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Modelling radiation fluxes in simple and complex environments—application of the RayMan model

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Abstract The most important meteorological parameter affecting the human energy balance during sunny weather conditions is the mean radiant temperature T_{mrt}. It considers the uniform temperature of a surrounding surface giving off blackbody radiation, which results in the same energy gain of a human body given the prevailing radiation fluxes. This energy gain usually varies considerably in open space conditions. In this paper, the model 'RayMan', used for the calculation of short- and long-wave radiation fluxes on the human body, is presented. The model, which takes complex urban structures into account, is suitable for several applications in urban areas such as urban planning and street design. The final output of the model is, however, the calculated T_{mrt}, which is required in the human energy balance model, and thus also for the assessment of the urban bioclimate, with the use of thermal indices such as predicted mean vote (PMV), physiologically equivalent temperature (PET) and standard effective temperature (SET*). The model has been developed based on the German VDI-Guidelines 3789, Part II (environmental meteorology, interactions between atmosphere and surfaces; calculation of short- and long-wave radiation) and VDI-3787 (environmental meteorology, methods for the human-biometeorological evaluation of climate and air quality for urban and regional planning. Part I: climate). The validation of the results of the RayMan model agrees with similar results obtained from experimental studies.

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Introduction

Climate and air quality must be considered in urban and regional planning at regional level, as it is relevant to human health and well-being. This task falls within the field of human-biometeorology, which deals with the effects of weather conditions, climate and air quality on humans (Mayer 1993, VDI 1998). Examples of inclusion of human-biometeorological results in urban planning processes are not rare any more; see for example; the Urban Climate Analysis of Freiburg (Röckle et al. 2003).

Linking human-biometeorology and town planning requires determining the human-biometeorological factors that are significant for the planning process. The human-biometeorological evaluation of the atmospheric environment can be used, for example, to clarify whether or not planning instruments are available for maintaining and improving the human-biometeorological situation in the planning and, if they are, which are the appropriate ones to use (VDI 1998; Matzarakis 2001).

For the evaluation of the thermal component of urban climate and applied climatology, the methods have been applied and tested in many studies (e. g. Jendritzky et al. 1990; Matzarakis 2001; VDI 1998). The presented analysis can be undertaken in different time and space scales. In addition to the mobility of humans in urban areas, a diversity of microclimates in urban areas also exists. Short-wave radiation fluxes have the greatest variation of meteorological parameters in urban areas (Matzarakis 2001). The biometeorological influences of short- and long-wave radiation fluxes can be transformed into a synthetic parameter, the mean radiant temperature (Wachter 1950; Bradkte 1951). T_{mrt} is defined as the uniform temperature of a hypothetical spherical surface surrounding the subject (emissivity $\varepsilon=1$) that would result in the same net radiation energy exchange

with the subject as the actual, complex radiative environment. The latter usually varies considerably under open space conditions.

On the one hand, existing measurements and methods for the calculation of short- and long-wave radiation fluxes are always applied for horizontal surfaces, and on the other hand radiation fluxes are very complex to measure in urban areas. For human-biometeorological studies, the radiation environment of the human body has to be established as three-dimensional.

The main purpose of this paper is to present a method for the calculation of T_{mrt} for thermal human-bioclimate studies in different time and space scales through the use of the RayMan model. The model is compatible with Microsoft Windows, and can analyse complex urban structures and other environments. The model requires only basic meteorological data (air temperature, air humidity and wind speed) for the calculation of radiation fluxes and common thermal indices for the thermal human-bioclimate. Applications and examples of T_{mrt} and thermal human-bioclimates for different structures and uses are demonstrated. Also shown in the present paper are validations of RayMan simulations with field measurements in the city of Freiburg, southwest Germany, in the summer of 2001.

Scientific background and methods

Atmospheric environment

Cause and effect relations between the atmospheric environment and human health or human comfort can be analyzed by a human-biometeorological classification (McKerslake 1972; ISO 1983; Jendritzky et al. 1990; Matzarakis and Mayer 1996; VDI 1998). The thermal component is an important factor and can be described and quantified by thermal indices. The thermal component comprises the meteorological parameters of air temperature, air humidity, wind velocity, and also short- and long-wave radiation, which thermo-physiologically affects human beings indoors and outdoors. This component is relevant to human health because of the close relationship between the thermoregulatory mechanism and the circulatory system.

Human-biometeorological studies have been carried out for some time. In the past, thermal indices were frequently used to estimate the thermal environment. These indices, however, were based on single or composite meteorological parameters, such as wet-bulb or equivalent temperature (Thom 1959; Steadman 1971; ISO 1982).

In the 1970s, several scientists began to use physiologically relevant indices that were derived from the human energy balance for the assessment of the thermal component (Höppe 1984, 1993). A common model for the human energy balance is MEMI (Munich energy balance for individuals), and the derived thermal assessment index PET (physiologically equivalent temperature). Other models are the predicted mean vote (PMV) (Fanger 1972) and standard effective temperature (Gagge et al. 1986). The three thermal indices PET, SET* and PMV are part of the RayMan model, as are energy fluxes and body parameters by MEMI. They all require mean radiant temperature T_{mrt} as input.

The following meteorological parameters were taken into account in the thermal indices:

- air temperature
- vapour pressure
- wind velocity
- mean radiant temperature

Body parameters used in MEMI are:

- human activity and body heat production
- heat transfer resistance of clothing.

The PMV, PET and SET* indices facilitate the thermophysiological acquisition of thermal conditions of indoor and surrounding outdoor air as point layers (VDI 1998).

Importance of radiation fluxes in human-biometeorological studies

For the estimation of thermal indices, common meteorological data like air temperature, air humidity and wind speed are required. The mean radiant temperature T_{mrt} is the most important meteorological input parameter for obtaining the human energy balance during summer conditions (Winslow et al. 1936; Clark and Edholm 1985). Therefore, T_{mrt} has the strongest influence on thermo-physiological significant indices like PET or PMV. T_{mrt} can be obtained through different measurement procedures and models. The procedure for determining T_{mrt} experimentally is very complex, time-intensive and expensive. This is due to the combination of pyranometer and pyrgeometer, which have to be oriented in six directions (4 cardinal directions, upwards, downwards) to measure the complete short- and long-wave radiation fluxes which are significant for a person in the 3D environment (Fanger 1972; Höppe 1992). Mean radiation flux densities of the human body can be calculated from the measured short- and long-wave radiation fluxes (Höppe 1992):

$$S_{str} = a_k \sum_{i=1}^{6} K_i F_i + a_1 \sum_{i=1}^{6} L_i F_i \qquad (1)$$

where K_i is the short-wave (solar) and L_i the long-wave (terrestrial) radiation fluxes, and a_k and a_l are the absorption coefficients for short-wave and long-wave radiation. F_i is the angle factors of the solid surfaces. Following the

calculation of T_{mrt}, it can be calculated through the use of the Stefan–Boltzmann radiation law (in °C), σ is the Stefan–Boltzmann constant (5.67*10^{-8} W/m^{-2}K^{-1}):

$$T_{mrt} = \sqrt[4]{S_{str}/(a_l\sigma)} - 273.2 \qquad (2)$$

The measured radiation fluxes have to be multiplied with weighting factors for the human body. For a standing man, the incoming radiation fluxes have to be known in the four horizons (vertical position of the instruments) which are more important than the radiation fluxes in the vertical direction. The advantage of this method is that it is integral for measuring the short- and long-wave radiation fluxes. The disadvantage of this method is that it cannot be applied for long-term experimental investigations and studies.

As a typical example, Fig. 1 shows the relationship between the measured T_{mrt} and the human biometeorological thermal index PET. The latter refers to measurements on both sides of a street and under a tree, which have been marked as the measurement sites for the human-biometeorological evaluations of urban structures. The measurements were carried out during summer weather on 17, 18, 19 and 25 July and 2 August 2001 in Freiburg, southwest Germany, within a radius of 100 m. The measurements were carried out daily from 5:00 CET to 22:00 CET.

For the estimation of long-term studies without directly measured radiation fluxes, T_{mrt} can be calculated through models like RayMan. In the literature, recommended methods for estimating radiation fluxes are based on parameters including air temperature, air humidity, degree of cloud cover, atmospheric turbidity, and time of the day and the year. The albedo of the surrounding surfaces and their solid angle proportions, however, must be specified. Additionally, other factors like the geometrical properties of buildings, vegetation etc. have to be taken into consideration.

For such models to be applied in simple situations, the following atmospheric parameters are required:

- direct solar radiation
- diffuse solar radiation
- reflected short-wave radiation
- atmospheric radiation (long-wave)
- long-wave radiation from the solid surfaces

The following parameters describing the surroundings of the human body also have to be known:

- sky view factor
- view factor of the different solid surfaces
- albedo of the different solid surfaces
- emissivity of the different solid surfaces

All the above parameters have to be known in order to calculate mean radiant temperature. Many methods already exist for the calculation of short-wave radiation fluxes that apply simple and complex models with different time resolutions on the basis of different methods, and these are well-tested (e.g. Valko 1966; Brühl and Zdunkowski 1983; Jessel 1983; Olseth and Skartveit 1993; VDI 1994; Badescu 1997, Ceballos and De Moura 1997; Meek 1997; Gul et al. 1998, Mora-Lopez and Sidrach-de-Cardona 1998; Kemmoku et al. 1999; Marki and Antonić 1999; Roderick 1999; Santamouris et al. 1999; Craggs et al. 2000; Gueymard 2000). Models using sunshine duration for the calculation of short-wave radiation fluxes are used (Valko 1966; Gopinathan 1992; Revfeim 1997; Sen 1998), as well as simple parameterizations for turbidity (Kasten 1980; Power 2001). Methods for the calculation of long-wave radiation fluxes also exist (Czeplak and Kasten 1987; Salsibury and D'Aria 1992; Diag et al. 2000; Nunez et al. 2000).

For complex situations in urban settings, several models and analytic methods are documented in the literature

Fig. 1 Relationship between T_{mrt} and PET for 17, 18, 19 and 25 July and 2 August 2001 in Freiburg

$$y = 0.5191x + 6.7986$$
$$R^2 = 0.7569$$
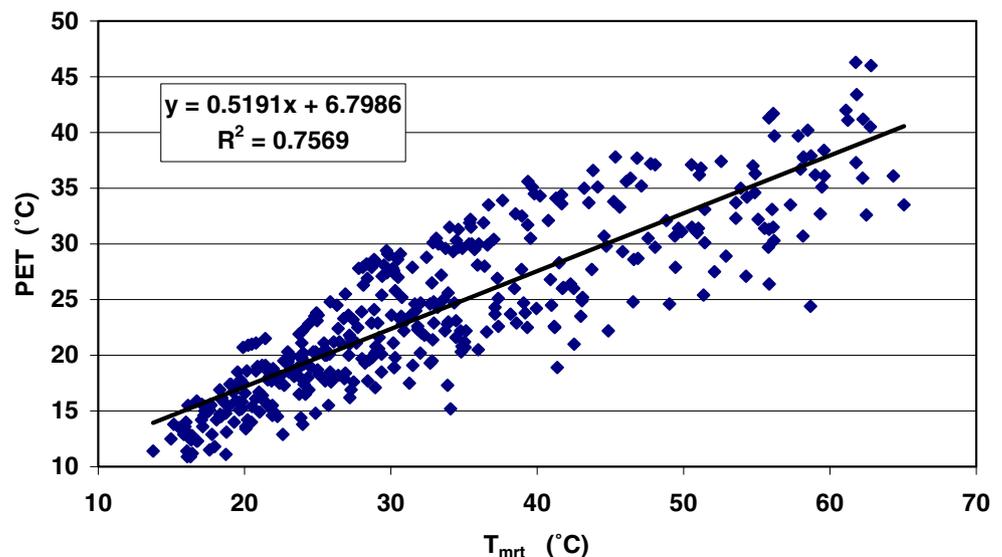
(Kaempfert 1949, 1951; Terjung and Louie 1974; Mohsen 1979; Frank et al. 1981; Zdunkowski and Brühl 1983; Littlefair 2001; Kanda et al. 2004).

The way in which radiation fluxes are modified in and around urban structures can be described by the sky view factor, which is also an important parameter for urban climate studies. There are many existing methods for its calculation (Johnson and Watson 1984; Watson and Johnson 1987, 1988; Becker et al. 1989; Chen and Black 1991; Holmer 1992; Rich et al. 1993; Chapman et al. 2001; Frazer et al. 2001; Pereira et al. 2001; Holmer et al. 2001). Also important on the local scale is the knowledge of shadowing (Niewienda and Heidt 1996; Matzarakis et al. 2000; Matzarakis 2001). Finally, radiative properties such as emissivity and albedo for the human body also have to be known (Underwood and Ward 1966).

To calculate the mean radiant temperature T_{mrt}, the relevant properties and dimensions of the radiating surfaces and of the visible section of the sky must be known. The posture of the human body (e.g. seated or standing) is also required. To calculate T_{mrt}, the entire surroundings of the human body are divided into n isothermal surfaces with the temperatures T_i ($i=1$ to n) and emissivities ε_i, to which the solid angle portions ("angle factors") F_i are to be allocated as weighting factors. Long-wave radiation ($E_i = \varepsilon_i * \sigma * T_i^4$) and diffuse short-wave radiation D_i are emitted from each of the n surfaces of the surroundings. This results in a value for T_{mrt} as (Fanger 1972, Jendritzky and Nübler 1981)

$$T_{mrt} = \left[\frac{1}{\sigma} \sum_{i=1}^{n} \left(E_i + a_k \frac{D_i}{\varepsilon_p} \right) F_i \right]^{0.25} \quad (3)$$

σ is the Stefan–Boltzmann constant ($5.67*10^{-8}$ W/(m^{2}K^4)), and ε_p is the emission coefficient of the human body (standard value 0.97). D_i comprises the diffuse solar radiation and the diffusely reflected global radiation. a_k is the absorption coefficient of the irradiated body surface area of short-wave radiation (standard value 0.7).

T_{mrt} is incremented to T^*_{mrt}, if there is also direct solar radiation:

$$T^*_{mrt} = \left[T_{mrt}^4 + \frac{f_p a_k I^*}{(\varepsilon_p \sigma)} \right]^{0.25} \quad (4)$$

In this case, I^* is the radiation intensity of the sun on a surface perpendicular to the incident radiation direction, and the surface projection factor f_p is a function of the incident radiation direction and the body posture (VDI 1998 and 2001). For applications in human-biometeorology, it is generally sufficient to determine f_p for a rotationally symmetrical person standing up or walking (Jendritzky et al. 1990).

On the basis of the literature (e. g. VDI 1998) and the information aforementioned, a model has been developed which is suitable for this application. The model takes all simple and complex environments with their radiation properties (albedo and emissivity) into account. The model RayMan (Fig. 2) is well-suited for the calculation of the radiation fluxes, since it considers various possibilities of input of complex horizons and related parameters:

- Topography input. Here, topographical data can be edited or created in order to limit the horizon by topographical effects and the modification of the radiation field and fluxes.
- Environmental morphology input (buildings, deciduous and coniferous trees)(Fig. 3). This window is designed for the graphical and numerical editing of concrete 3D-obstacles. A map of the local environment, which shall be computed with RayMan, is shown in the grid. It can be zoomed it in and out. The obstacles are drawn in different colours, so buildings (grey), deciduous trees (green) and conifers (teal) can be easily identified. Each obstacle has got "editable" points—the corners of buildings and the centres (trunk) of trees—which are indicated by a small circle around them if the mouse cursor is near or exactly on them. The z-coordinate of all obstacle points (corners etc.) represents their altitude above this surface level. RayMan makes its calculations on the place marked as 'Location', the red point on the map. 'Altitude' is the relative vertical distance between the 'Location' and the surface level. Each kind of obstacle can be switched on and off with regard to the RayMan calculations. Finally, the sample of obstacles can be saved in files and re-opened later for further editing and calculations.
- Free-hand drawing and fish-eye photographic input (Fig. 4). In this window you can edit the horizon limitation in a grid map in fisheye view and import fisheye photos as well. The horizon limitation is drawn freely by clicking on the map, which indicates corners of a grey "limitation polygon". Imported fisheye photos can be edited with useful functions.

The advantage of the model is that it does not only calculate the mean radiant temperature, but also:

- Sun paths (Fig. 5) for each day of the year can be calculated and graphically shown.
- Shadowing by urban and natural obstacles (Fig. 6) for each day of the year and for each specific period of the day, in order to quantify the areas where shadows occur and influence the radiation fluxes.
- Calculation of sunshine duration (with and without horizon limitations) in a daily resolution. It can be calculated for every simple and complex environment

Fig. 2 Input window of RayMan and the relevant values for the calculation of mean radiant temperature and thermal indices
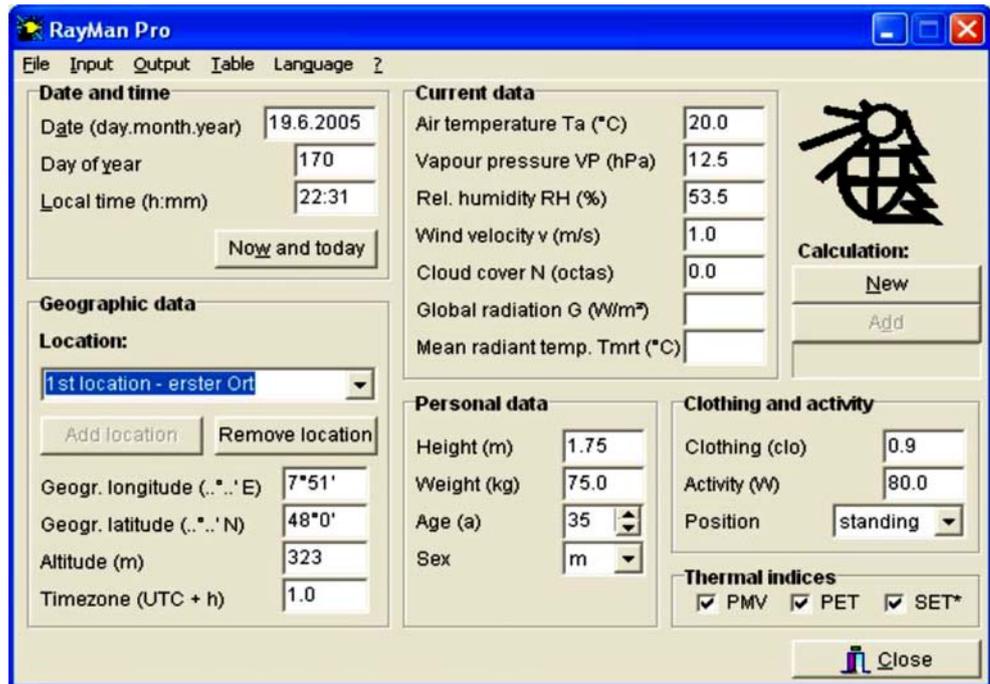
in order to have daily averages. The calculation of hourly, daily and monthly averages of short-wave and long-wave radiation fluxes is also possible.

– Calculation of thermal indices like PMV, PET and SET*.
– A full assessment of the thermal bioclimate for every type of landscape or urban structure is possible based on the output of the RayMan model.

Applications and validations

RayMan has been tested for different purposes. In the following, some typical examples of applications are given. An aim of the developers is to check the results produced by RayMan against measurements in different environments.

Fig. 3 Input window of urban structures (example: investigation area for Fig. 5 and 6)
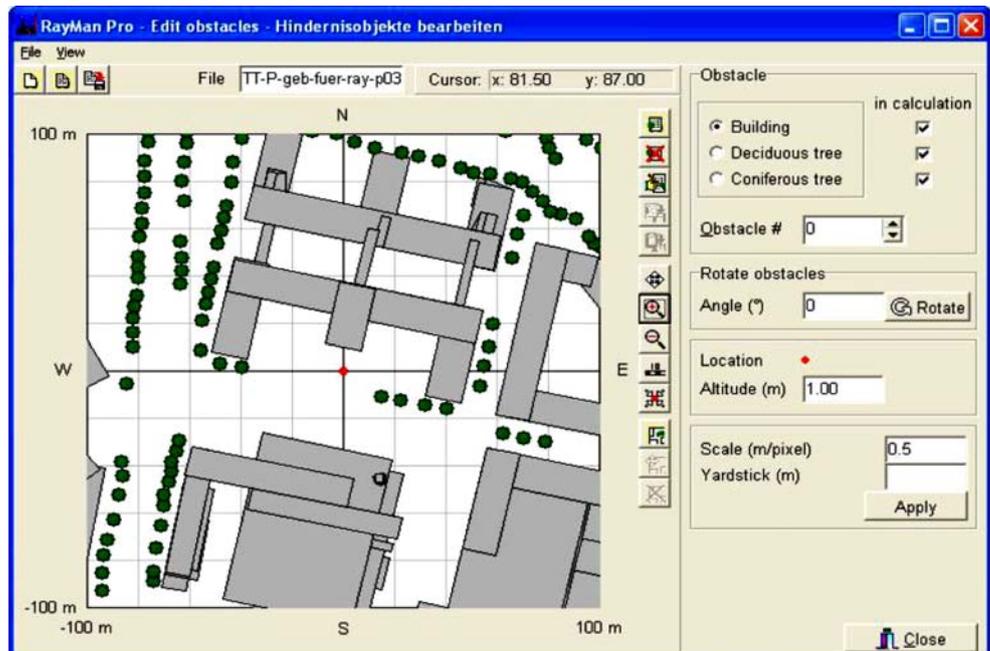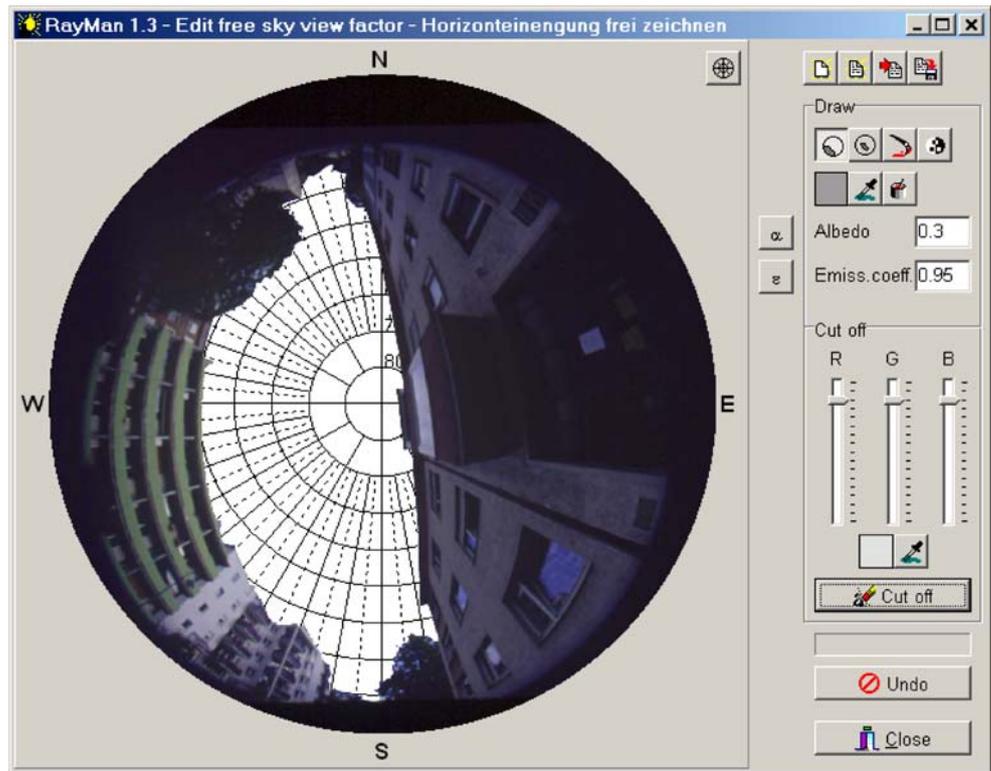
Fig. 4 Input window of free
drawing and fish eye photo-
graphs (example: investigation
area for Fig. 5 and 6)

General example of a yearly variation of PET for tourism
purposes

The thermal index PET, which can be calculated by
RayMan, is suitable for the evaluation of the thermal
environment not only in summer, but also throughout the

year. As an example of such an application in a Mediterra-
nean climate, Fig. 7 shows mean, highest and lowest PET
values at 12:00 UTC each day at Heraklion (on the island
of Crete) in Greece for the period 1980–1989. This kind of
illustration provides good information on the variability of
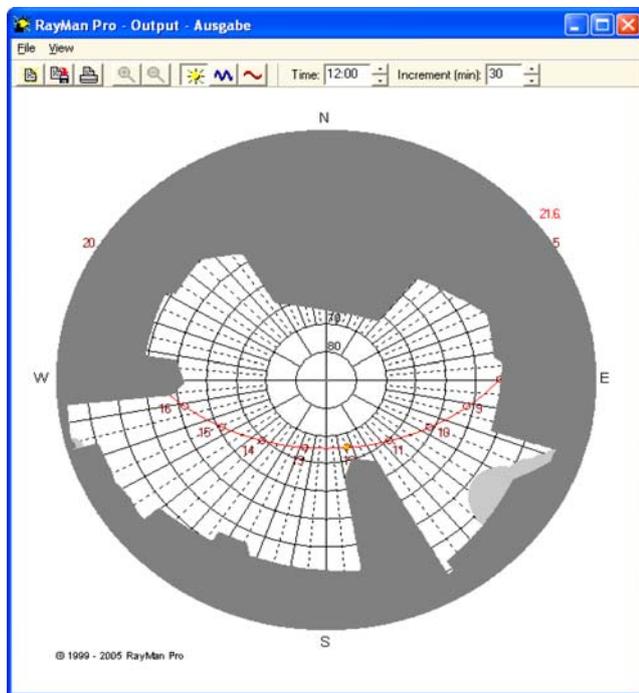PET on each individual day of the year within the study
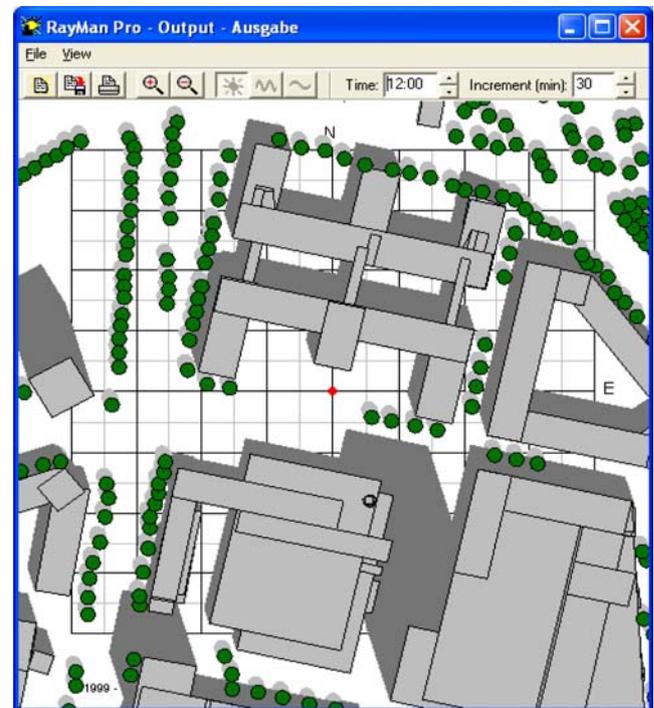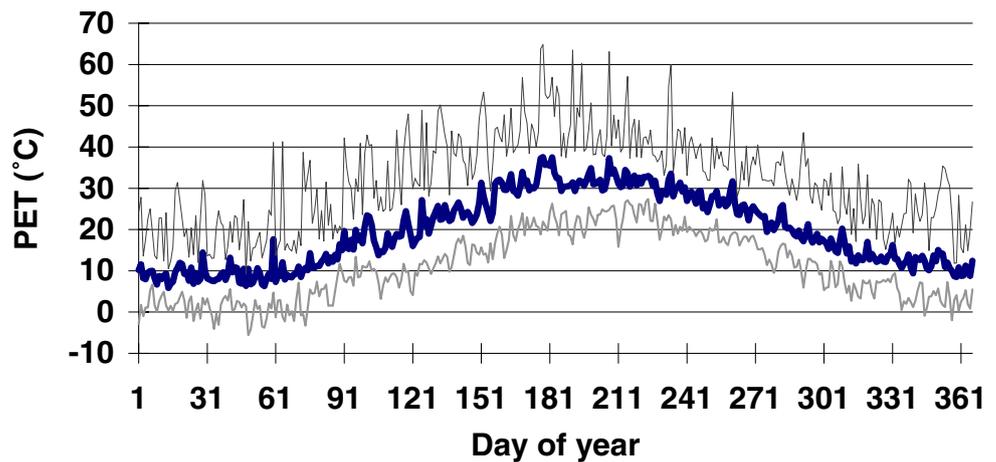

Fig. 5 Output of sun paths

Fig. 6 Output of shaded areas

Fig. 7 Mean, highest and lowest values per day of the physiologically equivalent temperature (PET) at 12:00 UTC at Heraklion/Greece, for the years 1980 to 1989

period. The results of Fig. 7 show that different grades of cold stress (PET<18°C) occur mostly from October to April. Mean PET values over 30°C, indicating at least moderate heat stress, occur from June to September. On some hot summer days from May to September, PET at 12:00 UTC exceeded 40°C. This represents a pronounced thermal stress level in Heraklion, which is the capital of the island of Crete and has an intensive tourism industry throughout the year. Due to the existence of the etesian winds, the PET conditions in Heraklion are lower during summer than on the mainland of Greece.

Conditions in urban areas

The thermal conditions in urban structures vary considerably, and the most influential thermal factor for human beings during summer results from the short- and long-wave radiation fluxes. For the quantification of the influence of urban canyons on the radiation field of human beings, measurements have been carried out at several locations in differently oriented streets, and with a nearby reference measurement site in a green area under a tree. The measurements were carried out on August 2nd 2001 in Freiburg, southwest Germany. The structures represent a typical street and a small green area in Freiburg (Fig. 8). The measurements have been carried out between 5:00 CET and 22:00 CET. In Fig. 8, fish-eye photographs of the five measurement sites are shown. During the period of measurements, the wind speed was lower than 3 m/s, and significant differences in the air temperature and air humidity between the different measurement sites were not expected. High variability was observed in the short- and long-wave radiation fluxes and the resulting human-biometeorological parameter, mean radiant temperature. In Fig. 9, the diurnal courses of T_{mrt} at the five different measurement sites are presented. Additionally, values for T_{mrt} calculated from measured data from the urban climate station on the roof of a 50 m high building are displayed in

Fig. 9. From Fig. 9 we obtain the indication that there are differences between roof and ground level in the morning and evening. These differences in T_{mrt} occur because of the higher long-wave emission of the solid surfaces near the ground (see fish-eye photograph). During that time, the
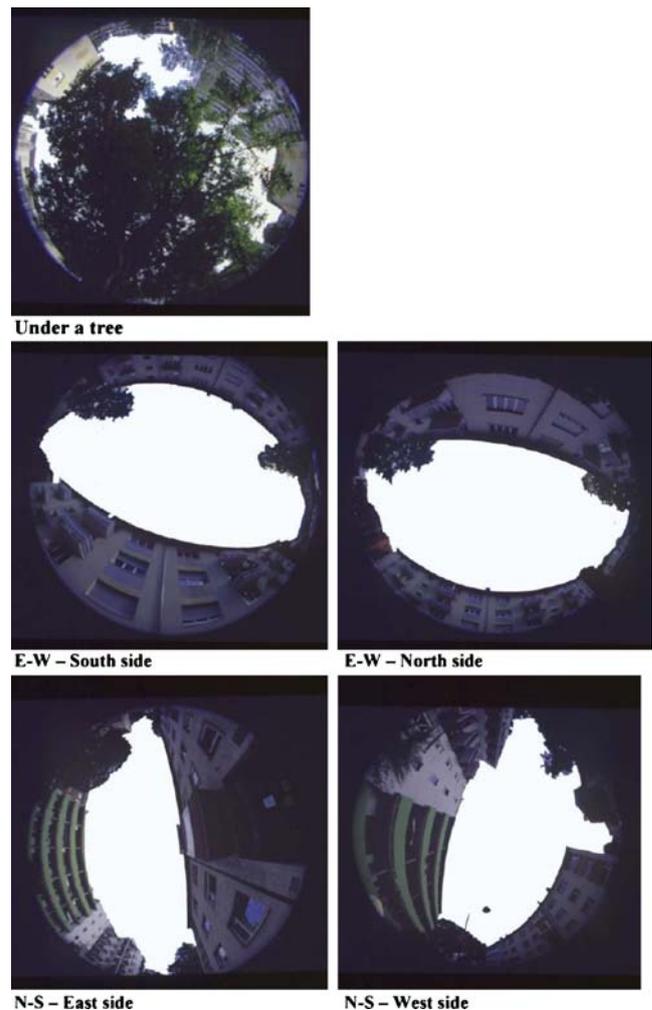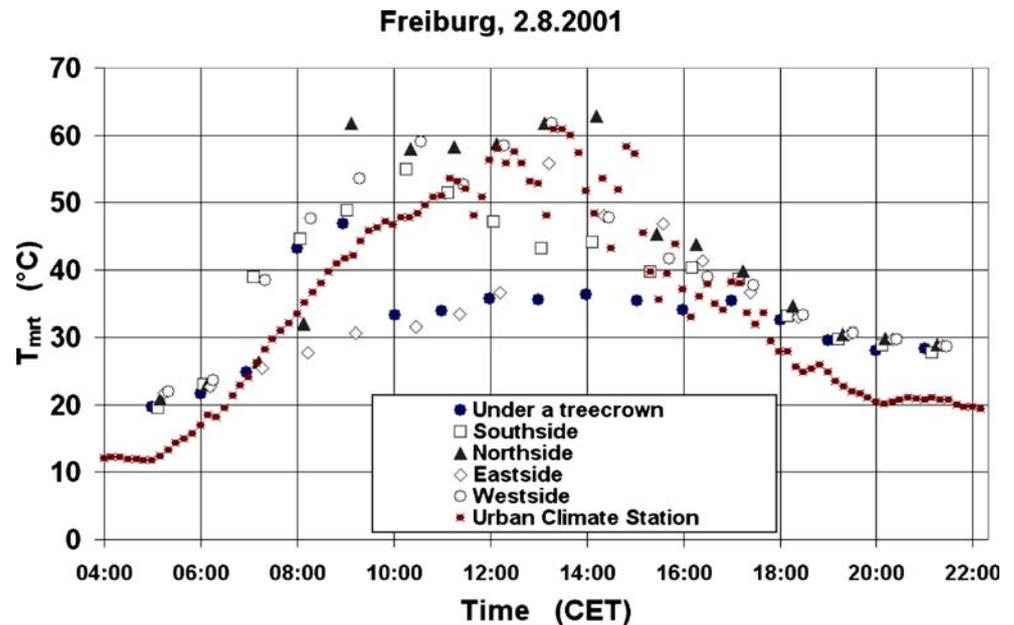

Fig. 8 Selected typical urban structures in Freiburg for human-biometeorological analyses

Fig. 9 Daily variation of T_{mrt} in five different urban structures for 2 August 2001 in Freiburg

differences in T_{mrt} at ground level were very small. At the point when short-wave radiation fluxes start to be present, the differences in T_{mrt} between the four different measurement points in the two differently oriented urban canyons are beginning to increase, and they show higher discrepancies compared with the reference point under a tree.

As explained in the previous chapter, a complete assessment of the thermal environment can be described through a thermal index such as the physiologically equivalent temperature (PET). Figure 10 shows the conditions of PET for the measurement sites of Fig. 8. This figure demonstrates that there are differences between roof and street level during the morning and evening hours. We attribute this mainly to higher wind velocities at roof level. For clear sky conditions and high short-wave radiation but no shadowing at the measurement points, we found that the thermal bioclimate in urban structures is very variable, and we found differences between the different measurement points that range from 10–15°C PET. In the afternoon (after 14:00 CET) the differences in PET between the sites in the urban canyon are not as high. This is mainly the result of the influence of air temperature, wind speed and, to a lesser extent, of the radiation fluxes.

Fig. 10 Daily variation of PET in five different urban structures for 2 August 2001 in Freiburg
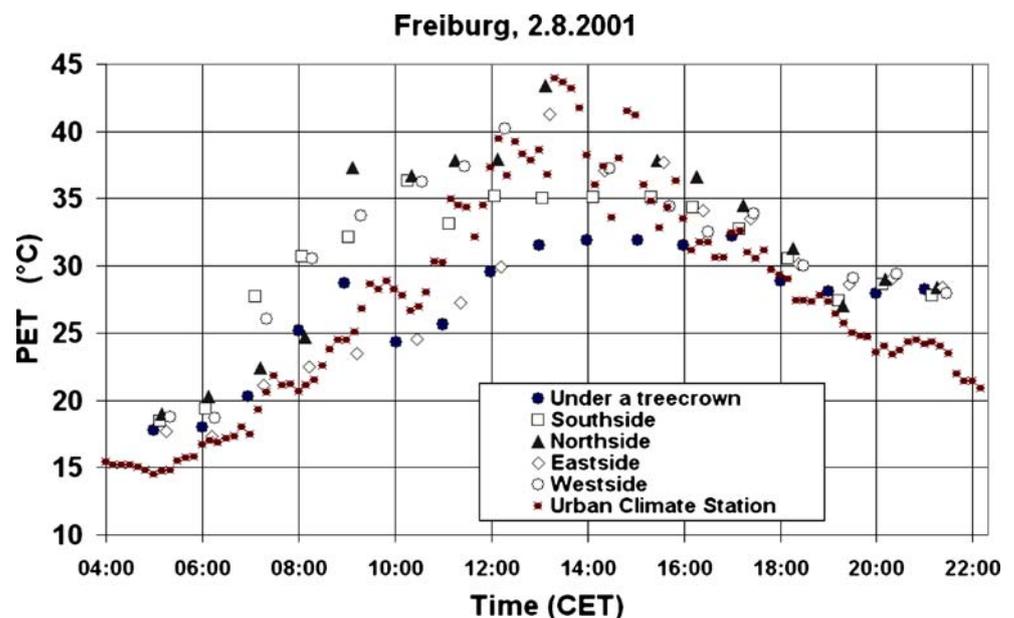
Validation of RayMan with measurements

To analyze the accuracy of the RayMan outputs, validating measurements have been carried out. Figure 11 shows the relationship between T_{mrt} modelled with RayMan and measurements that were carried out on 2 August 2001 in Freiburg, southwest Germany. Some scattering occurs, but the statistical relationship between T_{mrt} measured and modelled has an $r^2=0.7684$ and is statistically significant at 95 % level. The scattering is an effect of clouds appearing, which caused some variation. Differences can also be due to the effect of the extremely complex structures at the measurement sites. Nevertheless, the simulation of T_{mrt} by RayMan shows reasonable agreement with the measured values.

Discussions

As shown in the previous examples, the radiation fluxes are most important for the human energy balance of the human body and the resulting thermal index PET, especially during summer. Accordingly, a detailed and integrated estimation of the short- and long-wave radiation fluxes is most important for urban and landscape planning.

If continuous monitoring measurement systems are not available, it is necessary to estimate the three-dimensional fluxes of the radiation balance of the human body through modelling. The major problems in modelling the three-dimensional radiation fluxes for the human body are the reflection and emission coefficients of the solid surfaces in complex urban structures. The modelling of the atmospheric components of short-wave radiation and the long-wave radiation of the free atmosphere is less important. It is not yet known how inclined or vertical surfaces influence the three-dimensional radiation budget of human beings.
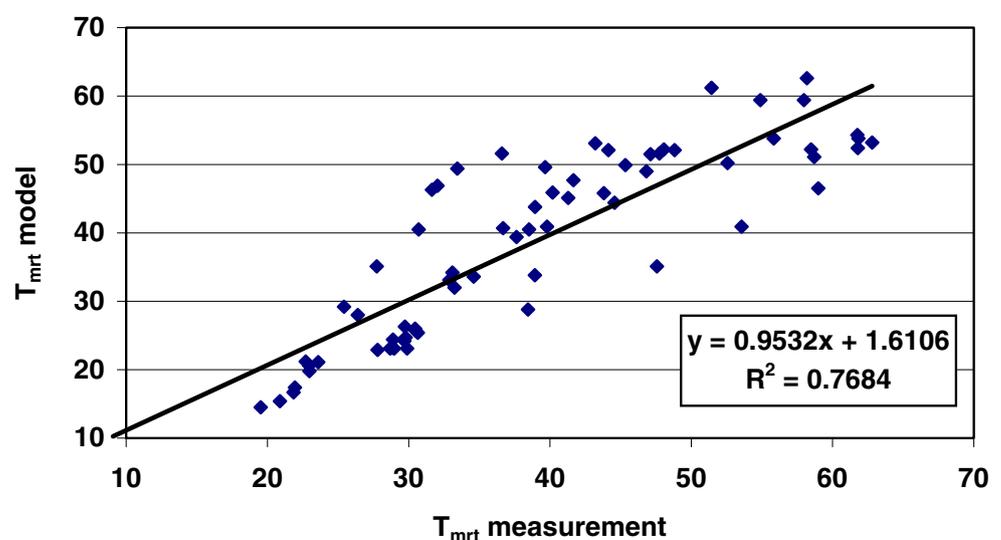
Therefore, the model presented here needs to be supported with accompanying measurements. Furthermore, the quantification of clouds in urban areas and the turbidity estimation need to be enhanced. Improvements of atmospheric turbidity in other places in the world are also important.

One future step in the development of the model is permanent validation with measurements, especially on vertical surfaces. Validations in simple environments, such as plane areas, don't show large differences in the radiation fluxes. Further applications of the RayMan model and improvements for difficult climates and areas, e.g. tropical regions, are planned.

The presented model is developed for operational use and for case studies for different planning levels. The advantages of the model are in the user-friendly environment, the easy input and the combination of different options in fish-eye photographs, buildings and vegetation properties, free drawing with facilities for modification and the possibility of its use with varying scenarios, making for different planning cases. This includes the calculation of the energy balance of human beings and assessment of the thermal bioclimate with the use of thermal indices. Another advantage is the running time, which is very fast. RayMan is transparent, which means that all the input parameters are clearly known as well as the resulting detailed radiation and energy fluxes.

The main advantage of RayMan is in the requirements of meteorological data which have no high spatial variability, such as air temperature and air humidity. The absence of modification in wind parameters and cloud information, which have to be known, is a drawback, which can be solved easily by preparing the data in the input files or running simulations with different wind speeds. Furthermore, the calculations comprise only point results but no continuous surface data. Needed meteorological data can be

Fig. 11 Relationship of measured mean radiant temperature $T_{mrt,measurement}$ and computed mean radiation temperature $T_{mrt,modeled}$ by RayMan for 2 August 2001 in Freiburg

produced by numerical models such as ENVI-MET (Bruse and Fleer 1998) and then imported in RayMan for specific studies. However, the implementation of spatial calculations would increase the run time tremendously and decrease the main advantage of RayMan.

The development of the RayMan model has not been completed yet. It is planned to continue the development of RayMan, especially in the modification of atmospheric parameters and the detailed input information in the artificial and natural geometrical properties in urban areas.

Conclusions

There exists an increasing demand to assess the thermal climate in a human-biometeorologically significant way. Therefore, assessment methods based on the human energy balance and resulting in thermal indices have been developed worldwide. To apply the thermal indices, suitable tools are necessary, which enable their calculation from the relevant meteorological and human variables. The RayMan model introduced in this study represents one of these tools. Due to its clear structure, the RayMan model can be applied not only by experts in human-biometeorology, but also by people with less experience in this field of science. By using thermal indices calculated with the RayMan model, the stationary perception of the thermal surroundings by people can be transformed into a numerical value.

Some extensions of the RayMan model are planned in the future. They include a more accurate consideration of the radiation fluxes within three-dimensional urban structures, e.g. street canyons or courtyards, with the consequence that the site-dependent correlations between simulated T_{mrt} by use of the RayMan model and T_{mrt} obtained from direct measurements of all relevant radiation fluxes will have higher coefficients of determination.

To consider adaptation and acclimatisation of people with their thermal surroundings, it is necessary to interview people about their perception of the thermal conditions. The results can be used to set up graded scales for the thermal indices. They are characterised by varying threshold values representing (i) the different adaptation and acclimatisation processes of people worldwide and (ii) varying behaviour of people in terms of their activity and the heat resistance of their clothing.

As a stationary model, RayMan cannot be applied to assess non-stationary thermal conditions of single persons, e.g. if they move from the sunny to the shaded sidewalk within a street canyon. For that purpose other models have to be used (e.g. Höppe 1993, 1999). The assessment of non-stationary thermal conditions, however, represents a special case, which is necessary for specific objectives; but for

general application purposes like in urban planning, it is sufficient to operate with the stationary RayMan model.

The RayMan model allows the integration of new thermal indices developed especially for application in complex environments. One of these indices is UTCI (universal thermal climate index), which is under development by an Expert Team at the WMO, and a Commission of the International Society for Biometeorology.

RayMan is available for general use under http://www.mif.uni-freiburg.de/rayman) with an easy user-friendly interface.

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