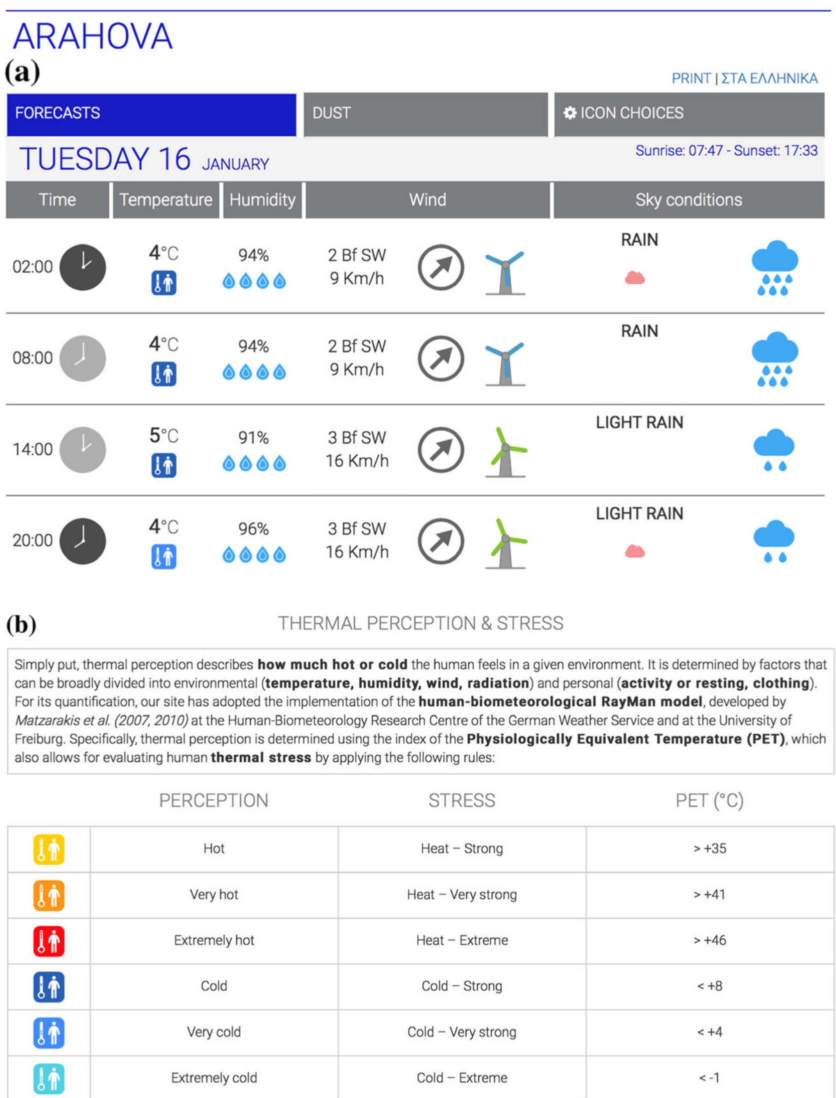

Figure 2 **a** Example forecast for Arahova, Greece, with embedded human-biometeorological information. **b** Explanatory text for the thermal perception and stress conditions forecasts. **c** Example forecasting map for Greece, valid for 26 August 2017 at 12 UTC

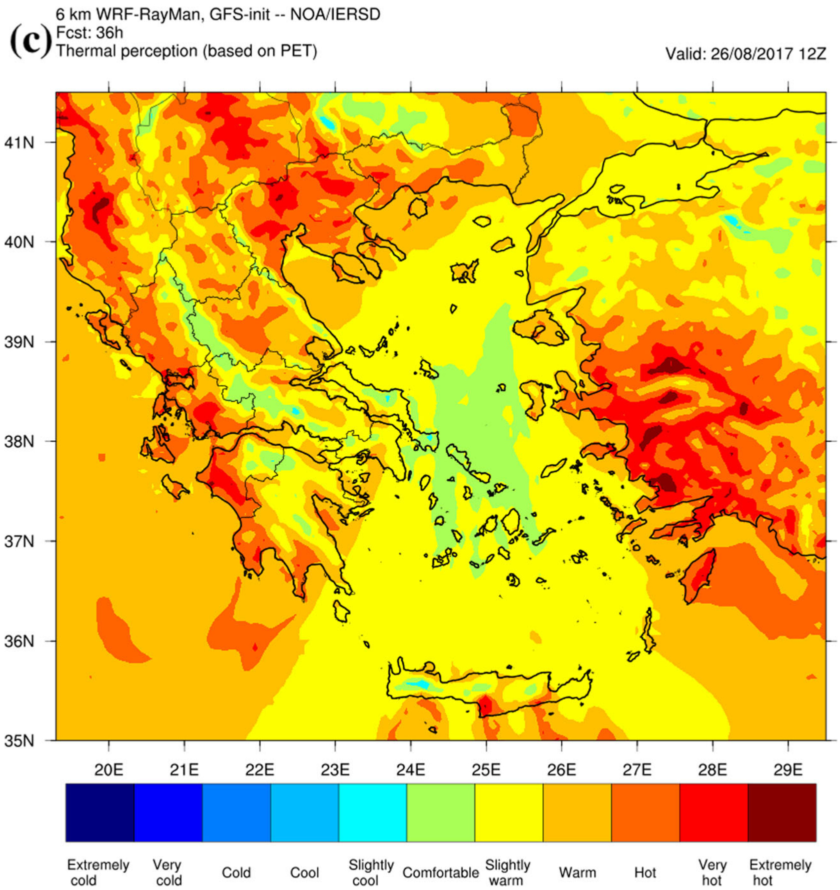

Fig. 2 continued.

Figure 2c presents an example of a forecasting map, issued on 26 August 2017. The map shows the model-predicted spatial pattern of thermal perception on 26 August 2017 at 12 UTC (36 h forecast). The explicit use of textual description for each of PET's thermal perception classes in the legend of the map, together with the adopted cold (blue) to hot (red) color map, facilitates interpretation of the provided information. A glance at the map allows the user to quickly identify regions with different grades of thermal perception. For instance, lowland and mountainous areas are clearly delineated by showing the highest and the lowest levels of thermal discomfort, respectively. It is also interesting to notice the contrast between the Aegean Sea and continental Greece, and the Ionian Sea to the west. This is attributed to the cool northerly winds, known as the Etesians, which reduce thermal stress to more comfortable levels (Giannaros et al. 2015).

Discussion and conclusions

Previous work has mainly focused on the climatology of thermal indices (e.g., Jendritzky and Tinz 2009). The latter have been also extensively used in the context of the human-biometeorological assessment of heat waves (e.g., Amengual et al. 2014), as well as for evaluating thermal conditions in urban areas (e.g., Charalampopoulos et al. 2013). On the other hand, the production and communication of human-biometeorological information using advanced thermal indices and user-friendly dissemination means has received considerably less attention. This is surprising considering the importance that such information has for setting up effective warning and protection strategies against thermal stress (Matzarakis and Amelung 2008; Jendritzky and Tinz 2009).

This paper introduces the development and implementation of an operational human-biometerological forecasting service in the region of the southeast Mediterranean. The service exploits traditional NWP-based weather forecasting techniques and a human heat budget-based numerical model in order to derive thermal perception and stress in a thermo-physiologically relevant context. Our key motivation and aim is to highlight that standard approaches used in operational weather forecasting for assessing the thermal environment can be replaced by existing advanced tools without a cost on the operational character of the provided services. In addition, we show that human-biometeorological information can, and should be, communicated to the public in effective, easy-to-understand ways. Last, it is worth mentioning that the presented service will be further developed, mainly in terms of calibrating the mPET-based thermal assessment scheme for Greece, using a human-biometeorological survey-based approach. This will also allow for estimating the uncertainty of the provided forecasts.

All the scripts that have been developed for the coupling of the NWP models with RayMan and for the automation of the procedures are freely available upon request, by contacting the corresponding author of this paper. The scripts have been thoroughly tested and found to work properly on common UNIX and Windows servers. Computational demands are generally low, depending though on the number of grid points for which the coupled system is applied.

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