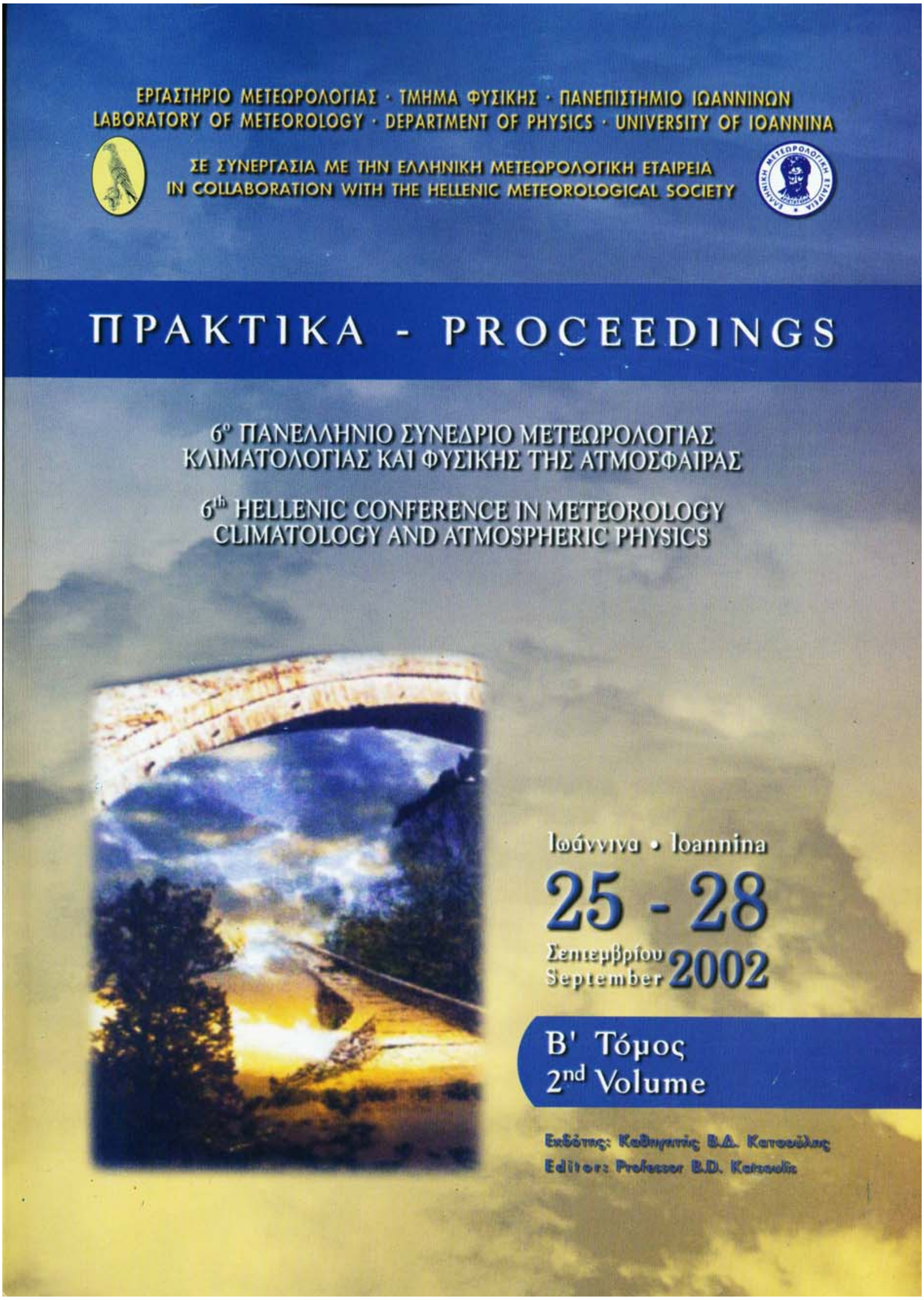
ΕΡΓΑΣΤΗΡΙΟ ΜΕΤΕΩΡΟΛΟΓΙΑΣ · ΤΜΗΜΑ ΦΥΣΙΚΗΣ · ΠΑΝΕΠΙΣΤΗΜΙΟ ΙΩΑΝΝΙΝΩΝ
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RADIATION AND THERMAL COMFORT

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Abstract
The model RayMan is presented, which can calculate the atmospheric influences of the short- and long-wave radiation. The model is valid for applications in urban areas which are characterized by the complexity of the urban structures and other environments in the micro-scale. The final result of the model RayMan is the mean radiant temperature T_{mrt}, which is important for the human-biometeorological assessment of the thermal environment. It can be quantified by use of thermophysiological indices like Predicted Mean Vote (PMV), or Physiological Equivalent Temperature (PET) or Standard Effective Temperature (SET*) which are based on the human energy balance. The model RayMan is free available for general use under (http://www.mif.uni-freiburg.de/rayman).

ΑΚΤΙΝΟΒΟΛΙΑ ΚΑΙ ΘΕΡΜΙΚΗ ΑΝΕΣΗ

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Περίληψη
Παρουσιάζεται το μοντέλο „RayMan“ με τη βοήθεια του οποίου υπολογίζονται οι ατμοσφαιρικές ενεργειακές ροές στο ανθρώπινο σώμα, που προκαλούνται από τη δράση της ηλιακής και της γήινης ακτινοβολίας. Το μοντέλο αυτό είναι κατάλληλο για εφαρμογές τόσο στις αστικές περιοχές, οι οποίες χαρακτηρίζονται από μια πολυπλοκότητα στους αστικούς σχεδιασμούς, όσο και σε άλλα περιβάλλοντα μικρής κλίμακας. Το άμεσο αποτέλεσμα της εφαρμογής του μοντέλου RayMan εκφράζεται με τη μέση θερμοκρασία της ακτινοβολίας, ενός μεγέθους που είναι απαραίτητο για την εκτίμηση του θερμικού ισοζυγίου του ανθρώπου και η οποία ορίζεται, για έναν άνθρωπο με καθορισμένη σωματική στάση και ενδυμασία, ως η αντίστοιχη μέση θερμοκρασία μέλανος σώματος, στο οποίο θα είχαμε τις ίδιες απώλειες και οφέλη ακτινοβολίας κάτω από όμοιες πραγματικές συνθήκες. Το ισοζύγιο ακτινοβολίας, με τη σειρά του, αποτελεί το βασικό στοιχείο για την εκτίμηση του θερμικού άνθρωποβιοκλίματος, το οποίο, ως γνωστό, μπορεί να εκφραστεί στη συνέχεια, μέσα από σειρά θερμικών δεικτών, όπως η Predicted Mean Vote (PMV), η Physiological Equivalent Temperature (PET) και η Standard Effective Temperature (SET*). Το μοντέλο RayMan είναι διαθέσιμο στην διεύθυνση (http://www.mif.uni-freiburg.de/rayman).

1. Introduction

The thermal complex of human-biometeorology comprises the meteorological factors air temperature, air humidity and wind velocity as well as the short- and long-wave three-dimensional radiative fluxes which affect people in indoor and outdoor climates. This complex is relevant to human well-being and health due to a close relationship between thermoregulatory mechanism and circulatory system (Jendritzky, 1992). In contrast to the air pollution complex, the thermal complex is often underestimated, especially in Central Europe. But that is not justified, because long-term data statistics show increasing mortality rates under extreme thermal conditions (Laschewski and Jendritzky, 2002).

2. Assessment of Thermal Ψomplex

Human-biometeorological studies have already been carried out for some time. In the past thermal indices were frequently used to assess the thermal environment. These indices were based on single or composite meteorological parameters, such as wet bulb temperature or equivalent temperature (Jendritzky, 1992). In the seventies of the 20th century, some scientists began to use physiologically significant indices which were derived from models for the human energy balance (e.g. thermal index *Physiological Equivalent Temperature* PET on the basis of the model MEMI, see Höppe, 1993, 1999).

It is necessary for the calculation of thermal indices to determine all meteorological parameters important for the human energy balance at a human-biometeorologically significant height, e.g. 1.1 m above ground (the average height of a standing person's centre of gravity in Europe). Dominant meteorological parameters influencing the human energy balance include

- air temperature T_a,
- vapour pressure VP,
- wind velocity v,
- mean radiant temperature of the surroundings T_{mrt}.

Depending on the objectives of the assessment, these meteorological parameters can be measured experimentally or calculated in a grid-net by numerical models. The human energy balance considers also body parameters, e.g. in the model MEMI:

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

Like the frequently used PMV index (*Predicted Mean Vote*), PET enables a problem-specific assessment of the thermal component of climate in the form of bioclimate maps (e.g. Matzarakis, 1995), frequency distributions or cycles (diurnal or annual variations).

Table 1. Linear relationships between PET and meteorological parameters x in the form of PET = a ∗ x + b; a, b: regression coefficients; R^2: coefficient of determination; T_a: air temperature, VP: vapour pressure, v: wind velocity, SW↓: short-wave radiation from the upper hemisphere, SW↑: short-wave radiation from the lower hemisphere, LW↓: long-wave radiation from the upper hemisphere, LW↑: long-wave radiation from the lower hemisphere, T_{mrt}: mean radiant temperature; basis: measurements on sunny days summer 2001 in Freiburg (SW Germany).

parameter	a	b	R^2
T_a (°C)	1.354	-5.0	0.620
VP (hPa)	1.111	7.5	0.300
v (m/s)	-1.660	25.6	0.021
SW↓ (W/m²)	0.017	20.7	0.366
SW↑ (W/m²)	0.136	0.9	0.247
LW↓ (W/m²)	0.090	-12.8	0.289
LW↑ (W/m²)	0.136	-39.8	0.746
T_{mrt} (°C)	0.519	6.8	0.757

3. Importance of Radiation in Human-Biometeorological Studies

Among the meteorological parameters required for the human energy balance, the mean radiant temperature T_{mrt} is most important during summer weather conditions (Mayer, 1993, Matzarakis, 2001). T_{mrt} is defined as the uniform temperature of a surrounding surface emitting blackbody radiation ($\varepsilon = 1$), which results in the same radiation energy gain for a human body as the prevailing radiative fluxes which are usually very varied under open space conditions. The procedure for the measurement of T_{mrt} is very complex and needs much time (Höppe, 1992; Matzarakis, 2001).

On sunny days in summer 2001 human-biometeorological measurements have been carried out in a East-West and a North-South street canyon as well as under an adjacent chestnut tree in Freiburg (SW Germany). One objective was to analyse the influence of different meteorological parameters on PET. T_a, VP, and v as well as the short- and long-wave radiative fluxes from the three-dimensional surroundings were determined by use of a special mobile human-biometeorological measuring system (Matzarakis, 2001). Based on the measured radiative fluxes, T_{mrt} could be calculated by a method which is described in detail by Höppe (1992) and Matzarakis (2001). The results of the data analysis in the form of linear regressions between PET and different meteorological parameters are summarized in Table 1. Highest values for the coefficient of determination were obtained for the relationships between PET and T_{mrt} ($R^2 = 0.757$) as well as LW↑: ($R^2 = 0.746$) and T_a ($R^2 = 0.620$), whereas the influence of v on PET was lowest. In addition, the impact of VP, SW↓, SW↑, and LW↓ on PET was relatively low. As typical examples for the data analysis, Fig. 1 and 2 contain the relationships between PET and T_{mrt} as well as T_a.

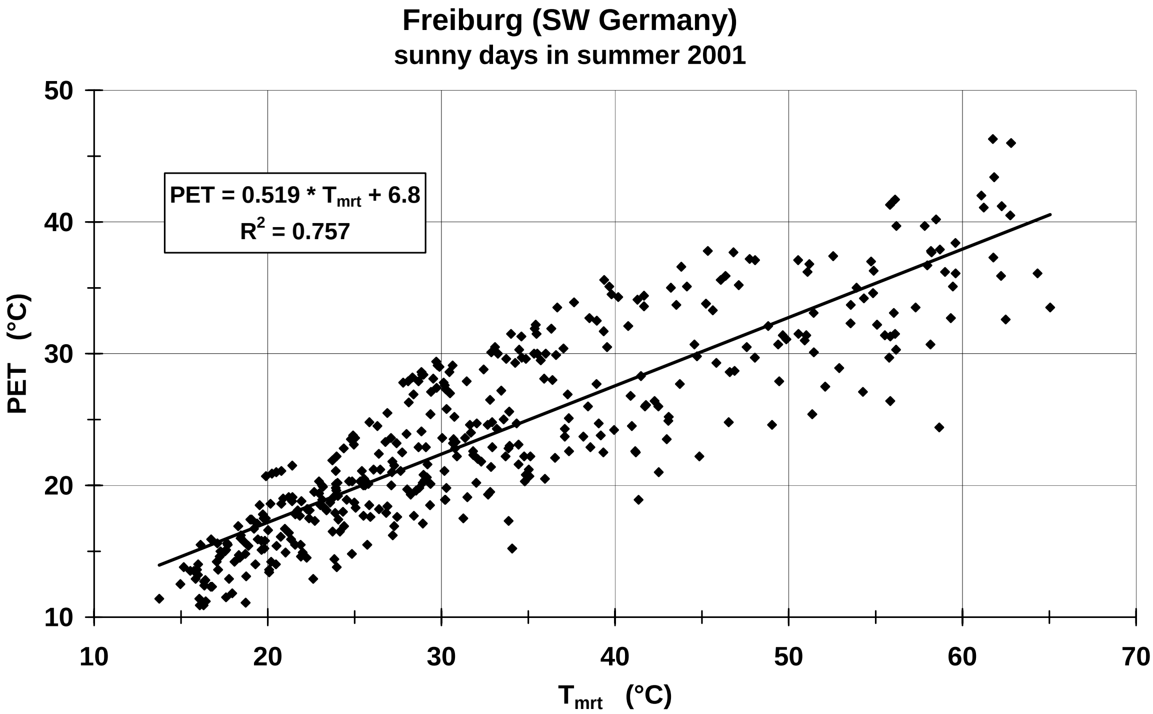

Figure 1. Relationship between Physiological Equivalent Temperature PET and mean radiant temperature T_{mrt} on sunny days in summer 2001 (July 17th, 18th, 19th, 25th, and August 2nd) in Freiburg (SW Germany).

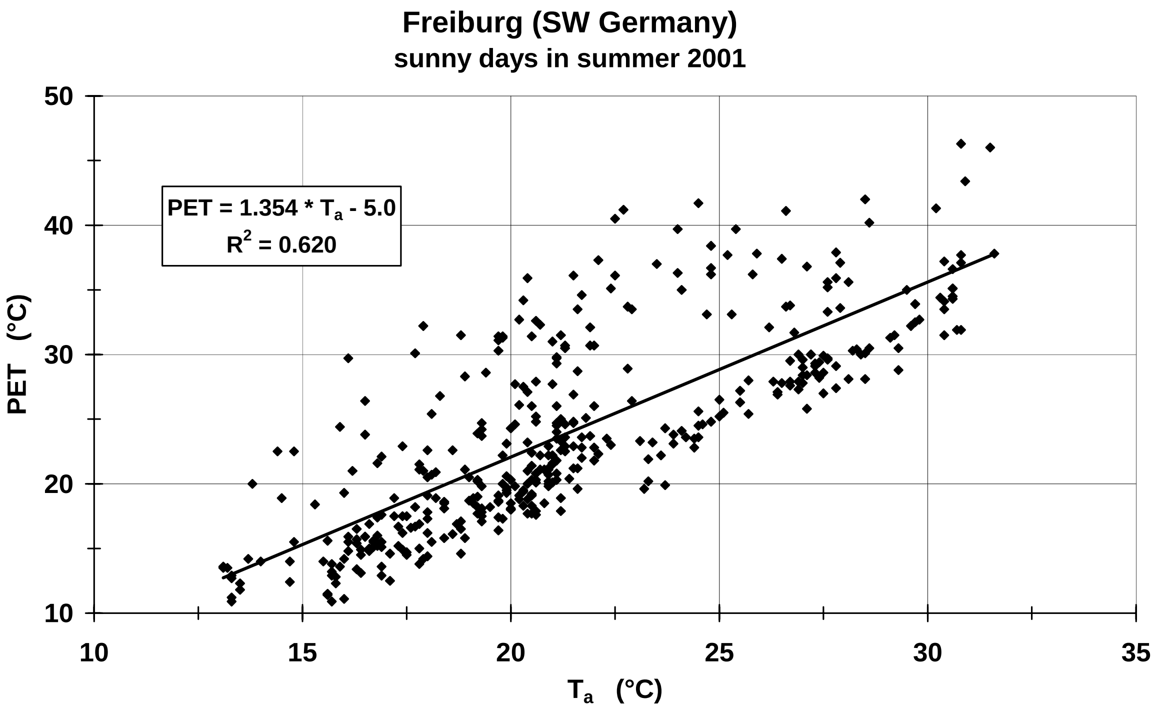

Figure 2. Relationship between Physiological Equivalent Temperature PET and air temperature T_a on sunny days in summer 2001 (July 17th, 18th, 19th, 25th, and August 2nd) in Freiburg (SW Germany).

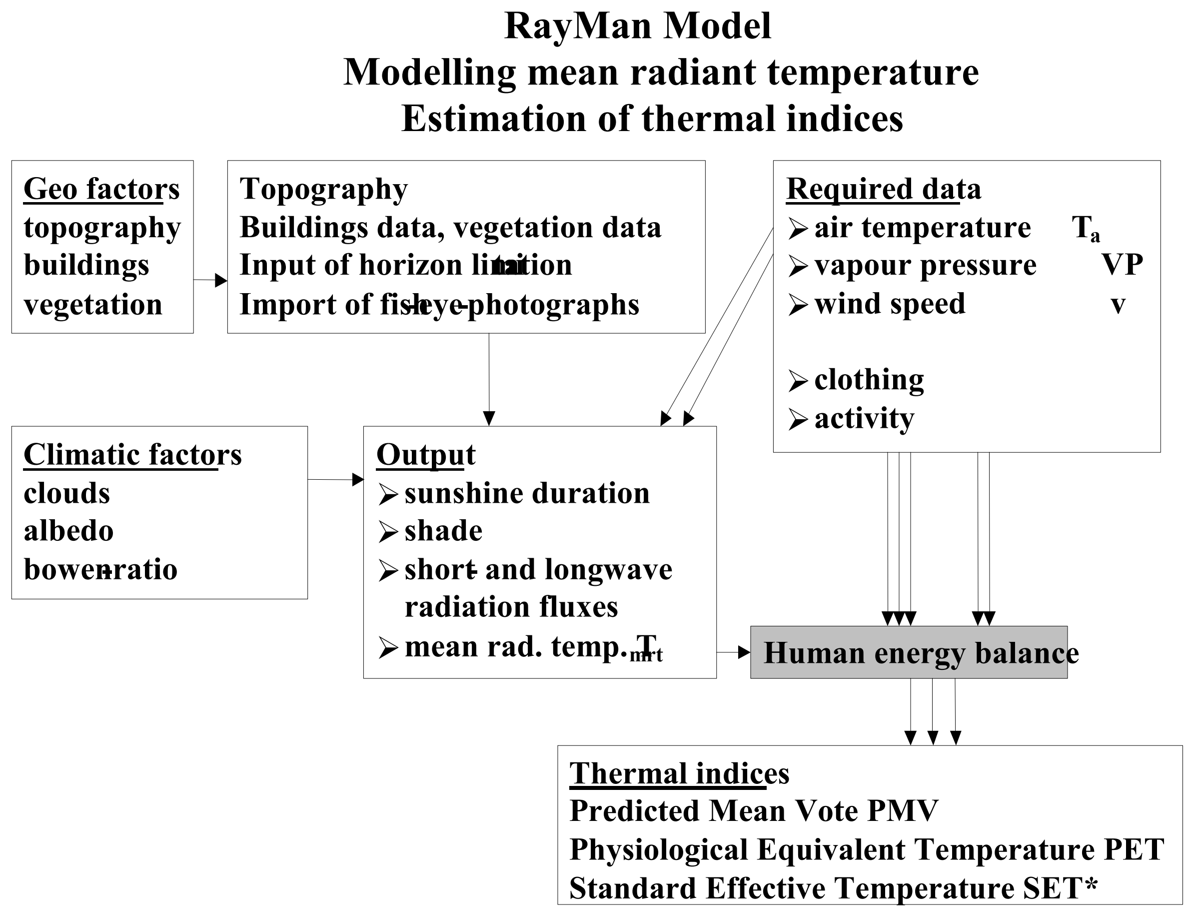

Figure 3. Structure of the human-biometeorological model RayMan, version 1.3

4. Modelling the Mean Radiant Temperature

Aside from measurements T_{mrt} can be simulated by use of an appropriate model. The model RayMan presented here is well suited for the calculation of the three-dimensional radiative fluxes in complex structures, which are the basis for T_{mrt} (Matzarakis et al., 2000). In addition, RayMan enables the determination of selected thermal indices. The structure of RayMan is illustrated in Fig. 3. The model RayMan is free available for general use under (http://www.mif.uni-freiburg.de/rayman).

Working with RayMan on a WINDOWS platform is very comfortable, because detailed characteristics of the structures under investigation (e.g. fish-eye photographs or free drawing of variable horizon) as well as the meteorological conditions can be considered in a user-friendly manner (e.g. Figure 4).

In the field of urban climatology and human-biometeorology one of the most important questions is, wether an object of interest is shaded or not. Hence, in the presented model shading by urban and natural obstacles is included. Horizon information needs to be known to obtain sun paths for the calculation of radiative fluxes in different micro-scale structures. Calculation of hourly, daily and monthly totals of sunshine duration, short-wave and long-wave radiative fluxes with and without topography and obstacles in urban structures can be carried out with RayMan. For the calculation of the mean radiant temperature with RayMan only air temperature, air humidity and wind speed have to be inserted manually or by files. The output is given in form of graphs and text data (Figure 5). The comparison of T_{mrt} values obtained by RayMan and determined by measurements of the three-dimensional radiative fluxes shows a good agreement for clear sky weather and simple geometric structures as well as satisfactory results for cloudy days and complex structures.

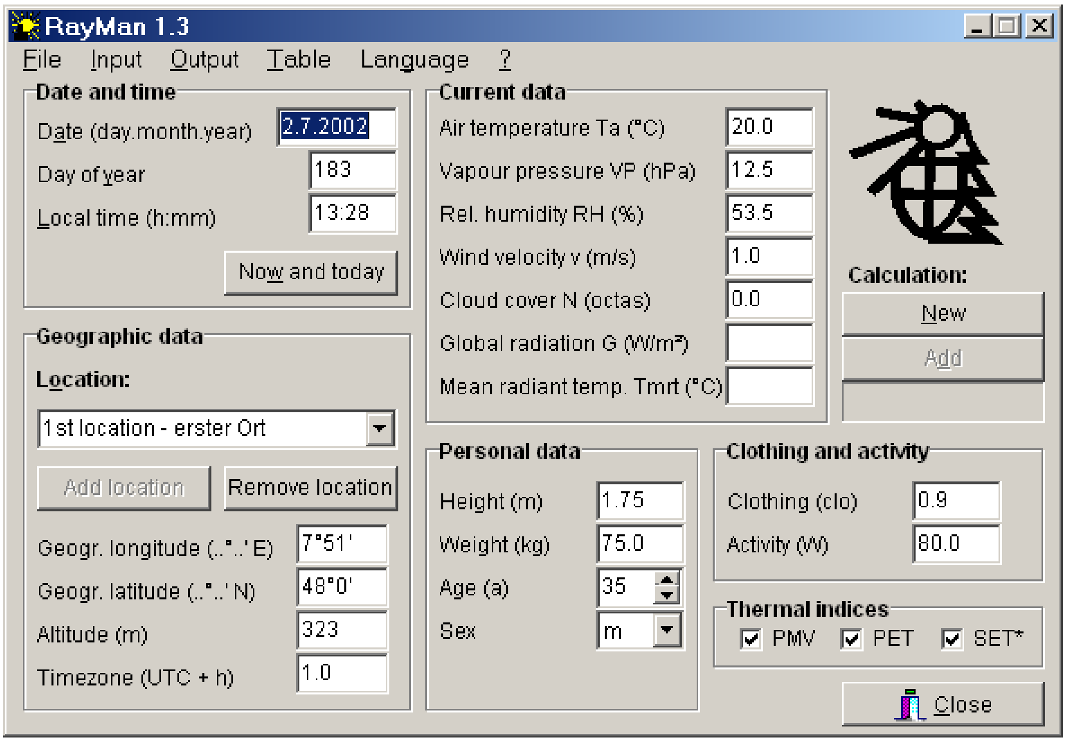

Figure 4: Input window of RayMan 1.3 and relevant values for the calculation of mean radiant temperature and thermal indices.

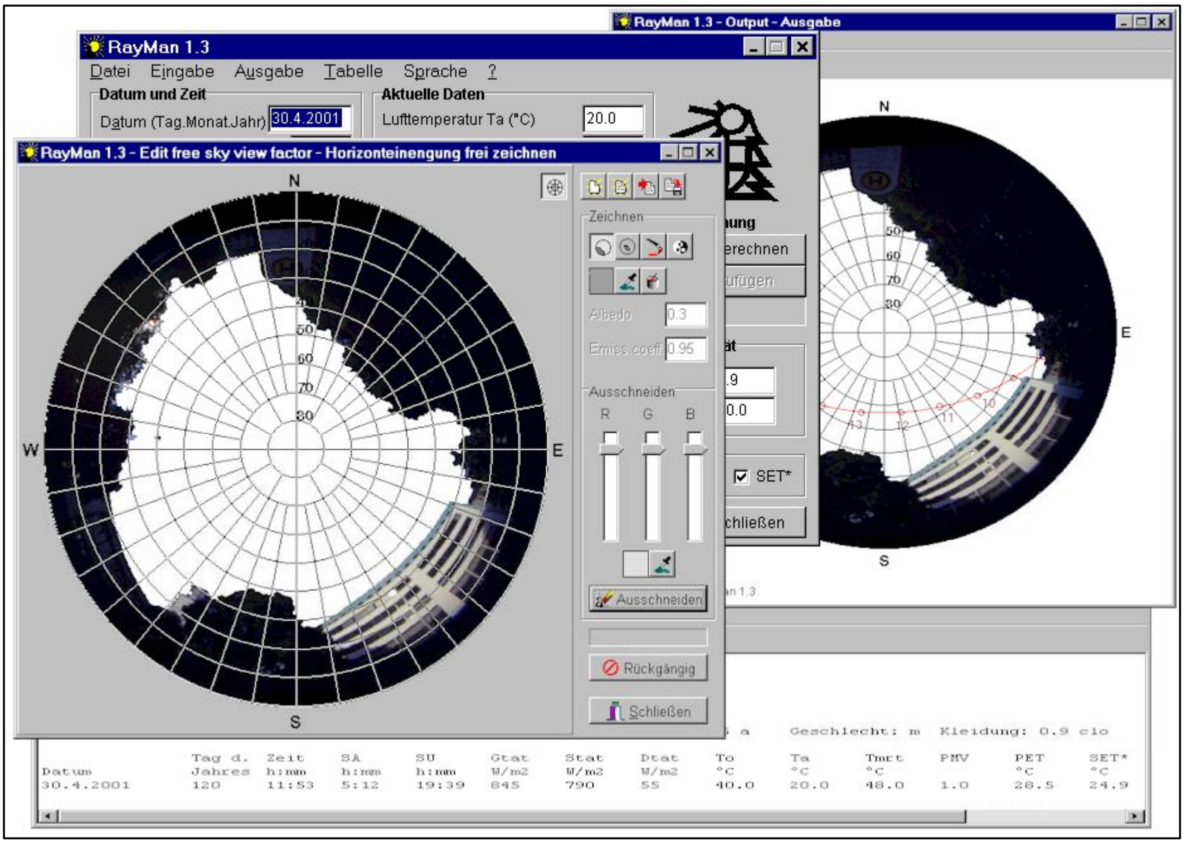

Figure 5: Output examples of RayMan 1.3.

Conclusions

Time dependent radiative fluxes in different spaces have to be precise, because they are very important for many applications in meteorology and climatology such as human-biometeorology or urban climatology. Possible applications of RayMan are in detail:

- urban and landscape planning (regarding investigation of impacts of big constructional projects),
- tourism (for the selection of holidays or the duration of holidays),
- giving advice concerning the location of residential areas,
- climate change and relation to human biometeorology,
- climate and health (for the analysis of thermal stress situations),
- agricultural and forest meteorology (calculation of radiation fluxes in complex surroundings), landscape ecology (estimation of nature processes).

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