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Article

Inclusion of short-term adaptation to thermal stresses in a heat load warning procedure

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Abstract

It is considered to be very probable that the frequency and intensity of heat waves will increase and that heat waves, such as the one experienced in Europe in 2003, will not remain an exception. Everything goes to suggest that human beings have adapted to their local climate. Extreme events such as heat waves, for example, can, however, cause considerable stress to the thermoregulative processes in the human organism. Heat load warning systems provide a possibility for reducing heat-induced morbidity and mortality. We are presenting a method that, apart from a thermophysiologically relevant evaluation of the environment, also takes into account short-term adaptation processes of human beings to the thermal environment. The forecast method differs from previously used methods in that it is based on a combination of absolute and relative thresholds and thus includes the local adaptation to the thermal conditions of the previous weeks. This is an attempt to give a quantitative description of the mainly qualitative statements in literature on acclimatisation. A further advantage of this method is that, due to the inclusion of relative, i.e. local, conditions, it can, in principle, be applied to all climates.

Zusammenfassung

Es gilt als sehr wahrscheinlich, dass die Häufigkeit und Intensität von Hitzewellen zunehmen wird und dass Hitzewellen, wie jene im Jahr 2003 in Europa kein Einzelfall bleiben. Alles deutet darauf hin, dass die Menschen an ihr Lokalklima angepasst sind. Extremereignisse wie beispielsweise Hitzewellen können jedoch erheblichen Stress auf die thermoregulativen Prozesse des menschlichen Organismus ausüben. Hitzewarnsysteme bieten eine Möglichkeit die hitzebedingte Morbidität und Mortalität zu verringern. Es wird ein Verfahren vorgestellt, dass neben einer thermophysiologisch relevanten Bewertung der Umwelt auch kurzfristige Anpassungsvorgänge des Menschen an die thermische Umgebung berücksichtigt. Das Vorhersageverfahren unterscheidet sich von den bisher gängigen Methoden dahingehend, dass es auf einer Kombination aus absoluten und relativen Schwellen basiert und damit die lokale Anpassung an die thermischen Bedingungen der vergangenen Wochen einbezieht. Damit wird versucht, die überwiegend qualitativen Aussagen in der Literatur zur Akklimatisation quantitativ zu beschreiben. Ein weiterer Vorteil dieses Verfahren ist, dass es aufgrund der Einbeziehung relativer, d.h. lokaler Bedingungen grundsätzlich in allen Klimaten angewendet werden kann.

1 Introduction

The IPCC Third Assessment Report (HOUGHTON et al., 2001) stated that "there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities". A changing climate is expected to increase average summer temperatures and the frequency and intensity of hot days and heat waves. Although heat waves are rare events, they are associated with significant mortality impacts (e.g. BASU and SAMET, 2002). In countries such as Australia and the United States, heat waves in the 20_{th} century caused more deaths than any other weather-related hazard (EMA, 2002). Europe has also been affected by heat waves during recent years. In August 2003 a major heat wave killed about 25,000 people all over Europe, about half of them in France (LARSEN, 2003). In Athens, a heat wave resulted in 926 directly heat-related deaths in 1987. The excess mortality, however, was estimated to be more than 2,000 (KATSOUYANNI et al., 1988). A heat wave in Portugal in June 1981 caused approximately 1,900 excess deaths (GARCIA et al., 1999). Many of the heat-related deaths may be preventable with adequate warning and an appropriate response to heat emergency measures (BASU and SAMET, 2002). Heat health warning systems consist of two parts: a meteorological component (issuing of a warning) and a public health component (action plans, intervention measures). The meteorological component is based on a heat stress indicator. Several procedures which aim at assessing the thermal environment of human beings in addition to air temperature are applied. However, procedures based on air temperatures, simple thermal indices, or weather classifications (holistic approaches) give no insight into cause-effect relationships. Fundamentally, we know the mechanism of heat exchange between the hu-

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man body and its thermal environment that is defined by air temperature, water vapour pressure, wind velocity, and mean radiant temperature[1] (FANGER, 1970). Thermophysiologically relevant assessment procedures that combine the above-listed meteorological variables with metabolic rate and with consideration of the insulation effect of clothing, require the application of complete heat budget models. Apart from the holistic approaches, heat load warning procedures are based on an absolute or a relative threshold. An absolute threshold implies that there will be no heat load in colder regions and frequent heat load in warmer regions. Relative thresholds (e.g. the 97 % percentile), on the other hand, are based on the assumption that the frequency of heat waves is in the same order of magnitude everywhere. Up until today the term "heat wave" has not been defined officially, e.g. by WMO. Heat waves as extremes are rare events. And an impact-related definition of a "heat wave" must also meet the criteria that society is susceptible to or unable to cope with these events. Nevertheless some attempts to define a "heat wave" do exist throughout the world (e.g. ROBINSON, 2001). Some of them are based on an air temperature threshold only, or they are based on simple thermal indices, some of them include also a minimum duration. Those heat wave definitions are often very specific and valid only for the population of the region from where they were derived. This is due to the societal character of the heat wave impact. Humans are adapted and acclimatised to a certain extent to their local climate. Therefore there is a spatial and temporal variability within the thresholds upon which health effects can be found (e.g. KALKSTEIN and GREENE, 1997). Because of short-term acclimatisation the threshold, above which an increase in mortality can be found, varies within the year. KYSELÝ and HUTH (2004) found this threshold for the Czech Republic to be 2–3 K lower in spring than in July or August. This study shows a possibility to include short-term acclimatisation in a heat load warning approach that can also be used for a general definition of the term "heat wave".

2 Scientific background: Physiological aspects of thermoregulation

2.1 Mechanisms of heat exchange

The body temperature regulation centres in the brain attempt to keep the body core temperature within healthy limits. At rest this is about 37°C. A deviation of the core temperature of a few degrees Celsius from the control range can have detrimental effects on human health. In order to stay within the control range, the body has to balance its heat production with heat loss. Heat is produced by metabolic activity which is required to perform activities. The body can lose heat by means of turbulent fluxes of sensible and latent heat as well as by radiation. Air temperature, mean radiant temperature, water vapour pressure, and wind velocity are the 4 fundamental environmental factors which determine the heat exchange. For the assessment of the impacts of the thermal environment on the human body it is therefore essential to include and to quantify all of these factors (PARSONS, 2003). Together with the metabolic heat production and the clothing, they form the 6 fundamental factors which determine the heat exchange of a human being with the environment.

2.2 Heat-related disorders

There are a couple of directly heat-related illnesses such as heat-stroke, heat syncope, heat exhaustion and heat cramps, skin eruptions, and heat fatigue. However, the heat load obviously does also affect not directly heat-related disorders. This may be due to the relatively high priority of the thermoregulatory system within the human body (PARSONS, 2003). Therefore, the increase in mortality during heat waves is also only to some extent directly heat-related, and probably to a greater degree indirectly due to heat-related failures, e.g. of the cardiovascular and respiratory system. A key factor for the appearance of heat-related disorders is, apart from a low fitness level, including already existing diseases, the lack of acclimatisation (PARSONS, 2003). Therefore the impacts of heat load are greatest in regions where people are not accustomed to hot weather (KALKSTEIN and GREENE, 1997). Hence, it is important to include this factor in a heat load warning approach.

2.3 Acclimatisation

Acclimatisation is defined as physiological adaptation that is gained after several days of heat exposure and that reduces the intensity of heat load in a hot environment (YOUSEF et al., 1986). Adaptation in contrast to acclimatisation also includes behavioural and societal aspects. It can be distinguished between long-term and short-term acclimatisation. During long-term acclimatisation to hot and humid environments, fully acclimatised individuals sweat less, have a lesser rise in core temperature and a lesser increase in heart rate, when compared with individuals not acclimatised to heat. These long-term adaptive changes to heat exposure are stable and maintained for a long period (HORI, 1995). In contrast, the physiological changes gained by short-term acclimatisation are not maintained if the individual is not exposed to heat any longer and disappear over a period of several weeks. These physiological changes include:

[1] The mean radiant temperature (°C) is defined as that uniform temperature of a black enclosure which would result in the same heat exchange by radiation from a person as from the actual enclosure under study (FANGER, 1970).

increase in sweat production, decrease in salt content of sweat and urine, reallocation of sweat glands, increase in blood volume, lower increase in core temperature, lower increase in heart rate (HORI, 1995). It takes the body from several days to about two weeks to gain short-term heat acclimatisation (e.g. KHOSLA and GUNTUPALLI, 1999). The short-term heat acclimatisation is lost about one month after the last heat exposure (e.g. YOUSEF et al., 1986). In spite of many case studies analysing single physiological elements that change during the acclimatisation process, a deterministic model that describes the whole process in a quantitative way, does not yet exist. MORGAN and DE DEAR (2003) were able to quantify behavioural adaptation by correlating the weighted mean daily outdoor air temperature of the previous days with clothing insulation values.

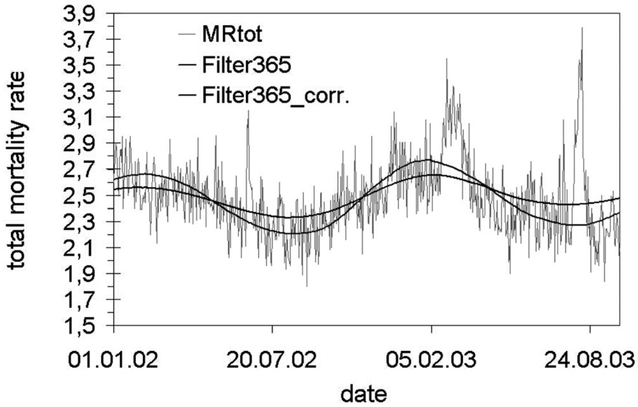

Figure 1: Total mortality rate (MRtot), Gaussian smoothing (Filter365) and corrected values of the filter function (Filter365corr.) for 1/2002–9/2003.

3 Materials and methods

3.1 Area under investigation

The study area is the Federal State of Baden-Wuerttemberg in south-west Germany. Baden-Wuerttemberg covers an orographically structured area of about 35,700 km^2. Its north-south extension is 220 km, with geographical latitudes ranging from 47° to 49°, and from west to east it extends from a geographical longitude of 7° to 10° (160 km). The difference between the highest and the lowest elevation is about 1,400 m. The climate in Baden-Wuerttemberg is temperate.

3.2 Mortality data

A time series of 36 years of daily total mortality data for the period 1968–2003 from Baden-Wuerttemberg was investigated. The daily mortality data as well as annual population data were obtained from the Baden-Wuerttemberg State Statistics Office. A linear interpolation of the annual population data provided daily population estimates in order to standardise the daily mortality data to 100,000 inhabitants. In order to allow for seasonal variations in the total mortality data (high mortality in winter and low mortality in summer), the data have been smoothed by using a 365-day Gaussian smoothing with a filter response function R (SCHÖNWIESE, 1992; LASCHEWSKI and JENDRITZKY, 2002).

$$R(f) = exp(-1/3\pi^2 f^2),$$

with f as the frequency of the time series. The Gaussian smoothing also eliminates trends (Figure 1). Using a 365-day Gaussian smoothing has the advantage, that there is no need to control for influenza or other effects in the data. Filters with lengths shorter than 365 can be influenced by single mortality events. Due to the length of the filter function of one year the minima and maximums of this function become too flat. In order to control for this fact TAUBENHEIM (1969) suggests to introduce a correction factor. This correction factor can be used if the oscillation of interest is sinusoidal as is the course of the year. We have chosen the correction factor in a way that the differences between the raw-data and the filter function were minimised. The corrected filter response function is taken as the expected mortality time series. For the analyses the deviation of the mortality rate from the expected mortality in percent was calculated. This procedure enables the comparison of different mortality datasets with different baseline populations. In order to account for the time lag between thermal stress and its impact on human health between 0 and 1 day, two-day averages of mortality rates were used for the comparisons with the thermal environment.

3.3 Meteorological data

The Klima-Michel-Model has been applied to assess the environment in a thermophysiologically relevant way (JENDRITZKY et al., 1979, JENDRITZKY and NUEBLER, 1981). The parameter used is the Perceived Temperature PT, which takes all relevant mechanisms of heat exchange into account with consideration given to well-adapted clothing. The meteorological input variables are air temperature, water vapour pressure, wind velocity and short-wave as well as long-wave radiant fluxes.

PT [°C] is defined as the air temperature of a reference environment in which the perception of heat and / or cold would be the same as under the actual conditions. In the reference environment the wind velocity is reduced to a slight breeze, the mean radiant temperature is equal to air temperature and relative humidity is 50 % (STAIGER et al., 1997). The model is originally based on the predicted mean vote (PMV) equation of FANGER (1970) and uses the PMV* correction of GAGGE et al. (1986) to account more accurately for

Table 1: Perceived Temperature (PT), thermal sensation and thermal stress (based on FANGER, 1970). *UCC: Upper constant comfort range **LCC: Lower constant comfort range.

PT in °C	Thermal sensation	Thermal stress level	Name
	Very hot	Extreme	
38			
	Hot	Strong	
32			
	Warm	Moderate	
26			
	Slightly warm	Slight	
20			UCC*
	Comfortable	None	
−0			LCC**
	Slightly cool	Slight	
−13			
	Cool	Moderate	
−26			
	Cold	Strong	
−39			
	Very cold	Extreme	

latent heat fluxes (evaporation). The thermophysiological assessment is made for a standardised person called "Klima Michel", who adapts his clothing between 0.5 clo[2] (summer clothes) and 1.75 clo (winter clothes). This standardised person is 35 years old, 1.75 m in height and weighs 75 kg. His work performance is 175.5 W, which corresponds to walking at approximately 4 km/h. The assessment procedure is designed as being representative for people staying outdoors (KOPPE et al., 2004a), although even in summer people live indoors most of the time. Therefore, an individually related PT value might differ significantly from the value used for the assessment. This is a fundamental issue in environmental epidemiology.

A problem for the comparison of the mortality data with the meteorological data is the coarse resolution of the mortality data. Therefore it was necessary to aggregate also the PT values from several stations in Baden-Wuerttemberg. In order to achieve a PT value that is representative for the mortality time series, daily PT values at 06:00 and 12:00 from four weather stations (Freiburg, Karlsruhe, Stuttgart and Konstanz) were averaged to represent the area mean. There were two reasons for using these stations. Firstly, their distribution over the State of Baden-Wuerttemberg, the weather stations being located in the south-western, south-eastern, north-western and north-eastern part of the State and secondly, because they represent the areas with the highest population densities. However, it should be noted that they do not represent the "mean" conditions for the whole region.

In order to eliminate trends and seasonal fluctuations, the Gaussian smoothing was also applied to the PT data. In contrast to the mortality data, for the smoothing of the PT data only a backward filter was applied (half Gaussian filter), which includes the 30 days before. The reason for using only the half filter and the shorter filter length is that the filter is considered to display the short-term acclimatisation processes. The conceptual model behind this assumption is that most of the physiological changes of short-term acclimatisation take place within one or two weeks and are lost within a month. Also short-term behavioural adaptation is included in the model, e.g. the amount of clothing worn (see MORGAN and DE DEAR, 2003), as this cannot be distinguished from acclimatisation (physiological adaptation) at the population level. Hence, the relative weight of the first one or two weeks should be higher than that of the end of the period. Therefore filter weights based on a normal distribution seem to be an appropriate approach.

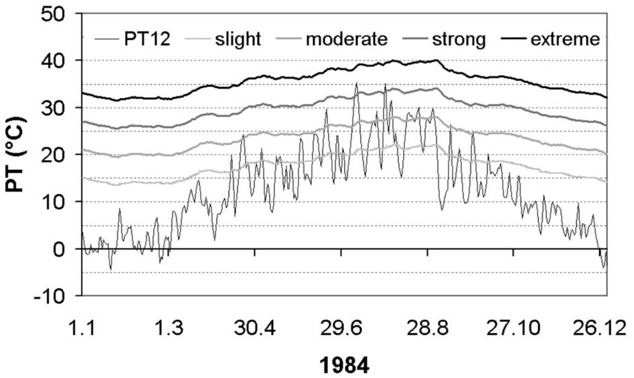

Figure 2: Annual course of PT12 and of the different heat load categories for 1984 in Baden-Wuerttemberg. PT: Perceived Temperature; PT12: Perceived Temperature at 12:00 UTC.

3.4 DWD heat load warning procedure

In order to overcome the shortcomings of the already existing heat indicators, a method has been developed that includes short-term adaptation in a thermophysiologically relevant assessment procedure. Among others, the inclusion of short-term adaptation has the advantage that the index can be used without modification in different climate regions and during different times of the year. The DWD procedure accounts for short-term adaptation by including the last 30 days. Therefore it is not necessary to define artificially a summer season or to include the day of the year (season) in the model.

The DWD heat load warning approach is based on PT. It combines an absolute with a relative threshold. The absolute part is based on the thresholds for heat load and cold stress shown in table 1 based on the PMV values of FANGER (1970). The relative part is introduced by using the Gaussian smoothed values of PT. These

[2]Clo: clothing insulation value. 1 clo is equal to 0.155 m^2 K / W.

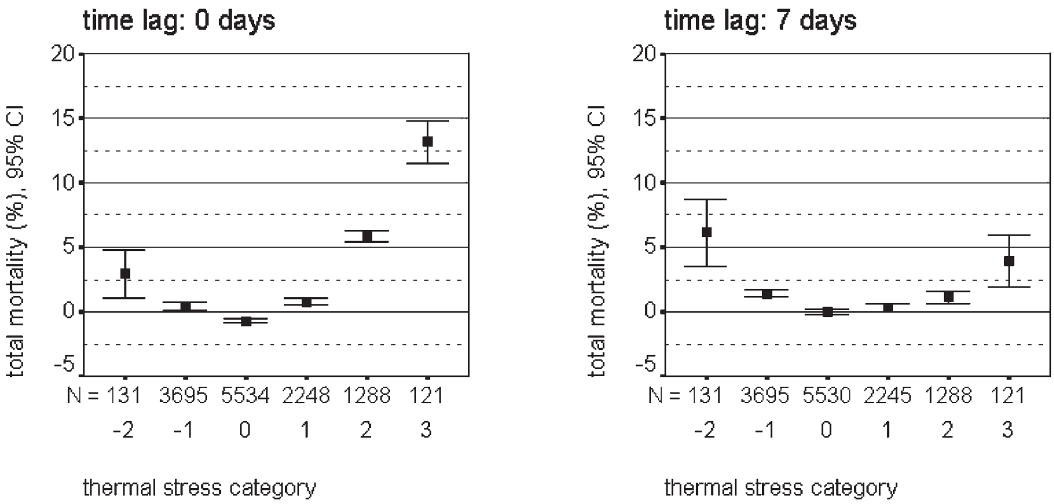

Figure 3: Mean mortality increase (decrease) in percent of the different thermal stress categories in SW Germany from 1968–2003 for no time lag (Figure 3a) and a time lag of 7 days between thermal load and mortality (Figure 3b). –2: moderate cold stress; –1: slight cold stress; 0: comfortable; 1: slight heat load; 2: moderate heat load; 3: strong heat load. Bars indicate the 95 % confidence interval, N: number of days.

represent the temperature to which a human being can adapt by short-term adaptation.

The upper value for the adapted comfort range (UACR) which is 20°C by using the absolute threshold only (UCC), is calculated as follows:

$$UACR = UCC + (F12 - UCC) * 0.33[°C].$$

The lower value for the adapted comfort range (LACR) is 0°C by using the absolute threshold only (LCC) and is modified accordingly for the new approach:

$$LACR = LCC + (F06 - LCC) * 0.33[°C].$$

F12 is the smoothed value of PT at 12:00 UTC and F06 is the smoothed value for PT at 06:00 UTC, respectively. The absolute part is weighted with 2/3 and the relative part with 1/3. The weight for the relative part was chosen arbitrarily. It refers to the experience that populations do not adapt completely to the weather conditions of the past few weeks. For example, within a population there are unfit individuals who acclimatise to a lesser extent than the fit persons. Therefore, the weighting factor has to account for such intra-individual differences within a population.

For the assessment of the heat load the PTs at 12:00 UTC are used here because they are available for many weather stations and are normally close to the maximum value. Accordingly the PTs at 06:00 UTC were chosen to represent the minimum conditions in winter. In order to calculate the different heat load and cold stress levels the differences between the absolute levels are added to UACR and LACR. For conditions above the comfort range the increment is 6 K and for conditions below the comfort range the increment is –13 K (Table 1). By including the relative part, the thresholds listed in Table 1 are modified.

Figure 2 exemplifies the annual course of the different thresholds for 1984. In order to catch heat waves in contrast to single hot days the thresholds are compared to the two-day average of PT at 12:00 UTC (PT 2d smooth).

4 Results

In Figure 3a the mean relative mortality changes for the different heat load / cold stress categories in Baden-Wuerttemberg are shown for no time lag between thermal stress and mortality. Between heat and mortality the correlation is closest with no or only a one day time lag. There is a significant difference between the categories. The lowest mortality rates appear within the comfort range. In the categories of a slight heat load and slight cold stress, the mortality is around the expected value (0 %). Moderate cold stress is accompanied by a slight increase in mortality (2.5 %). A moderate heat load, however, seems to have greater effects on human health, and mortality increases up to 6 percent above average. The largest effect on mortality can be found during periods with a strong heat load with an increase in mortality of up to 13 % (+/–1.4 %).

An interesting feature that emerges from Figure 3a is that the impact of cold in Baden-Wuerttemberg seems less pronounced than the impact of heat. This can be put down to several factors: people living indoors are not exposed to cold, it is easier for individuals to protect themselves against the cold by putting on more clothes

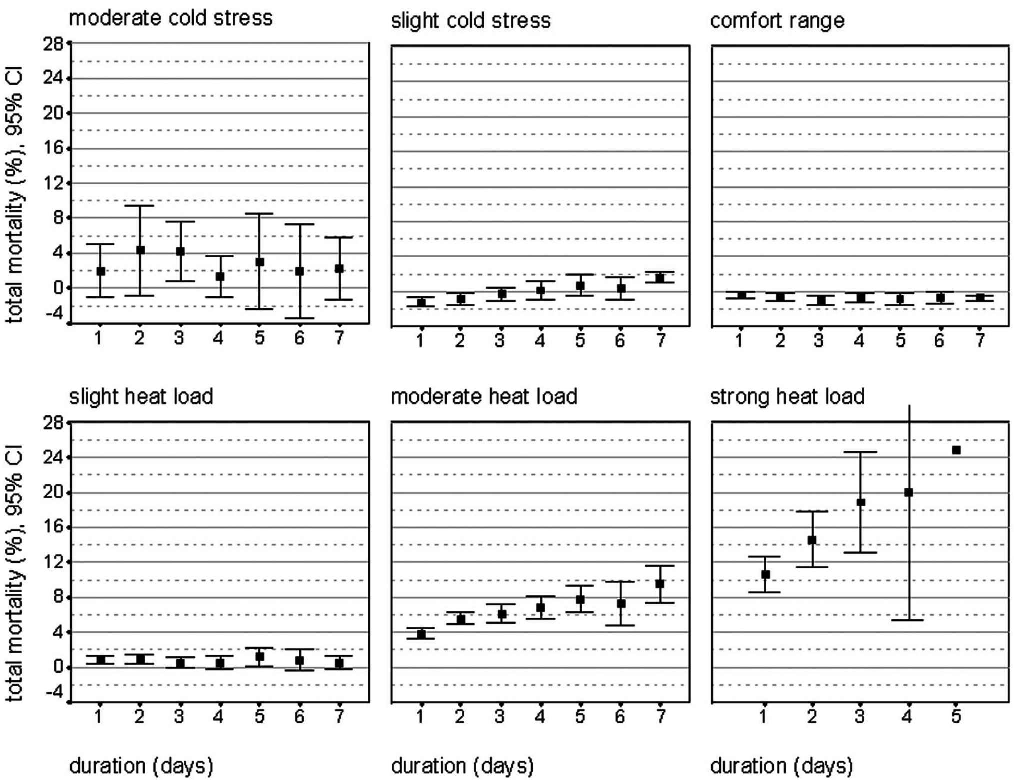

Figure 4: Effect of persistence (days in a row) within the different heat load and cold stress categories on the mean mortality increase (decrease) in percent in SW Germany from 1968–2003.

or by heating the indoor environment. In contrast to indoor heating, air conditioning is not very common in private houses in Germany. Studies like the one published by LASCHEWSKI and JENDRITZKY (2002) have shown that the time lag between cold and mortality goes up to at least one week. With respect to the optimum time lag for cold related mortality of more or less one week, the mortality increase for moderate cold stress amounts to that for a moderate heat load with no time lag (Figure 3b). Thus the effects of the same level of thermal load on mortality for heat and cold are in the same order of magnitude when the optimum time lags are applied.

Within the thermal stress categories, the mortality increase is determined by the persistence of the situation. In contrast to thermal comfort and slight heat load and cold stress conditions, where persistence seems to play a minor role, for a moderate or strong heat load or for moderate cold stress mortality increases with the number of days in a row (Figure 4). For a strong heat load the mortality doubles for a duration of 3 days or longer compared to that of only one day. The persistence contains the time information in the assumed dose response relationship (dose = intensity * time) between heat stress and its impacts on human health.

The findings considered above allow to run heat load warnings based on the different heat load categories. The heat load warning can be calculated based on the outputs of the numerical weather forecast models LM or GME. Therefore it is possible to predict the heat load warning indicator not only for single cities but also for most parts of Europe (Figure 5).

Figure 5 shows the heat load forecasts for Central Europe for the 23 July 2004. According to the above given definition that a heat warning is issued whenever the threshold for a strong heat load is reached or exceeded, warnings would have been issued for great parts of Europe between a geographical latitude of 43° and 49°. There was one region in southern France even with an extreme heat load.

In addition it is possible to identify heat episodes with significant impacts on mortality based on a condition that includes the duration on a situation. In Figure 6 heat episodes for 2003 are displayed whenever:

– the threshold for a strong heat load is reached or exceeded or

– the persistence of a moderate heat load is forecast to be at least 3 days (Figure 4).

In most of the cases when a heat episode was identified an increase in the two day moving average was registered. During the heat wave in August 2003 mortality increased up to 60 percent above the expected value.

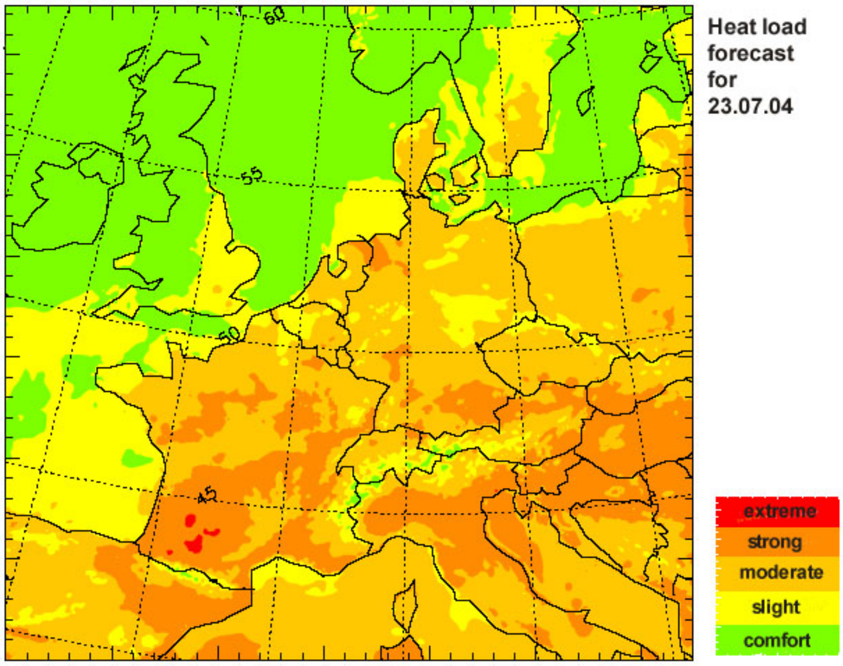

Figure 5: Heat load forecasts for 23 July 2004 for Central Europe.

5 Discussion and conclusions

This study shows a possibility of including short-term adaptation in a health-related heat load warning approach by using a conceptual model for short-term acclimatisation. Short-term adaptation is one of the reasons why thresholds, above which increases in mortality occur, vary within space and time, even if short term adaptation will not be complete at the population level. Between the minimum PT thresholds for a given heat load level and the maximum PT thresholds there is a variation of about 8 K. This is more than the variation in the thresholds upon which an increase in mortality can be found in the Czech Republic (2–3 K) (KYSELÝ and HUTH, 2004). However, it should be noticed that these refer to just air temperature and not to PT, which has a higher margin of fluctuation.

Therefore, by including short-term adaptation in the heat load warning procedure it is not necessary to define an artificial summer or warning season as practised, for example, by heat warning systems that are based on the synoptic approach. In addition, there is probably no need to calibrate the method for each city or region for which a warning is given, as it has to be done for the synoptic systems (KALKSTEIN et al., 1996). However, it should be borne in mind that the DWD heat load model does not include the level of long-term adaptation to a certain climate. Possible long-term adaptation measures include appropriate building and urban design, other behavioural factors (such as the siesta in southern Europe), etc.. In addition, heat-related mortality depends on societal factors such as the age structure and the health status of the

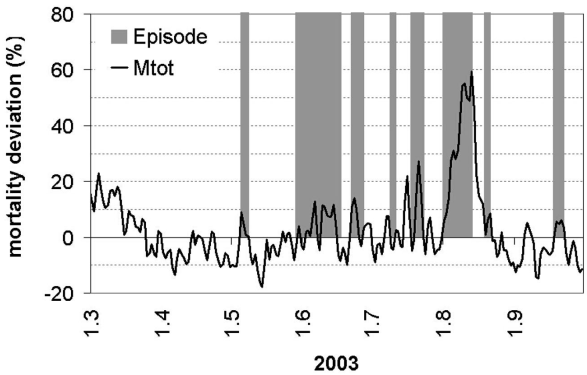

Figure 6: H: Heat episodes during summer 2003 in Baden-Wuerttemberg (grey bars) and the deviation of the mortality from the expected value (Mtot) in percent (black line).

population. If the adaptation level and societal factors are set as constant over time, differences between populations in mortality increase must be expected for the different heat load categories. These differences indicate the sensitivity of a society and provide a possibility of comparing the vulnerability of different populations.

The described procedure shows significant differences in the effect of the diverse thermal stress categories on the mortality rate. Therefore, these categories can be used as heat load indicators and as basis for a general definition of the term "heat wave". The "strong heat load" category satisfies both requirements for an extreme event. In SW Germany within the 36 years (1968–2003) only 121 days have been classified as days with a strong heat load. At the same time these days show on average an elevated mortality (13 percent more than expected), indicating the susceptibility of the society. It was shown that it is important to include a time factor in the assessment of thermal stress. Mortality increases with the persistence (days in a row) of a moderate and strong heat load because of the assumed dose response relationship. Another reason might be that with prolonged periods of heat indoor environments also become hotter and the net heat load increases. During the August 2003 heat wave 3 days in row exceeded the threshold for a strong heat load. It is unlikely that heat waves as experienced in 2003 will remain a unique feature within this century. Regional simulations predict that air temperatures will increase by several Kelvin locally in central and southern Europe in summer by the end of this century. Therefore it is necessary for European countries to prepare for a warmer climate with an increasing frequency and intensity of heat waves. This can be done by the introduction of heat health warning systems and by appropriate planning and building design (KOPPE et al., 2004b).

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