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Looking for a Universal Thermal Climate Index UTCI for Outdoor Applications

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Abstract

The International Society of Biometeorology ISB has established a commission to review recent advances in the assessment of the outdoor thermal environment, and to integrate new knowledge and concerns into a Universal Thermal Climate Index UTCI, see:

www.dwd.de/UTCI . An essential requirement for a UTCI is that the same index value must always have the same thermophysiological meaning, independent of the combination of the meteorological input values. Therefore only an index which takes into account all mechanisms of heat exchange can be universally valid and can be applied to all climates, all regions, every season, every scale, and in general, every biometeorological application. A brief presentation of the requirements for a UTCI is given, followed by an explanation of the Klima-Michel-model KMM, an operational model already meeting several UTCI requirements. Selected applications of KMM are given to refute the objection that complex models are not appropriate for daily applications.

Keywords: human biometeorology, heat budget modelling, outdoor thermal assessment, thermal indices, windchill

1 Introduction

A thermophysiological significant assessment of the atmospheric environment is one of the key issues in human biometeorology. Starting from the fact that air temperature is not the only relevant variable, in the last 150 years more than 100 simple thermal indices - most of them two-parameter indices - have been developed in order to describe the complex conditions of heat exchange between the human body and its thermal environment. Excellent reviews have been made; see e.g. Fanger (1970), Landsberg (1972), Givoni (1976), Wenzel & Piekarski (1982), and Driscoll (1992).

For cold conditions the approaches consist of combinations of temperature and wind velocity, focussing on the turbulent flux of sensible heat, with the windchill equivalent temperature as best example. Heat load conditions have been mainly described by combinations of temperature and one of the measures for humidity to express the role of latent heat flux. However, none of the formerly indices, and to some extent still popular, take into account all mechanisms of heat exchange. Consequently such simple indices are not able to meet the requirement for a thermophysiological significant assessment procedure, such that the same value of an index must always mean the same with respect to thermophysiology, independent of the combination of the meteorological input values from which the index was achieved. Therefore they are not universally valid and cannot be applied to all climates, all regions, every season, every scale, and in general, every biometeorological task.

Of course it can be assumed that the authors of former simple indices basically knew the complexity of heat exchange. However, there have been several reasons for adopting a simple approach, e.g. due to lack of knowledge (heat transfer coefficients, geometry etc.), availability of data, access to computer power, and interest in a limited issue only (e.g. windchill). Höppe (1999) shows the long and stepwise scientific development of a complete simulation of the thermal comfort conditions, plus/minus small deviations from these. Thus Fanger's (1970) work can be taken as a "quantum jump" in heat budget description.

Encouraged by the discussions and recommendations of a stimulating Internet Workshop on Windchill, hosted by Environment Canada (April 3-7, 2000), meanwhile: www.msc-smc.ec.gc.ca/education/windchill/index.cfm (see also Maarouf and Bitzos, 2000), and considering the recent successful experience with the introduction of a universal UV-index under the umbrella of WHO and WMO, the idea came up to review what has been achieved in the past 30 years in thermophysiological modeling and integrate new knowledge and concerns into a Universal Thermal Climate Index UTCI for assessments of the outdoor thermal environment. Increased international travel and easy worldwide access to information give justification for global harmonization of the development and dissemination of various weather and climatic indices. For this task the International Society of Biometeorology ISB established a commission, chaired by the first two authors with another 12 core group members from 8 countries, who have experience in the different fields of relevance, see, www.dwd.de/UTCI.

2 Basis

A Universal Thermal Climate Index should meet the following requirements,

- i) thermophysiologicaly significant in the whole range of heat exchange
- ii) valid in all climates, seasons, and scales
- iii) useful for key applications in human biometeorology (e.g. daily forecasts in the public weather service, warnings, urban bioclimatology (design and engineering of outdoor spaces), outdoor recreation and climatotherapy, bioclimate maps in all scales from micro to global, epidemiological studies, climate impact research)

The degree of sophistication of the complete procedure should focus on the aims listed in the above three conditions in order to run reliable applications. So certain standardizations - which also mean simplifications - are necessary. For example, it seems appropriate to concentrate on steady-state conditions in order to achieve representative results. Characteristics of individuals such as age, gender, specific (i.e. unusual) activities and clothing can also be neglected.

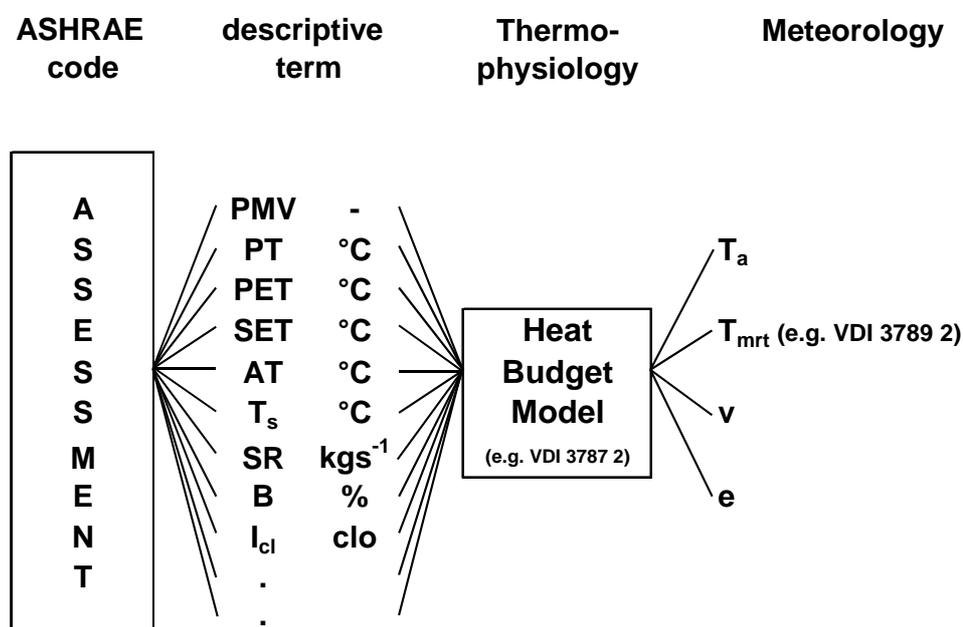


Fig. 1 Possible modular design for the assessment of the thermal environment, depicting the relevant partial components (meteorological input variables, heat-budget models and various output descriptive indices). See also VDI (1994).

The UTCI challenge can be distinguished in the following partial list of issues (Fig. 1),

1. Meteorology, where the relevant atmospheric conditions are determined,
2. Thermophysiology, the physiologically correct description of heat exchange,
3. the Communication issue, dealing with the most appropriate term to transfer the information to the various end-users,
4. the Assessment should be health-related and/or oriented on perception scales (e.g. ASHRAE 1966, 1993) which describe the human response (strain) to the total environment.

ad 1 Meteorology

The atmospheric variables determining the complex heat exchange conditions are air temperature, wind velocity, water vapour pressure, and short wave (solar) and long wave (infrared) radiation fluxes. The problem of the meteorological input data is often underestimated, particularly with respect to wind and radiation. Data availability and observational practices in various geographical regions need to be addressed in consultation with WMO standards and guidelines.

According to WMO wind should be measured at 10 m height, but we need the wind velocity at a height representative of the human being, e.g. 1-2 m. Wind speed reduction using vertical wind profiles requires surface friction and vertical temperature stratification, which are usually unknown. In addition, wind measurements are often taken on rooftops of high buildings which increase the problem of wind speed reduction. Further problems come up with the additional wind speed by the movement of the human being requiring a "relative" wind velocity, and with windward cooling (Osczevski, 2000).

Even more complex is dealing with radiant fluxes. Representative data are more often than not unavailable. They must be parameterized and then be related to the special geometry of a - normally upright standing - human being. Calculation of solar radiation even for a plain area (no limits to horizon) is quite complex. Sun elevation, turbidity, cloudiness, altitude and - for the reflected portion - albedo are input variables. Direct and diffuse fluxes must be distinguished due to the deviation of an upright standing person from a horizontal acceptor area. The infrared radiation of the ground depends on surface (not air!) temperature (rarely measured) and emissivity, that of the sky on air temperature, water vapour pressure and also

clouds (VDI, 1994). Numerical forecast models of the national weather services open the possibility for direct access to the necessary radiant fluxes. In more complex environments such as street canyons modeling of radiant fluxes becomes even more difficult (see e.g. Matzarakis et al., 2000).

Some investigators relate the radiant fluxes to the human being by a mean radiant temperature T_{mrt} , an approach described comprehensively by Fanger (1970). But other procedures are possible also, e.g. the direct consideration of the radiant fluxes within the heat budget calculations (Steadman, 1984; Blazejczyk, 1998), accounting for sub-clothing air layer ventilation effects (Pickup and de Dear, 2000). The human heat budget is very sensitive to radiation, especially when wind velocity is low. Preliminary studies show that differences in the necessary assumptions when modeling radiant fluxes usually result in larger differences in an assessment of a given climate than differences between the heat budget models in consideration.

ad 2 Thermophysiology

Since Fanger's (1970) work which is based on extensive studies in climatic chambers some progress has been made in modeling the different heat fluxes (latent, sensible and radiant), taking covered and uncovered parts of the skin into account. It is possible also to calculate the volume of blood circulating in order to maintain thermal balance including the thermoregulatory conditioned dilatation or constriction of the peripheral blood vessels (Höppe, 1984; Gagge et al., 1986). The temporal course of heat storage can be simulated in minute steps in order to consider non-stationary heat exchange conditions (Gagge et al., 1986; Höppe, 1999). Skin and core temperature, sweat rate and degree of skin wettedness can also be calculated.

Complete heat budget models, which take all mechanisms of heat exchange into account, can be considered as state-of-the-art. This is certainly true for MEMI (Höppe, 1984), and the Outdoor Apparent Temperature (Steadman, 1984, 1994), however it would not be the case for the simple Indoor AT which forms the basis of the US-Heat Index and which is often used in outdoor studies tacitly forgetting the addition "Indoor". Other good indices include the Standard Predictive Index of Human Response approach (Gagge et al., 1986) and Out_SET* (Pickup and de Dear, 2000; de Dear and Pickup, 2000) which is based on Gagge's work. Blazejczyk (1994) presented the man-environment heat exchange model MENEX, and the

extensive work by Horikoshi et al. (1995, 1997, 1998) resulted in a Thermal Environmental Index. With Gagge's et al. (1986) improvement in the description of latent heat fluxes by the introduction of PMV*, the Fanger (1970) approach can also be counted among these advanced heat budget models.

Although thermoregulation is considered as a continuum in the whole range of possible heat exchange conditions, investigators from North America (Osczevski, 2000; Bluestein and Zecher, 1999) insist on calculating a "cooling power" from a simple two-parameter model of sensible heat transfer. An issue in question is what windchill means to the public. If people want to know how chilling the weather is, a whole body heat loss model as suggested above would be the appropriate choice, but if people want to know how chilling the weather feels, an exposed skin model is more appropriate. Both authors (Osczevski & Bluestein) believe that windchill indices should be based on calculating the cooling of exposed skin. However, this concept would not fulfill the requirements listed in the beginning of section 2 above.

As already mentioned, a rough comparison of some advanced heat budget models show only slight differences in the results based on similar environmental conditions. However, a systematic sensitivity analysis in the whole range of possible combinations of the meteorological input variables must be conducted to confirm this finding.

Of great importance, of course, are the non-meteorological variables metabolic rate MET and thermal resistance of clothing. When MET is derived from tables based on given activity levels, an error in the order of $\pm 20\%$ can be assumed due to the influence of training, shoes, soil and other individual effects. This results in heat flux changes of the same order.

Comparable problems occur with clothing. The thermal resistance of a business suit, for example, is given as $1 \text{ clo} = 0,155 \text{ Km}^2/\text{W}$. However, nobody can determine the actual clo-value of clothing, especially when questions of humidity transfer are involved. All these uncertainties suggest that it may be reasonable to avoid too sophisticated formulations with minor contribution in heat budget models.

ad 3 Communication

There are some popular terms such as windchill equivalent temperature or in Germany "Schwüle" (sultriness) which are more-or-less independent from the calculation procedure.

The Internet Windchill Workshop in April 2000 showed that “equivalent temperature” is very attractive to the end users (the public, media, decision makers etc.) because they can relate to it. On the other hand, such values can also cause misunderstanding and confusion with the actual air temperature. There was an overwhelming agreement that an index in physical dimensions (e.g. Wm^{-2}) would be inappropriate and unwelcome. It seems doubtful however whether the popular scale of the UV-Index - multiplication of the UV-fluxes by a constant factor in order to get an easy-to-use scale between 0 and 10 - would be transferable to the heat exchange continuum (e.g. -10 +10). Undoubtedly, further discussions of this problem would be required involving the various stakeholders.

ad 4 Assessment

In the area of comfort or weak discomfort probably the ASHREA (1966, 1993) approaches can be adopted. For the more extreme environmental conditions health-related information from environmental and occupational medicine and from military research should determine the assessment scale. However, both communication and assessment must allow for typical differences in behavioral and physiological adaptation in the different countries and climates.

3 Example

3.1 Klima-Michel-model

In this section an example of an advanced model will be presented which meets most of the requirements listed in section 2 above, and which has been used extensively in a variety of applications, perhaps more than any other published model. The development started in the seventies as a result of the discontent with the two-parameter indices which had been in use for a long time. Because the development has taken place in a National Weather Service (human biometeorological unit of the Deutscher Wetterdienst) the aim from the very beginning was to have a tool appropriate for a wide range of routine applications, which is based on thermophysiological significant assessments of the atmospheric environment.

At the time of model development, the best documented heat budget approach was the PMV-equation of Fanger (1970). This book also gives a comprehensive description of the Tmrt approach, which is directly applicable to outdoor conditions if the radiant fluxes were available. So a radiation model was developed based on readily available meteorological data from first-order weather stations according to code FM 12 of the WMO or a numerical

weather forecast which contains cloud cover data or alternative forecasts of short-wave and long-wave radiant fluxes. So, for the complete PMV/Tmrt-model the following data from a Synop observation are required,

- air temperature (t_a) and dew point temperature (t_d) at 2 m above ground
- wind velocity (ff) (and height of anemometer above ground)
- total cloud amount (N)
- cloud amount with low-level/medium-level clouds (N_h) and cloud types of the levels low, middle and high (groups 8, FM 12).

Some standardizations were necessary, e.g. with respect to clo, Met, wind profile etc. and then the Klima-Michel-model KMM for outdoor assessments was published in German (Jendritzky et al., 1979, 1990) then in English (Jendritzky and Nübler, 1981). Michel is a typical German name, also a nickname as "German Michel". Klima-Michel is male, 35 years old, 1,75 m tall, weighing 75 kg. His work performance is 172,5 W which corresponds to a metabolic rate of 2,3 MET, and to walking with ca. 4 km/h on flat ground. Depending on outdoor conditions Klima-Michel could choose his clothing between summer (0,5 clo) and (German) winter (1,75 clo), in order to gain thermal comfort as fast as possible. Summing up it can be said that KMM resulted in the transfer of Fanger's PMV-equation to outdoor conditions mainly by solving the problems related to the complex short-wave and long-wave radiation field.

Of course the pitfalls in the PMV-equation were evident, particularly with respect to the simple approaches for skin temperature and sweat rate. However, at that time it was the most reasonable and efficient procedure available. Meanwhile KMM experienced some revisions,

- 1995, introduction of a Perceived Temperature PT instead of PMV (Fig.2). PT is the temperature of a standard environment ($t_a = t_{mrt}$, calm wind, walking speed 4 km/h, adaptation of clothing between 0,5 and 1,75 clo). The rationale for PT was a demand from media people in Germany - usually influenced by North America - to compute windchill temperatures! From a total body cooling point of view negative values of PT can be regarded - and therefore also communicated - as windchill temperatures!

- 1998, complete revision of the radiation model based on the VDI-guideline 3789, 2.
- 2000, introduction of Gagge`s et al. (1986) PMV* approach to better meet heat change in warm/humid conditions which yields to PT.

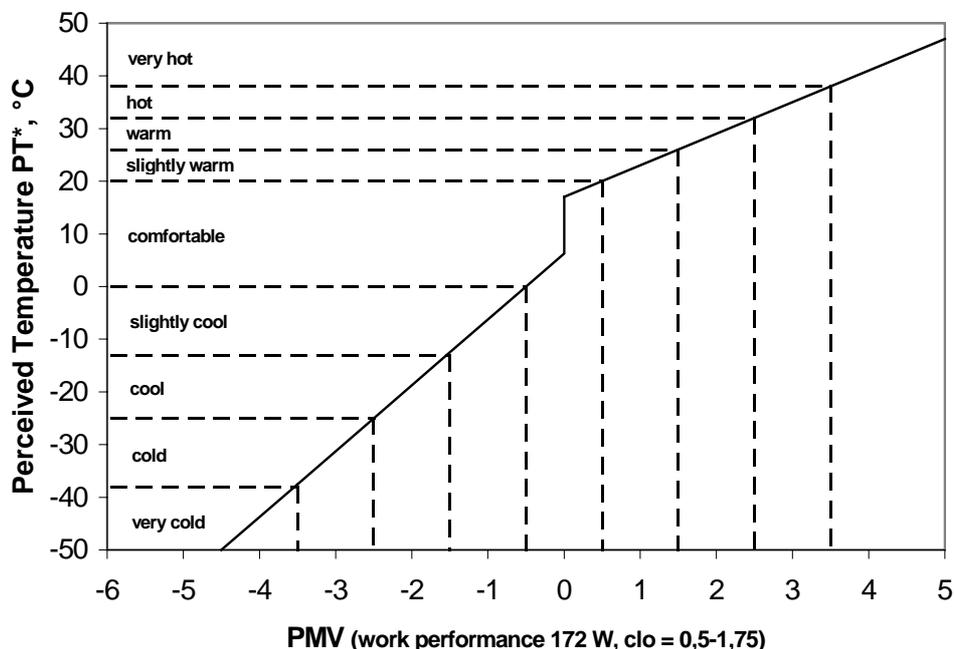


Fig. 2 Relationship between Perceived Temperature PT and Predicted Mean Vote PMV.

One advantage of KMM is the modular construction of a) the radiation model (with an extra version for urban canopy conditions), b) the Tmrt approach completely following Fanger (1970), c) the heat budget model, and d) the PT calculation. All modules can easily be exchanged to other approaches if necessary, and can also be adapted to future developments, particularly with respect to the expected recommendations emerging from the UTCI discussion by the ISB commission.

3.2 Selected Assessments with the Help of the Klima-Michel-Model

3.2.1 Bioclimate Maps

In the field of tourism, outdoor recreation, climatotherapy, leisure time and sports information on heat load in summer and cold stress in winter is necessary for people to compare climates in space and time in order to choose the climate of preference (Jendritzky, 1991). The attempt to develop mesoscale bioclimate maps has succeeded, first by analyzing 30 years of meteorological data from Germany with the help of the Klima-Michel-model (Jendritzky et al. 1990). Second, by using GIS-techniques spatial interpolation of the information of single

weather stations was done on 1-km up to 100-m grids, depending on the desired scale. Unfortunately none of the results can be presented here because all maps were originally printed in color, but the cover of Kalkstein et al. (1996) gives an impression. In the case of maps with higher resolution additional land-use data (e.g. open land, forest, settlements, water bodies and eventually infrared information by satellite) are necessary (Jendritzky and Menz, 1987). Such maps contain valuable information for regional planning purposes.

Meanwhile the monthly and seasonal distributions of Perceived Temperature PT have been computed for Europe based on the analysis of 30 years of 3-hourly data of more than 900 first-order weather stations. These distributions have a resolution of 5'. In addition to the climate factors altitude, longitude, latitude and orography, as used in the German approaches discussed above, the distance to the ocean has also been taken into account.

3.2.2 Urban Bioclimatology

Urban climate represents an impressive example of a man-made climate change that is susceptible to significant variations, and therefore has to be considered early on in urban planning. From a thermal assessment point of view the urban-rural temperature differences, usually described in terms of an urban heat island, are of interest. After comprehensive simulations using the 2-dimensional microscale urban climate model MUKLIMO_2 to study the meteorological fields (including the relatively complex problem of Tmrt calculation) which are required to determine the heat exchange conditions of a human being within the urban canopy layer (Jendritzky and Sievers, 1987, 1989), the urban bioclimate model UBIKLIM has been developed (Jendritzky and Graetz, 1994; Jendritzky, 1995). UBIKLIM computes the thermophysiological significant meteorological fields required to generate PT* in an urban area based on urban planning variables and topography in a typically 10 m resolution. The most recent version of UBIKLIM (Jendritzky et al., 2000) applies the 1-dimensional MUKLIMO_1 at each grid point, then computes the results at any location (interpolation between neighbouring grids) using a set of reasonable assumptions based on expert knowledge. So UBIKLIM does not really represent a completely objective urban boundary layer model but can be considered an expert system to answer practical questions of urban planners, decision makers and other stakeholders. For advising these groups UBIKLIM serves as the standard tool of the Deutscher Wetterdienst. The best example is the urban bioclimate assessment of the German capital Berlin (a map with several millions of pixels).

3.2.3 Epidemiology

Most of the past epidemiological studies of the effects of the thermal environment on mortality used air temperature only, or at best simple two-parameter indices. An extensive study of 30 years of daily mortality data (total, CVD and RD; ca. 2.8 million cases) from Baden-Württemberg (Southwest Germany) shows firstly that the application of a complete heat budget model based on easily available meteorological data is quite feasible (Jendritzky et al., 1998, 2000). Secondly, the results are surprisingly good. While the findings of other

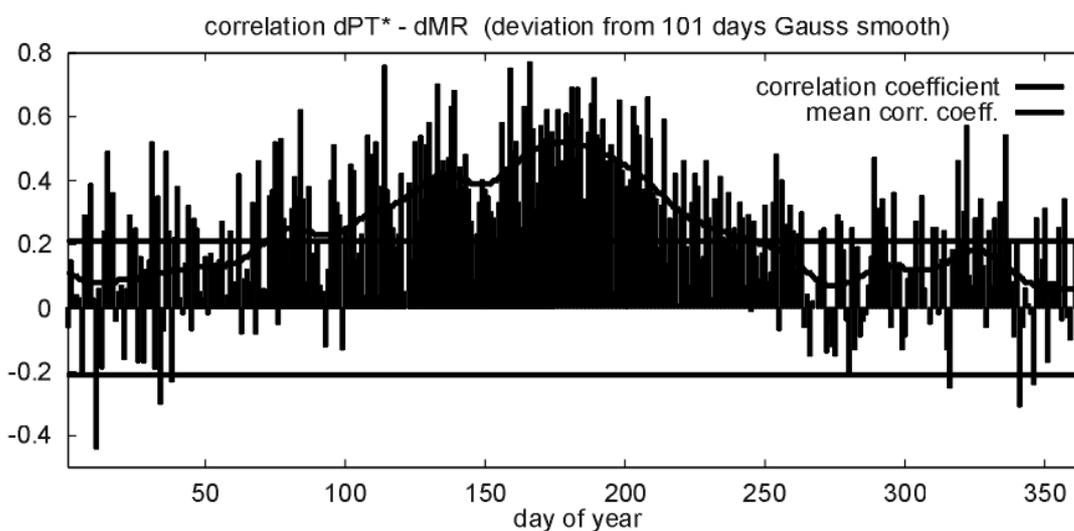


Fig. 3 Seasonal variation of the correlation coefficient (r) between daily total mortality and the thermal load expressed in terms of Perceived Temperature PT in SW-Germany, based on 30 years of data. Solid curve represents smoothed correlation coefficient.

investigators in extreme climates could easily be confirmed, the close relationship particularly in summer (more than 20% of the variance explained) in this moderate climate was not expected (Fig. 3). Encouraged by these outcomes it is planned to establish a Heat Health Watch/Warning System as an example of the WMO/WHO/UNEP showcase projects (Kalkstein 2001), however, the German system will be based on Perceived Temperature PT forecasts.

3.2.4 Health Resort Climatology

In Germany all health resorts and spas are evaluated by government. One criterion of the official assessment procedure is mean frequency of heat load (i.e. in excess of a given threshold). This is derived from the computational procedure of the bioclimate map

mentioned in 3.2.1 based on Klima-Michel-model. Considering the concept of treatment or cure by actual weather and climate (cure "by" instead of "in" climate) a number of specific procedures have either been developed or still under development within a model KURKLIM (KURort-KLima-Modell, health resort-climate model), based fundamentally on the Klima-Michel-approach. The complete system would compute a micro-scale thermal assessment of the municipality (10 m grids) as well as an assessment of the terrain of the hiking trails. Through a computer-based service actual data of an automatic climate station can be utilized to provide individual advice via a user-friendly menu on a PC. In order to better assess the constantly changing heat exchange conditions when walking in various environments the usual Klima-Michel-approach has been replaced by the non-stationary heat budget model IMEM of Höppe (1993,1999).

3.2.5 Climate Impact Research

When dealing with climate change related health risks climate impact researchers apply scenario-based risk assessment methods. Assuming that in a warmer world the most pronounced direct climate impact is caused by altered intensity and/or frequency of heat waves, the results of numerical climate change simulations must be assessed in thermophysiological terms. In addition, scenarios produced on this basis must have an appropriate spatial resolution and must also take non-climatological effects into account. On a global scale the necessary meteorological input variables for the Klima-Michel-model are not available with sufficient reliability, even for the analysis of the current climate. So data have to be used from climate simulations with atmosphere/ocean coupled general circulation models AOGCMs, such as the time-slice experiment with ECHAM4/T106 (Jendritzky and Tinz, 2000). Although it is still unsatisfactory in resolution, additional statistical downscaling, e.g. as in the European map described in 3.2.1, will allow a certain improvement in future.

The global bioclimate maps show marked spatial differences in the increase in warming (in terms of Perceived Temperature PT) in the period 2041-50 compared to the control run 1971-80. If the predictions were correct, densely populated areas in the Mediterranean, in parts of the USA, the Amazon basin, and in south-east Asia, would be particularly affected. Based on a rough estimation derived from the study in 3.2.3 this would result in an increase in heat load related mortality of up to 5% if no adaptation to the altered atmospheric environmental

conditions would occur. But due to several uncertainties these results should only be used to elucidate the problem and not be taken as a definite outcome.

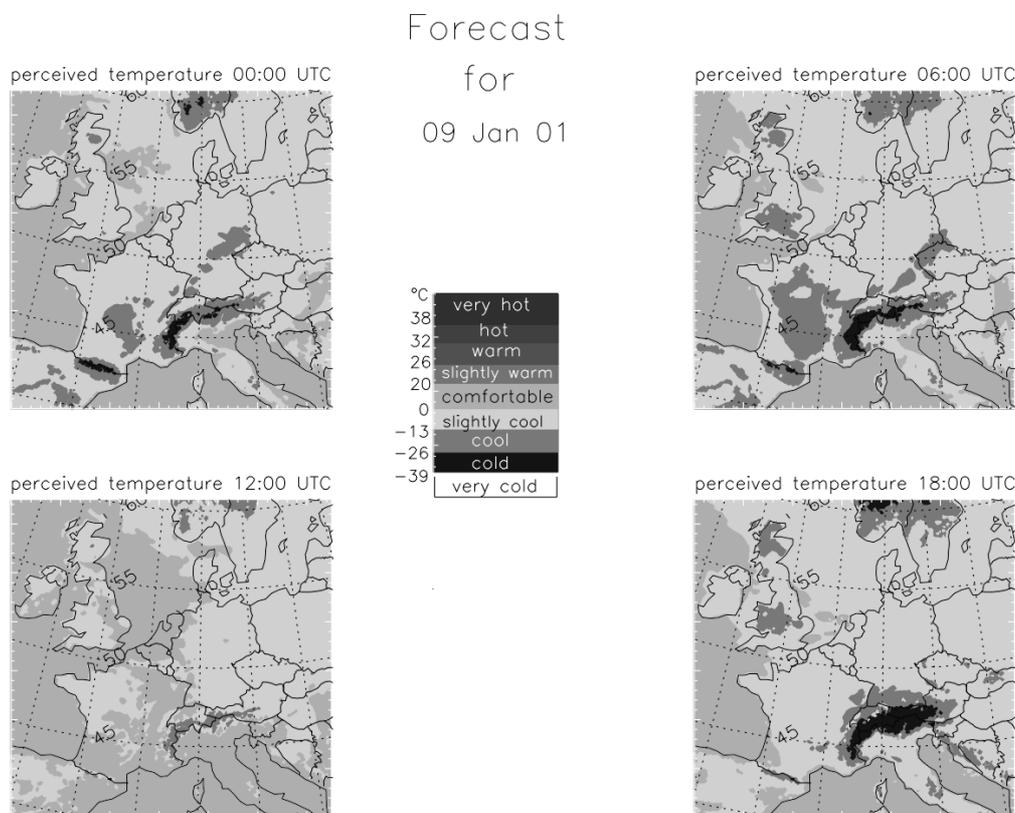


Fig. 4 Example of forecast Perceived Temperature PT for central and western Europe based on the numerical weather forecast model LM of the Deutscher Wetterdienst.

3.2.6 PT Forecasts

Perceived Temperature PT* forecasts are also used to advise weather-sensitive persons whose reaction thresholds against external stimuli are extremely attenuated. Particularly patients with cardiovascular and/or respiratory problems and elderly people can take such information into account when planning their day, e.g. by avoiding unfavourable outdoor conditions or by reducing unusual thermal strains. The system for Meteorological Applications (MAP), serving branch offices of the Deutscher Wetterdienst to provide meteorologists in charge with basic information, also offers PT by a mouse click. The computation is made both on the systems themselves based on actual synoptic observations as well as in routine numerical forecasts by the non-hydrostatic „Lokal Modell“ of the Deutscher Wetterdienst for central and western Europe on 7-km grids (Fig. 4). This PT calculation uses short-wave and long-wave radiation forecasts resulting from the numerical model. Tmrt can also be determined directly.

Considering the present climatic regime in Germany there are no official threshold values set for issuing warnings of dangers due to extreme cold stress caused by very low temperatures and high wind velocities. In the south-west of Germany, however, there is a heat load warning service for rehabilitation purposes and spas. Its aim is to control the physical stress of cardiovascular patients and to recommend for them a suitable behaviour in their leisure time.

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