Modelling the thermal bioclimate in urban areas with the RayMan Model

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ABSTRACT: To calculate thermal indices for urban climate conditions, meteorological data (air temperature, wind speed, air humidity as well as and short- and long-wave radiation fluxes) and thermo-physiological data (activity and clothing) are required. The model RayMan, which is presented and discussed here, allows the calculation of short- and long-wave radiation fluxes affecting the human body. The model estimates the radiation fluxes and the effects of clouds on short-wave radiation fluxes. RayMan, which takes complex urban structures into account, is suitable for land use and planning purposes in urban areas. The final output of the model, however, is the calculated mean radiant temperature, which is required for the human energy balance and, therefore, for the assessment of urban bioclimate using indices like PMV, PET or SET* (Standard Effective Temperature). Examples from Freiburg, Germany and other locations are presented.

Keywords: radiation, thermal Indices, RayMan

1. INTRODUCTION

Many climatic parameters and conditions are affected by natural and artificial morphology at a meso- and micro scale, with influences the temporal and spatial behaviour of the parameters. These effects are significant at different levels of regional and urban planning i.e. urban parks, and they are also of importance for the planning and design of new buildings, recreational facilities and a variety of other applications. With some modification, existing methods for assessing climate in human biometeorology and applied climatology can be applied to tourism climatology [1, 2].

For example, thermal indices that are derived from the energy balance of the human body can be of great advantage for regional and urban planning. Standard climate data, such as air temperature, air humidity and wind speed are required in order to calculate and quantify the thermal bioclimatic conditions. The most important environmental parameters for deriving modern thermal indices, however, are the short and long wave radiation (and the derived mean radiant temperature). These can be determined using special techniques. For these purpose, several models and possibilities are existing, i.e. the RayMan model, which has been developed for urban climate studies, has a broader use in applied climatology [1, 2, 3]. Further outputs, such as sunshine duration and shadow, can be helpful in the design and structure of recreational areas and design of urban structures.

2. DESCRIPTION OF RayMan

The model „RayMan“ estimates the radiation fluxes and the effects of clouds and solid obstacles (urban morphologies) on short wave radiation fluxes (Fig. 1). The model, which takes easy and complex structures into account, is suitable for land use and planning purposes on various local to regional levels (Fig. 2 left). The final output of this model is the calculated mean radiant temperature, which is required in the energy balance model for humans. Consequently, it is also required for the assessment of urban bioclimate and several thermal indices, such as Predicted Mean Vote (PMV), Physiologically Equivalent Temperature (PET) and Standard Effective Temperature (SET*).

The model is developed based on the German VDI-Guidelines 3789, Part II: Environmental Meteorology, Interactions between Atmosphere and Surfaces; Calculation of the short- and long wave radiation [4] and VDI-3787: Environmental Meteorology, Methods for the human-biometeorological evaluation of climate and air quality for the urban and regional planning at regional level. Part I: Climate [5]. Based on the human energy balance, meteorological data (air temperature, wind speed, air humidity and short and long wave radiation fluxes) and thermo physiological data (activity and clothing) are required for the calculation of thermal indices [6]. Data on air temperature, humidity, and wind speed are required to run RayMan [3, 7].

Additional features, which can be used for the evaluation of a region’s climate or the development of new tourism facilities, are: a) calculation of sunshine duration with or without sky view factors; b) estimation of daily mean, max or total global radiation; and c) determination of shaded areas are outputs of RayMan.

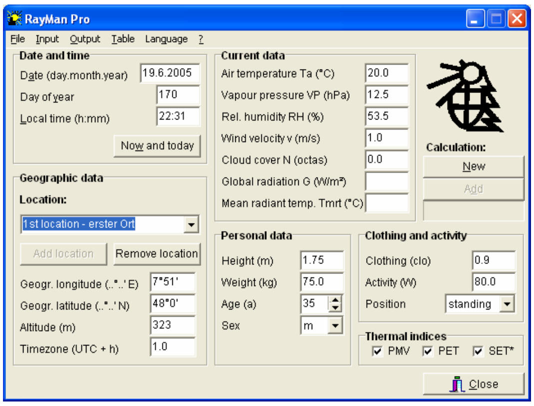

Figure 1: Main window of RayMan.

Using the computer software “RayMan” (Fig. 2) an input window for structures (buildings, deciduous (Fig. 3) and coniferous trees (Fig. 4)) is provided. The produced data on trees and buildings can be stored as files and the data can be used for other or future studies and runs. Additional information about the physical properties of the urban morphologies can be entered, i.e. albedo and emissivity, and considered in the calculations.

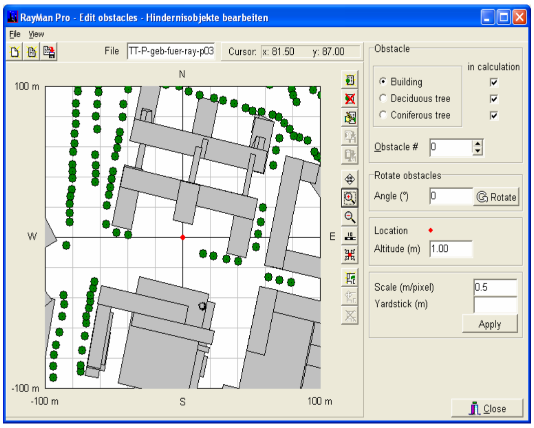

Figure 2: Input windows for morphologies.

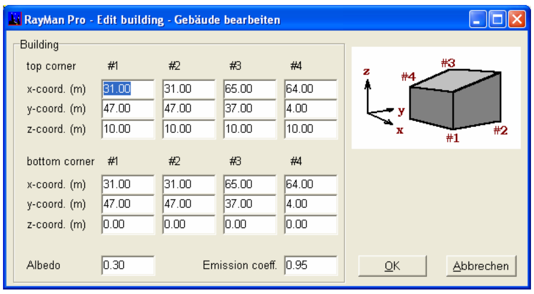

Figure 3: Input window for buildings.

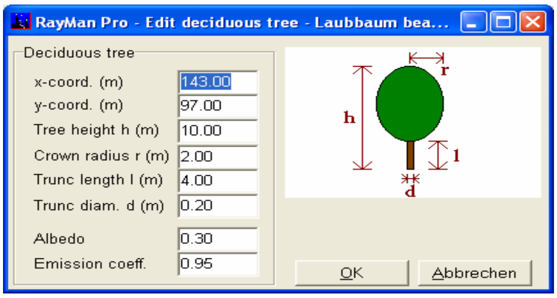

Figure 4: Input window for deciduous trees.

The possibility of free drawing and output of the horizon (natural or artificial) are included for the estimation of sky view factors (Fig. 5). The input of fish-eye-photographs for the calculation of sky view factors is also possible. The amount of clouds covering the sky can be included by free drawing while their impact on the radiation fluxes can be estimated (Matzarakis 2001, Matzarakis and Rutz, 2005). The produced information and data can be stored as files (graphs and raw data) and used for future runs.

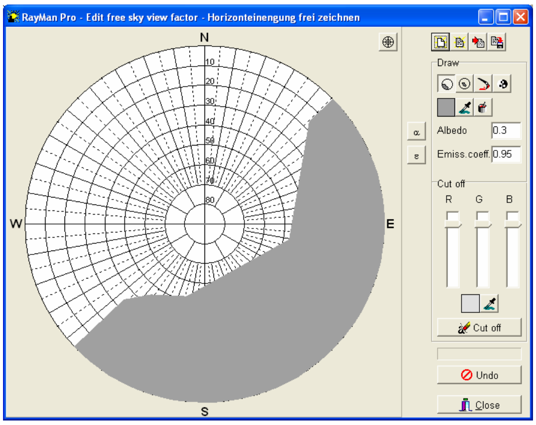

Figure 5: Input window for free drawing and import of fish eye photographs.

3. RESULTS AND EXAMPLES

The RayMan model can be applied for diverse applications. Results of radiation fluxes, sunshine duration and shadow can even be produced without any meteorological or climatological data.

Horizon information (in particularly Sky View Factor) needs to be known to obtain sun paths (Fig. 6 and 7). The calculation of hourly, daily or monthly averages of sunshine duration, short wave and long wave radiation fluxes with and without topography, and obstacles in urban structures can be carried out with RayMan (Fig. 7). Data can be entered through manual input of meteorological data or the import of pre-existing files. The output is given in form of graphs and text data (Fig. 6 and 7).

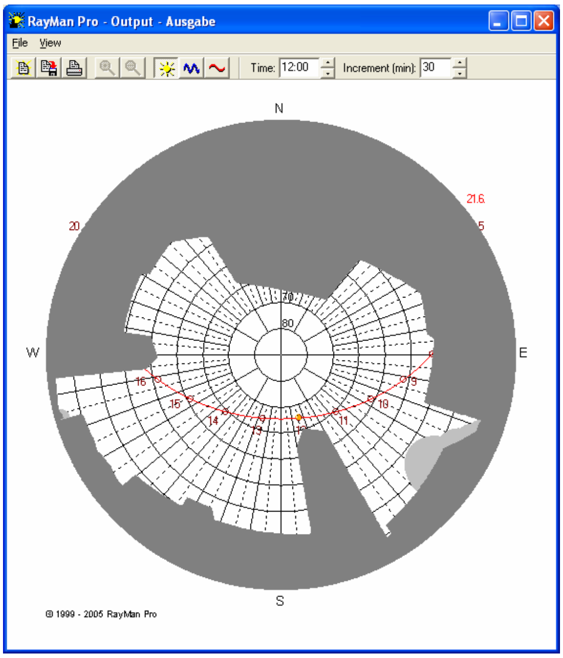

Figure 6: Output of sun path and horizon limitation.

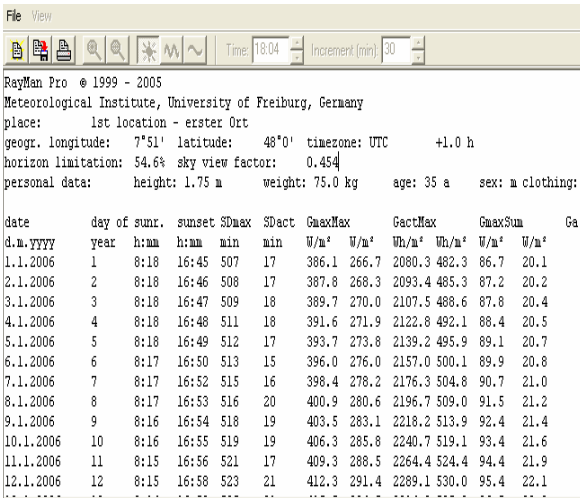

Figure 7: Table output of daily information about maximum and actual sunshine duration and global radiation.

In order to gain information about the thermal comfort or thermal bioclimatic conditions in simple and complex environments, the knowledge of the sunshine duration and the short wave radiation fluxes are required. The short and long wave radiation fluxes are usually data that are neither easy to obtain nor are they included in routine measurements. Table 1 shows the mean monthly sunshine duration of an urban structure (Fig. 2 and 7) with and without horizon limitation for the Freiburg coordinates. Additionally, the maximum sum of monthly hours of sunshine duration with and without horizon limitation are shown in table 1. The sunshine duration and sum of monthly sunshine hours can vary strongly during the winter months under the urban morphology given for all months of the year.

Table 1: Mean monthly sunshine duration without (Sdmax) and with horizon limitation (Sdm), sum of monthly sunshine hours without (SDm) and with (SDsm) horizon limitation in h for Freiburg, Germany, in a latitude of 48 °N. Urban morphologies (horizon limitations) are given in figure 2.

Without horizon			Without horizon	
Month	Sdmax (h)	SDsum (h)	SDm (h)	SDsm (h)
1	9.1	281.9	1.7	52.6
2	10.3	289.6	4.8	133.6
3	11.9	369.4	7.7	237.5
4	13.6	406.8	8.0	238.6
5	15.0	464.3	8.3	258.1
6	15.7	471.5	8.5	255.1
7	15.4	492.2	8.5	271.7
8	14.1	438.3	7.9	245.0
9	12.6	376.9	8.3	247.7
10	10.9	338.8	6.0	186.0
11	9.5	284.2	2.7	82.3
12	8.7	269.5	0.4	11.8

Table 2 shows the Percentage ratio of actual sunshine duration to maximum possible for northern latitudes in 5° steps from 0° to 60°. The ration of sunshine duration varies from south to north strong during the winter months and less strong during the summer months.

Table 2: Percentage ratio of actual sunshine duration to maximum possible for northern latitudes.

	1	2	3	4	5	6	7	8	9	10	11	12
0°	84	80	64	64	64	56	61	64	60	76	83	81
5°	81	82	67	62	65	64	64	64	60	79	84	76
10°	71	84	69	61	65	65	65	63	62	81	78	66
15°	64	82	72	59	64	65	65	61	65	82	69	62
20°	61	76	74	60	63	64	64	59	67	80	63	60
25°	59	69	74	61	60	64	62	59	69	76	60	58
30°	57	63	73	63	57	60	58	59	69	71	58	55
35°	52	58	72	63	57	56	56	60	68	66	55	45
40°	38	55	69	61	57	55	56	60	67	61	45	33
45°	25	49	65	59	56	54	55	57	66	56	33	10
50°	5	37	61	59	52	53	53	54	64	48	13	4
55°	3	18	55	58	49	48	48	54	60	35	4	3
60°	5	5	46	55	47	44	45	52	55	17	4	6

RayMan provides the shadow for every day and minute of the year for any given simple or complex urban morphology as an additional output. Figure 8 shows the shadow for the morphology of Fig. 2 for the Freiburg latitude (48° N). Information on shadow in simple and complex environments is of particular importance for the quantification of intensity and duration of thermal stress in summer. It is also important for recreational and environmental issues regarding urban green space and the effects of trees in urban areas.

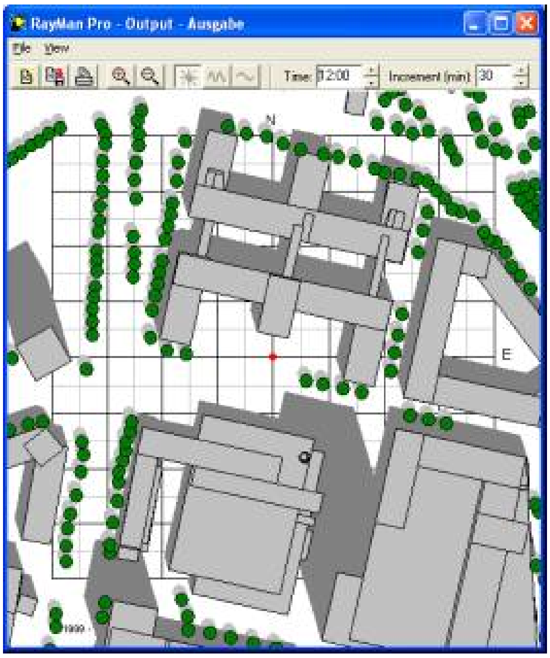

Figure 8: Shadow output.

Figure 9 shows the frequencies of the PET-classes from very cold to very hot according to the scale developed by Matzarakis and Mayer [7] (Tab. 3) to describe the general bioclimatic conditions of City of Freiburg. Figure 9 illustrates that in 39.1 % of the studied hours, the PET conditions are lying in the class of very cold, followed by the cold class (11.1 %) and cool (12.7) and slightly cool (12.6). Only 8.2 % are in the range of thermal comfort; 6.0% and 4.5 % in slightly and warm class respectively. 3.7 and 2.2 % of the hours of 2003 was lying in the hot and very hot class.

Table 3: Ranges of physiologically equivalent temperature (PET in °C) for different grades of thermal perception by human beings according to [8].

PET (°C)	Thermal perception
<4	Very cold
4-8	Cold
8-13	Cool
13-18	Slightly cool
18-23	Comfortable
23-29	Slightly warm
29-35	Warm
35-41	Hot
>41	Very hot

Figure 10 shows the frequency analysis of the PET-classes calculated with a modified urban morphology (from Figure 2). Here, the PET conditions are different because of the modification of the short and long wave radiation fluxes according to the urban structure. It can be seen that there is a reduction of the very cold conditions from 39.1 to 38.3 % and a reduction of the warm, hot and very extreme hot conditions. An increase of the cool and comfortable conditions is visible.

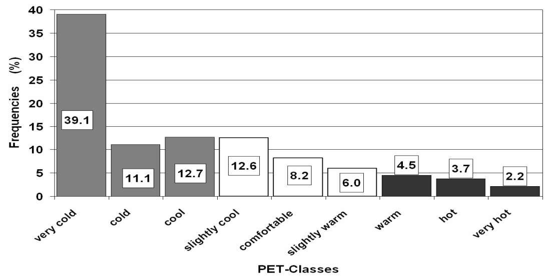

Figure 9: Frequency analysis of the PET classes for Freiburg in 2003.

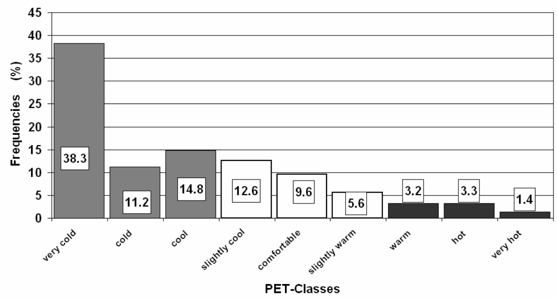

Figure 10: Frequency analysis of the PET classes for Freiburg in 2003 (with modified mean radiant temperature) based on the urban morphology of Figure 2.

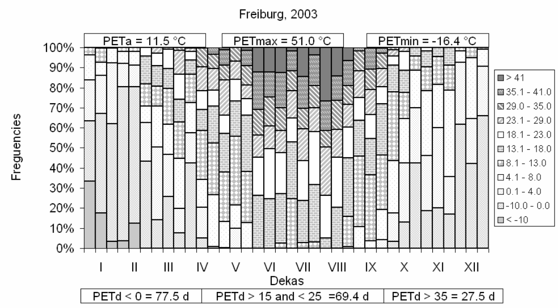

Figure 11: Bioclimate diagram of PET for the Urban Climate Station Freiburg for 2003.

Based on PET a bioclimate diagram, which includes ten days frequencies of the daily PET values for the year 2003 was calculated for the analysis of the general bioclimate conditions (Figure 11). The thermal human-bioclimate conditions are expressed in percentages of the occurrence of classes for ten day intervals. The data are hourly data. Figure 9 depicts that 26 dekas of the whole year are conditions with a PET less than 18 °C. 4.4 dekas are conditions with PET higher than 29 °C and 3.3 dekas with thermal comfort (between 18 and 23 °C). PET > 35 occurs from the 12th dekas (end of April) to 27th (end of September). Additionally, the mean PET (11.5 °C), the absolute maximum (51.0 °C) and minimum (-16.4) value and also the frequencies of cold days (days with PET < 0 °C), thermal comfort and slight stress days (days with PET between 15 and 25 °C) and heat stress days (days with PET > 35 °C) resp. 77.5, 69.4 and 27.5 days are presented in Figure 11 for 2003. Good description of the general thermal bioclimatic regime is possible using this kind of bioclimate diagrams, including relevant information in terms of frequencies and extremes.

5. CONCLUSION

The presented model provides diverse opportunities for research in applied climatology and education. With easily available climate or meteorological data air temperature, air humidity, wind speed radiation fluxes, and thermal indices for easy and complex environments can be estimated. Additional information about clouds and global radiation imported in the model can be the basis for a more appropriate estimation of the radiation fluxes. Therefore, the RayMan model is a valuable tool for the planning and construction of climate oriented dwellings and facilities for tourism resorts and urban planning. It can also be used for the calculation of shade to be provided by special devices in tourism areas and resorts in order to create more comfortable thermal conditions for recreational users and visitors through protection from direct sunlight.

Micro scale models for urban climate studies have to be easily understandable and user friendly. Models with long running time are not of great advantage for the quantification of climate effects on the regional and urban planning level.

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