Estimating down- and up-welling thermal radiation for use in mean radiant temperature

Henning Staiger[1], Andreas Matzarakis[2]

[1] Former affiliation: German Meteorological Service, Germany
[2] Meteorological Institute, Albert-Ludwigs-University of Freiburg, Germany

Abstract

Thermal radiation significantly impacts the energy balance of human beings, and is usually assessed via mean radiant temperature T_{mrt}. The longwave down-welling radiation (*LDR*) and the up-welling from ground (*LUR*) are rarely measured, but are in the same order of magnitude as daily means of shortwave irradiation. This study evaluates simple, but theoretically based algorithms for *LDR* and *LUR* by comparison with measurements in regionally differing climates of Germany. *LDR* is modelled via the clear-sky algorithm (LDR_c) of Prata in a version converging against a realistic value for a completely dry atmosphere. Its advantage is an improved predicted variance. To account for cloud impact, a shortwave cloud modification factor (CMF_{sol}) derived from frequently measured solar global irradiation is applied for daylight hours and observed total cloudiness at night-time, respectively. It is accounted for the diurnal course in the effective temperature via relative humidity, whose impact is modulated dependent on cloud cover and altitude. *LUR* is modelled using the parameterisation of the Klima-Michel-Model. The selected algorithms show a universal applicability. A CMF_{sol} is more closely related to hemispherical cloud base emittance than any cloud correction scheme requiring synoptic cloud observations. The *LUR* model accounts for 90 − 97 % of variance in observations. The uncertainty in T_{mrt} due to estimated *LDR* and *LUR* is comparable to that of the shortwave radiation components.

1. Introduction

Atmospheric longwave down-welling radiation (*LDR*) and up-welling from the ground (*LUR*) are in the same magnitude as daily means of shortwave irradiation. Their impact on the energy balance of human beings is usually assessed by mean radiant temperature T_{mrt} (Matzarakis et al. 2007, ASHRAE 2001, Jendritzky et al. 1990). Furthermore, *LDR* and *LUR* are required in estimating the latent heat flux used in applied agricultural and forest meteorology.

Because of mostly unavailable observations of longwave radiation, *LDR* and *LUR* must be parameterised. Modelling of *LDR* in applied bioclimatology is usually restricted to simple, nevertheless theoretically based algorithms, because a complete radiation transfer calculation is time-consuming, and frequently lacks in required profiles.

LUR is the sum of longwave radiation emitted based on the surface temperature and the usually relative small part of *LDR* reflected by the surface. The surface temperature can strongly deviate from temperature T_0 (K) at screen-level (2 m above ground), and thus, it must be predicted from T_0 (K) and further observations.

This study assumes that the shortwave fluxes are observed and is concerned with the longwave components. It evaluates the performance of the algorithms by comparison with observations in regionally differing mid-latitude climates of Germany. The uncertainty in T_{mrt} using predicted *LDR* and *LUR* instead of observations will be assessed.

2. Methods

Mean radiant temperature (T_{mrt})

In operational human biometeorology the radiation fluxes required in calculation of T_{mrt} (K) are related to an upright standing or walking person, respectively (Matzarakis et al. 2007, Jendritzky et al. 1990). Most frequently the complex structured environment of a person is unknown. Thus, an un-shadowed plane is assumed with solid angles f_a of the surface and the sky set at 0.5: Then T_{mrt} (K) is given by:

$$T_{mrt} = \left\{ \sigma^{-1} \cdot \left[f_a \cdot LDR + f_a \cdot LUR + \alpha_{ir} \cdot \varepsilon_p^{-1} \cdot \left(f_a \cdot D_{sw} + f_a \cdot R_{sw} + f_p \cdot I_{sw} \right) \right] \right\}^{0.25} \quad (1)$$

σ is the Stefan Boltzmann constant. D_{sw} denotes the isotropic diffuse and R_{sw} the surface reflected shortwave radiation flux. I_{sw} is the direct and by definition an-isotropic short-wave radiation flux. $\alpha_{ir} = 0.7$ is the effective shortwave and $\varepsilon_p = 0.97$ the effective longwave absorptance of the body surface (clothing and skin). The projected area factor f_p accounts for the directional dependence and is a function of the solar zenith angle and assumed body posture.

Longwave down-welling radiation (*LDR*)

LDR is a function of all-sky emissivity ε and T_0: $LDR = \varepsilon \cdot \sigma \cdot T_0^4$. In general, *LDR* modelling predicts first a value for a cloudless sky (LDR_c). This is than adjusted to account for clouds, which increase the atmospheric emittance beyond its clear-sky value, because cloud droplets also emit in the atmospheric window.

Clear-sky parameterisation

$LDR_c = \varepsilon_{ac} \cdot \sigma \cdot T^4_{atm}$ ($W \cdot m^{-2}$) can be regarded in terms of a grey body emitting at uniform temperature. ε_{ac} is the effective atmospheric clear-sky emissivity, which is closely related to precipitable water u ($kg \cdot m^{-2}$) in the atmospheric column. T_{atm} (K) is an effective temperature of the atmospheric boundary layer. Approximately 63 % of LDR_c is due to emission within the lowest 100 m of the atmosphere, less than 5 % originates from layers above an altitude of 2 km altitude (Schmetz et al. 1986). This enables LDR_c to be estimated from T_0 (K) and water vapour e_0 (hPa) at screen-level taking climatological profiles as a basis. Prata (1996) develops an analytical solution of the radiation transfer equation, which corresponds to a slab emissivity model with a continuum correction. It provides ε_{ac} as function of u ($kg \cdot m^{-2}$):

$$\varepsilon_{ac} = 1 - \left(1 + u/u_P\right) \cdot \exp\left(-\sqrt{\left(a_1 + a_2 \cdot u/u_P\right)}\right) \quad (2)$$

$u_P = 10$ ($kg \cdot m^{-2}$) is a scaling constant. Using a temperature lapse rate and an inverse scale height for water vapour pressure derived from the US standard atmosphere, precipitable water can be predicted by $u \approx 465 \cdot e_0 / T_0$. This study deviates from Prata's (1996) original coefficients and sets a_1 at 0.068. Thus $\varepsilon_{ac} \rightarrow 0.23$ for $u \rightarrow 0$ (completely dry atmosphere), a more realistic value accounting for CO_2 and additional greenhouse gases (Skarveit et al. 1996, Konzelmann et al. 1994). The coefficient a_2 is selected so that the absolute difference of ε_{ac} between the formula with the original and the adjusted coefficients falls into to the broad minimum in the e_0/T_0 interval 0.004 - 0.080. This modified version deviates less then 3 % from the original in the range $e_0/T_0 > 0.024$. Prata (1996) provides an altitude correction $\delta\varepsilon_p$ to be subtracted from ε_{ac}.

$$\delta\varepsilon_p = 0.05 \cdot \left(1013.25 - p\right)/303.25 \quad (3)$$

p (hPa) is the barometric pressure at site altitude.

All-sky parameterisations

The all-sky emissivity ε is derived correcting ε_{ac} for clouds. For observed total fractional cloud cover n (0−1), ε is calculated using Eq. (4) of Maykut and Church (1973):

$$\varepsilon = \varepsilon_{ac} \cdot \left(1 + 0.2234 \cdot n^{2.75}\right) \quad (4) \qquad \varepsilon = \varepsilon_{ac} \cdot (1-n) + n \quad (5)$$

Due to unavailable synoptic cloud observations, Crawford and Duchon (1999) introduce a cloud fraction term n = 1-CMF_{sol}. The solar cloud modification factor CMF_{sol} is the ratio of measured solar global irradiation to that of the cloudless atmosphere. In this study, the ESRA clear-sky algorithm (Rigollier et al. 2000) is applied. The required Linke turbidity factors are taken from Remund et al. (2003). ε than is given as fractional reduction of the longwave radiation loss (Eq. 5).

Diurnal variations of emissivity

For cloudless skies, Long and Turner (2008) provide a relative humidity dependent factor for ε_{ac} in Eq. (4) and (5), which accounts for diurnal variations due to haze and dew formation. Under cloudy skies these diurnal variations will be reduced. Additionally, it has to be accounted for the site altitude:

$$fact_{rh} = 1 + \left(3.36 \cdot 10^{-12} \cdot rh^{5.1938} \cdot CMF_{sol} / 1.24\right) / \left(1 + 20 \cdot \delta\varepsilon_p\right) \quad (6)$$

rh (%) is the relative humidity and $\delta\varepsilon_p$ is given by Eq. (3). In case of observed total fractional cloud cover, CMF_{sol} in Eq. (6) has to be replaced by (1-$n^{2.75}$).

Longwave up-welling radiation (*LUR*)

LUR is predicted according to Jendritzky et al. (1990): *LUR* (W·m^{-2}) = $0.95 \cdot \sigma \cdot T_s^4$ + 0.05·*LDR*. T_s (K) is the surface temperature, which usually is unknown. It is parameterised dependent on the shortwave radiation balance, on assumptions concerning physical properties of the soil, the Bowen ratio, and on the flux of sensible heat between atmosphere and surface. The parameterisation is solved via a Newton approximation using the screen-level temperature as first guess.

3. Observational data

This study uses for southwest Germany the same measurements for the sites Bremgarten (212 m) and Feldberg (1489 m) from 1991–1996 as described by Iziomon et al. (2003). For northeast Germany, the observations at Warnemuende (4 m) from 2001-2003 are available. The site is located directly on the Baltic Sea. In screen level are observed: down-welling and up-welling longwave and shortwave radiation, direct shortwave irradiation via a SONIe sunshine duration sensor, as well as ambient temperature, relative humidity, and wind speed.

Synoptic observations of total cloudiness are available for Bremgarten (1991 –Feb. 1993), for Feldberg (1991-1995) and for Warnemuende (June 2001 –2003).

4. Results and discussion

Table 1 summarises the comparison of modelled and observed LDR_c and *LDR*. An hour is identified as "clear-sky", if its CMF_{sol} > 0.95 at daylight hours, or n = 0 at night-time, respectively. Comparison with LDR_c from Prata's original and other theoretically based algorithms shows within an individual site that the scattering in the correlation coefficients between the algorithms is quite low. However, the slope of the regression line (the modelled variance) is closer to unity for the scheme with adjusted coefficients.

Table 1: Predicted compared to observed longwave down-welling radiation for clear-sky (LDR_c obs) and all-sky (LDR obs) conditions. Bias is predicted minus observed radiation, RMSE is the root mean square error, SE the standard error

	clear-sky					all-sky				
site	LDRc obs	bias	RMSE	SE	corr. coeff.	LDR obs	bias	RMSE	SE	corr. coeff.
	W/m^2	W/m^2	W/m^2	W/m^2		W/m^2	W/m^2	W/m^2	W/m^2	
daylight hours										
Bremgarten	319.7	8.2	22.8	17.6	0.931	327.7	7.6	19.0	16.3	0.932
Feldberg	265.7	-0.6	27.0	25.1	0.837	291.0	-0.6	22.1	20.9	0.883
Warnemuende	318.0	0.8	30.5	26.3	0.848	338.4	-1.9	18.1	17.1	0.928
day and night										
Bremgarten	307.9	3.3	23.8	22.4	0.918	323.9	2.6	21.1	20.6	0.907
Feldberg	241.7	2.9	29.0	26.6	0.834	286.9	-12.9	37.0	33.0	0.745
Warnemuende	300.8	-4.4	23.9	23.4	0.921	329.4	-3.6	20.2	19.8	0.925

The *LDR* cloud correction scheme of Crawford and Duchon (1999) performs the best provided that it is based on CMF_{sol}. At night-time CMF_{sol} is undefined, and thus cloud correction requires a synoptic observation as input. Concerning bias, the Maykut and Church (1973) cloud correction scheme is at the lowland sites comparable with the CMF_{sol} scheme. However, related to the CMF_{sol} scheme, the root mean square error (RMSE) is increased by 33 %. Under all-sky conditions, the RMSE is noticeably reduced compared to clear-sky at daylight hours. This may result from the high number of all-sky hours. Nevertheless, it indicates that the main part of scattering in modelling is due to estimation of clear-sky emissivity.

LUR modelling applies the Bowen ratio for land use "settlements". Dependent on the site, the *LUR* model can determine 90 % (Feldberg) to 97 % (lowland sites) of the observed variance. At Feldberg, the five months with snow cover conflict somewhat with modelling assumptions. Most frequently the current surface albedo will not be available. The additional modelling error due to a set albedo of 20 % and due to scattering in modelled *LDR* is approximately 2 %.

Table 2: T_{mrt} based on modelled versus T_{mrt} based on observed *LDR* and *LUR*

sites	Tmrt obs	STD	bias	RMS error	SE
	K	K	K	K	K
Bremgarten	296.2	18.9	0.6	2.5	2.4
Feldberg	287.0	19.5	-0.5	4.7	4.5
Warnemuende	290.7	19.1	-0.5	2.2	2.1

The mean radiant temperature T_{mrt} (K) is calculated applying Eq. (1). Measured diffuse irradiation is unavailable for Bremgarten and Feldberg, thus it is modelled from observed global irradiation applying the algorithm of Skartveit et al. (1998). A predicted T_{mrt} is calculated based on observed global irradiation and modelled *LDR* and *LUR*, assuming a shortwave surface albedo of 20 % and predicting diffuse irradiation via the algorithm of Skartveit et al. (1998). The bias (Tab. 2) is within ±0.6 (K), the RMSE is less than 3 (K) for the lowland sites, and 5 (K) for Feldberg. The coefficient of determination for modelled values is greater than 95 %.

Figure 1 exemplifies the result for the site Bremgarten. Dependent on the time, the residuals reveal a slight daily course with highest values during noon and lowest around midnight. This may be influenced by estimating the cloud impact at night-time based on observed cloud cover with a tendency toward too low predicted *LDR* especially at the mountain site, where the daily course is most pronounced.

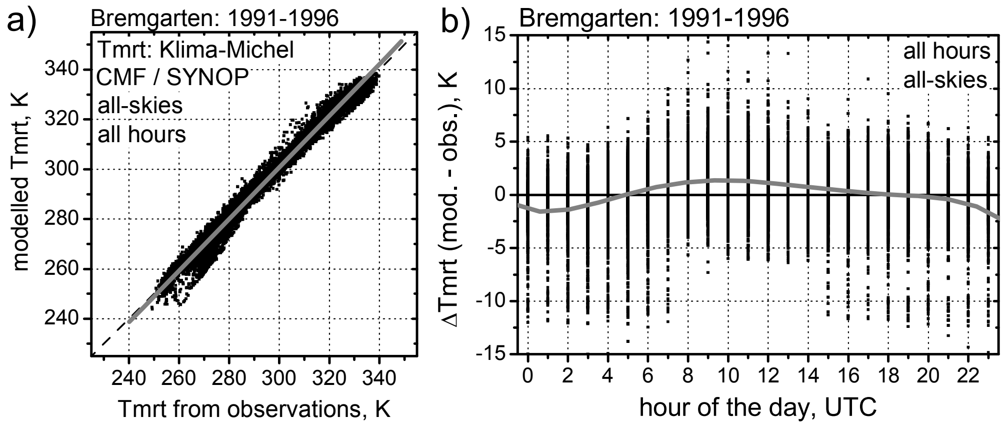

Fig. 1: Bremgarten: (a) Scatter-gram and (b) residuals for modelled versus observed T_{mrt}

5. Conclusions

Prata's (1996) scheme for LDR_c with adjusted coefficients has advantages, because modelled variances are closer to observations. The algorithm of Long and Turner (2008) improves the results, because it can be accounted for diurnal variations in effective temperature of the atmospheric boundary layer. The *LDR* cloud correction scheme of Crawford and Duchon (1999) using CMF_{sol} performs the best and should be preferred. If only observed total cloud cover is available, the Maykut and Church (1973) algorithm shows a comparable low bias, but an enlarged RMSE. Referring to publications, a universal applicability of the schemes can be anticipated.

The *LUR* algorithm performs well and with low uncertainty.

The uncertainty in T_{mrt} due to estimations of *LDR* and *LUR* can be expected to be in the magnitude of that of the shortwave radiation components in T_{mrt}.

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Authors' address:

Dipl. Met. Henning Staiger (Henning.Staiger@gmx.de)
Alte Yacher Str. 43, D-79215 Elzach, Germany

Prof. Dr. Andreas Matzarakis (Andreas.Matzarakis@meteo.uni-freiburg.de)
Meteorological Institute, Albert-Ludwigs-University of Freiburg
Werthmannstr. 10, D-79085 Freiburg, Germany