ALBRECHT KESSLER
LUTZ JAEGER

Analysis of long time series of long-wave radiation
fluxes above a pine forest

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A. Kessler and L. Jaeger

With 6 Figures

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Summary

The long-term variations of upward terrestrial (E) and downward atmospheric (A) long-wave radiation fluxes above a pine stand in the southern part of the upper Rhine valley plain are analysed based on monthly mean values from 27 years of monitoring.

Equivalent blackbody temperatures of the canopy and the atmosphere are calculated and compared to air temperatures at nearby sites.

Based on 324 monthly values each, correlations between A and E as well as A and global radiation G are analysed. Only the former are highly correlated. Monthly mean values of long-wave radiation A can be calculated from air temperature, water vapour pressure and cloud cover.

The long-term yearly average of equivalent blackbody temperature of the canopy is 0.6 K lower than kinetic air temperature at nearby sites.

Only small, insignificant increases of both blackbody temperatures and air temperature are found. Despite the strong forest growth, it is surprising that the ratio of canopy emission temperature to air temperature did not change significantly.

Relationships between the changes of general atmospheric circulation and equivalent blackbody temperatures of the canopy point to a strong dependence on shifts of general atmospheric flow.

1. Introduction

Few long-standing measurements of terrestrial upward E and atmospheric downward A long-wave radiation fluxes exist (Garratt and Prata,

1996; Stanhill, 1997; Gilgen et al., 1997). This fact is astonishing and regrettable, because the atmospheric long-wave radiation flux is a major factor in the investigation of the global greenhouse effect. It should be mentioned, in addition, that the long-wave radiant fluxes at and near the earth's surface are much larger in general than the solar radiant fluxes, as far as the daily averages are concerned. Exceptions can be found in the polar regions in their respective high summer seasons, when the daily mean of the solar radiation is greater than the daily mean of the long-wave radiation fluxes, due to the extended day-lengths of the polar days (Kessler, 1985; Hantel, 1989; Hupfer, 1991).

At the Hartheim energy balance site (Forstmeteorologische Messstelle Hartheim des Meteorologischen Instituts der Universität Freiburg) the yearly averages (1974–2000) of the downward long-wave radiation flux A ($= 327 \text{ W/m}^2$) and of the upward terrestrial long-wave radiation flux E ($= 366 \text{ W/m}^2$) are nearly three times higher than the solar radiation flux G ($= 129 \text{ W/m}^2$).

A further fact should be mentioned. Hitherto, special emphasis has been given to the turbulent fluxes of the energy balance in solving the closure problem of the energy balance equation (Foken, 1998). But it has been shown (Kessler

and Jaeger, 1999) that, related to all energy balance terms, the second most important factor is the long-wave radiation flux loss normalised by means of the global radiation $(E-A)/G$. For this reason analysing A and E also has to be considered as more important.

The aim of the present paper is to discuss the special aspects of the upward and downward long-wave radiation fluxes above the pine stand surface at Hartheim, based on monthly values of a time series containing over 27 years of measurements.

2. Radiation and energy balance of the pine stand

2.1 Radiation flux

To characterise the radiant flux densities (in W/m^2) on the horizontal reference plane we use the following symbols:

G = global radiation (=total downward short-wave solar radiation),

R = reflected global radiation,

A = atmospheric downward long-wave radiation (=back radiation),

E = total of the upward terrestrial long-wave thermal radiation including the atmospheric long-wave radiation reflected at the canopy surface,

Q = net radiation.

$$Q = G - R + A - E \quad (1)$$

Equivalent blackbody radiant temperatures were calculated and compared with air temperatures at the Bremgarten site measured in screens at 2 m level. Thus we are able to compare temperature values which had been measured by means of different methods.

From E we can determine the equivalent blackbody radiant temperature T_c of the canopy, with σ Boltzmann constant:

$$T_c = (E/\sigma)^{0.25} \quad (2)$$

We define an equivalent blackbody radiant temperature T_{atm} of the atmosphere likewise:

$$T_{atm} = (A/\sigma)^{0.25} \quad (3)$$

In order to discuss changes in the downward long-wave radiation flux A in connection with other climatic parameters, we used the Ångström

formula because the necessary input data of measurements and observation are available at the nearby official climate station Bremgarten (screen air temperature, water vapour pressure and, in addition, hourly observations of cloud amount from the period 1974 to 1991). Keding (1989) has already discussed in detail the application of different formula for the determination of the long-wave downward radiation flux at the Hartheim site. He used hourly values of the different climatic parameters to determine the local coefficients:

$$A = \sigma T_a^4 (a - b10^{-cw})(1 + dN^e) \quad (4)$$

With T_a = temperature of the air (K), measured at 2 m height; σ = Stefan-Boltzmann constant; $a = 0.92$, $b = 0.7$, $c = 0.12$, $d = 0.153$, $e = 2.183$ (according to Keding, 1989); w = water vapour pressure (hPa) and N = total cloud amount (tenth).

2.2 Radiation measurement, calibration, data management

The radiation sensors, fixed to an extending aluminium tower, have always been exposed approximately 2 m above the canopy surface of the pine stand. The radiation fluxes have been measured by means of pyranometers (solarimeters of type Moll-Gorczyński, Kipp and Zonen CM5 and CM6) and by means of pyrrometers (Schulze-Däke net radiometers).

All sensors are ventilated. Each of the up- and downward-facing thermopiles of the Schulze device is calibrated separately in the long-wave and in the short-wave range.

During the 27 years of monitoring 8 pyranometers of the same type and 6 pyrrometers of the same type were installed. Thus, the sensors were changed every 1–3 years.

Calibration of the sensors was performed either by the manufacturers (Kipp and Zonen, Delft/Netherlands and Dr. Lange, Berlin/Germany) or was kindly done by the former Hamburg observatory of the German Weather Service (Director Dr. F. Kasten). The Lange company in Berlin uses similar calibration routines to those of the Hamburg observatory. Measuring accuracy of the long-wave radiation fluxes is assumed to be ca. 4% (Schmetz et al., 1986). The lack of an absolute radiation reference related

to long-wave radiation processes and calibrations is considered to be a general international problem (Ohmura and Schroff, 1983; Field et al., 1992; Halldin and Lindroth, 1992). We have found some confusion about the magnitude of the Boltzmann constant σ in the literature concerning the changes from the International Pyrheliometric Scale, fixed in 1956 (IPS 1956) to the World Radiometric Reference 1981 (WRR 81). The radiation flux data reported and discussed here are related to the World Radiometric Reference 1981 (WRR 81). The atmospheric downward long-wave radiation A and the upward terrestrial long-wave thermal radiation E were measured and calculated as:

$$A = s_u - G + \sigma T^4 \quad (5)$$

with s_u being the signal output of the pyrrometer concerning the upward-facing thermopile; σT^4 is the thermal radiation of the device, calculated by means of its internal temperature, which is measured separately. The downward exposed thermopile of the net radiometer yields:

$$E = s_d - R + \sigma T^4 \quad (6)$$

with the signal output s_d , as in the case of A .

Data management and error analysis may be described as follows: Hourly values of the measurements are the basic input data for the database to be analysed. Before that, each single value was examined using several criteria, e.g. monthly means and standard deviations. Global radiation was checked by comparison with the maximum value possible; furthermore the realism of the relationship to the total cloud amount was also checked. A further test criterion concerning the short-wave radiant fluxes was the ratio R/G (ratio of reflected short-wave radiation R to incoming short-wave radiation G). Another criterion concerning the long-wave radiant fluxes was the check $(|E| - |A|) > 0$. $(|E| - |A|) \leq 0$ is only possible when fog occurs. A threshold variable k was used, which depends on daytime and seasonal radiation fluxes, checking consecutive hourly values (x_n) and (x_{n+1}) : $|(x_n) - (x_{n+1})| < k$. Furthermore, hourly values of the equivalent blackbody temperature of the emission of the stand were estimated and compared to the air temperature in the screen. Up to 1994 all components of the net radiation were measured and recorded

twice over, so that gaps in the hourly values could largely be eliminated.

2.3 Energy budget of the outer active layer of the pine stand and of the atmospheric column

Several papers have already reported the energy balance of the Hartheim pine stand (e.g. Schott, 1980; Garthe, 1985; Jaeger and Kessler, 1996; Gay et al., 1996; Jaeger and Kessler, 1997).

To describe the energy fluxes at canopy height we use the following simplified energy balance equation. All flux densities are defined as being positive if they transport energy to the reference level (outer active layer of the pine stand):

$$Q + (S + J) + H + \lambda V = 0 \quad (7)$$

with Q = net radiation, S = soil heat flux, J = stand heat storage per unit of ground area, H = turbulent sensible heat flux, λV = latent heat flux (λ latent heat of vaporisation of water). Since 1974 we have estimated monthly totals of these terms at Hartheim site (Jaeger and Kessler, 1997).

Q is determined by adding all components of the net radiation, which were measured by means of pyranometers and pyrrometers. The soil heat flux S is computed by means of a combination method. From the soil surface to a depth of 20 cm the rate of change in the heat content in this layer is used, at deeper levels the heat conduction equation is used. J is calculated by means of the rate of change in the heat content of the biomass and the air between soil surface and reference level.

The water balance equation applied at the Hartheim site is formulated as follows:

$$V = P - U + \Delta M \quad (8)$$

with V = evapotranspiration, P = precipitation, U = percolation, ΔM = change of soil moisture.

As percolation is assumed to be negligible at the Hartheim pine stand (Hädrich, 1979), the determination of totals of V is reduced to the recording of the precipitation P above the canopy and the measurement of the water content in the soil (Sturm et al., 1996).

Monthly mean values of the turbulent sensible heat flux H were calculated by means of Eq. (7).

Finally, the simplified equation used to estimate temperature changes of an air column above

the pine stand and a grass surface respectively is:

$$\delta T_a / \delta t = \{1/c_p\} (dW/dt + \nabla F) \quad (9)$$

with T_a = temperature of the air column, t = time, c_p = specific heat of air at constant pressure; W = diabatic absorption or loss of heat by unit mass due to radiation and turbulent heat fluxes; ∇F = divergence of the horizontal heat flux by unit of time and mass.

$$W = LWB + SWB + TB \quad (10)$$

LWB = long-wave radiation budget of the atmospheric column = $E - A - OLR$, SWB = short-wave radiation budget of the atmospheric column = $NSR - G + R$. TB = heat budget due to turbulent heat fluxes of the atmospheric column, with OLR = outgoing long-wave radiation flux at the top of the atmosphere and NSR = net solar radiation flux at the top of the atmosphere.

3. The experimental site Hartheim and the surrounding climate

3.1 Experimental site

The experimental site is located in the lower part of the Upper Rhine valley near the village of Hartheim, 21 km south-west of Freiburg, 47° 56' N, 7° 37' E, 201 m above sea level. The area is a highly uniform flood plain. The approximate dimensions of the pine forest are 10 km (N–S) and 1.5 km (W–E). The site is considered to be an ideal place to carry out radiation measurements. The view of the horizon is reduced by values of just under 3° (Jaeger, 1978). In 2002 the trees (*pinus sylvestris*) were 43 years old. The mean stand height more than tripled from the beginning of the monitoring up to now (from 4.45 m in 1974 to 14.57 m in 2001). The forest management carried out three thinnings in the years 1970/1971, 1981/1982 and 1991/1992.

3.2 The climate

The climate of the central part of the southern Rhine rift valley is characterised by relatively high air temperatures and low precipitation compared to other parts of Germany. The average yearly air temperature T_a is approximately 10°C. The average yearly total of precipitation P (period 1974–1997) at the Hartheim site is 631 mm. Percolation and surface runoff is

negligible below the pine stand. The mean annual amount of evapotranspiration V therefore nearly equals precipitation, namely $V \approx P$ (Kessler et al., 1988).

In order to interpret the results of the study, the equivalent blackbody temperatures of the canopy of the Hartheim pine stand T_c (Eq. 2) and of the atmospheric radiation T_{atm} (Eq. 3) were compared with the measurements of air temperature T_a and with other climatic data, such as cloud amount and water vapour pressure taken at the official climate station Bremgarten (47° 55' N, 7° 38' E, 208 m a.s.l.), which is situated approximately 4 km south-east of the Hartheim pine forest stand. The Bremgarten site was not influenced by urbanisation effects during the period of observation.

4. Results

The results of the study are presented in Tables and Figures. The following results are stressed in particular.

4.1 Radiation values

Table 1 shows the mean annual pattern of A and E compared to the global radiation G . The annual variation of A (81 W/m²) and E (96 W/m²) is half as large as the variation of global radiation G (201 W/m²). It should be pointed out in particular that the minimum of A (290 W/m²) in February occurs two months after the minimum of G (30 W/m²), which is in December. This is the result of the influence of advection (i.e. the divergence of the horizontal heat flux) on the long-wave atmospheric radiation A . One of the properties of the air-masses, transported in the west-drift, is the Atlantic temperature pattern. Thus, the minimum of A is shifting towards springtime. In contrast, the maximum of A (371 W/m²) in July is shifted by just one month in relation to G (231 W/m²) in June. This is mainly due to the local energy exchanges, as will be explained below.

Only one month of delay of the extremes related to G could be observed when looking at the air temperatures T_a in the air layer close to the ground (Table 2), which is right next to the energy exchange plain for short-wave solar radiation (the grass-covered earth surface), and

Table 1. Monthly mean values of global radiation G , atmospheric downward radiation A and terrestrial upward thermal radiation E [W/m^2] at Hartheim pine forest, period 1974–2000, and standard deviations of the individual monthly means about longterm monthly means

	J	F	M	A	M	J	J	A	S	O	N	D	
G	37	66	111	165	207	231	230	198	139	80	45	30	mean
	8	10	18	24	31	27	29	32	28	13	7	5	st dev
A	292	290	303	313	337	356	371	366	350	332	309	300	mean
	11	16	17	12	17	20	19	16	16	9	10	9	st dev
E	321	325	345	360	384	403	417	411	389	365	340	328	mean
	12	14	10	6	9	8	9	12	16	7	9	10	st dev
$A-E$	-29	-35	-42	-47	-47	-47	-46	-45	-39	-33	-31	-28	mean

Table 2. Monthly mean values of temperatures [$^{\circ}\text{C}$]: T_a screen temperature Bremgarten (1974–1998), T_c equivalent blackbody radiant temperature of the pine canopy (1974–2000) and T_{atm} equivalent blackbody radiant temperature of the atmosphere above the pine stand (1974–2000); standard deviations of the individual monthly means about the longterm monthly means

	J	F	M	A	M	J	J	A	S	O	N	D	
T_a	1.9	2.7	6.6	9.5	14.1	17.5	19.8	19.2	15.3	10.4	5.3	2.9	mean
	2.7	2.9	1.9	1.1	1.6	1.1	1.5	1.4	1.3	1.4	1.7	1.9	st dev
T_c	1.0	1.8	6.0	8.9	13.5	17.0	19.5	18.5	14.5	10.0	4.9	2.4	mean
	2.6	3.1	2.0	1.2	1.7	1.4	1.6	2.3	3.2	1.3	1.8	2.2	st dev
T_{atm}	-5.7	-6.4	-3.3	-1.1	4.3	8.0	10.7	10.1	6.8	3.2	-1.8	-3.7	mean
	2.8	4.1	3.9	2.6	3.6	4.1	4.2	3.1	3.2	2.0	2.4	2.2	st dev
T_a-T_c	0.9	0.9	0.6	0.6	0.6	0.5	0.3	0.7	0.8	0.4	0.4	0.5	
T_a-T_{atm}	7.6	9.1	9.9	10.6	9.8	9.5	9.1	9.1	8.5	7.2	7.1	6.6	

accordingly when looking at the equivalent blackbody temperature of the canopy T_c , which is similar to E .

It should be stressed that A (and in addition E and T_a) retains relatively high values in winter despite very low values of G . The reason for this is the divergence of the horizontal heat flux ∇F . We are able to estimate ∇F by means of the mean energy fluxes at the Hartheim pine forest (Kessler et al., 1988; Jaeger and Kessler, 1996) and of average earth radiation budget measurements from satellites (Ellis and Vonder Haar, 1976; Stephens et al., 1981; Kyle et al., 1990) (see Tables 3 and 4). High intensities of long-wave radiation flux A , and indirectly of E in January are supplied to a considerable extent by the advection of heat. The divergence ∇F shows a large positive value. The magnitude of $|\nabla F|$ is one decimal power higher than the magnitudes of the other energy budget components of the outer active layer of the pine stand. In July, we

Table 3. Radiation budget of the earth/atmosphere system and radiation and heat budget of the air column above the Hartheim pine forest [W/m^2]; OLR Outgoing long-wave radiation flux at the top of the atmosphere, NSR Net solar radiation flux at the top of the atmosphere, LWB Long-wave radiation budget of the atmospheric column, SWB Short-wave radiation budget of the atmospheric column, TB Heat budget due to turbulent heat fluxes of the atmospheric column, ∇F divergence of the horizontal heat flux of the atmospheric column

	OLR	NSR	LWB	SWB	TB	∇F
Jan	181	52	-152	20	13	119
Jul	237	297	-191	82	159	-50

observe export of heat from the air column. Its magnitude $|\nabla F|$, however, is less by a factor of more than two ($50 \text{ W}/\text{m}^2$).

Figure 1 shows the correlation of monthly values of the long-wave atmospheric radiation A and G and of A and E , for the period 1974 to 2000. It confirms the close relationship between the

Table 4. Energy budget of the outer active layer of the pine stand [W/m^2]

	Q	S + J	H	λV
Jan	3	5	17	-25
Jul	169	-5	-85	-79

long-wave fluxes. The correlation coefficient of the linear regression is $r=0.91$. Both fluxes G and A rise from winter to summer, but the correlation coefficient is considerably lower ($r=0.68$). Thus, the strong dependence of the long-wave fluxes on advection is confirmed indirectly. The poor correlation with G may be explained simply as follows: Advection of air-masses associated with high cloudiness N tends to heighten the level of long-wave radiation flux A and to reduce G . Conversely, advection of air-masses of equal temperature, under conditions of low cloudiness N , reduces A and simultaneously raises the level of global radiation G .

The relationship between A and certain properties of the air-mass is demonstrated in Fig. 2. We applied monthly mean values of the air-temperature T_a , water vapour pressure w and total cloud amount N from the nearby Bremgarten site from the years 1974 to 1991. With this data, monthly mean values of the long-wave atmospheric radiation A were estimated using Eq. 4

from 1974 to 1991. Linear regression between observation and calculation was $r=0.92$. We could further improve this very satisfying result if we were able to use data of precipitable water and temperatures of the air-column above the pine forest, which are unfortunately not available. This has already been mentioned by Keding (1989). He used formula 4 on an hourly basis at the Hartheim site.

4.2 Temperature values

The following points must be made before presenting comparisons of temperature values. Throughout the 27 years of observing and measuring air temperature T_a at the Bremgarten site (data from DWD) there were no changes in the distance between thermometer and main energy exchange plain (in this case the grass surface), nor in the plain of exchange itself. In contrast to that, the following changes occurred in the properties of the outer active layer of the pine stand. As the result of a growth in height by 10 m (Kessler and Jaeger, 1999), the main energy exchange surface rose to 14 m away from the soil surface. In 1974, the mean canopy height was 4 m above ground, in 1997 approximately 14 m. In that way the turnover of short-wave radiation ($G-R$) took place more and more in a continuously growing layer. Furthermore, the structure of the canopy and the

Fig. 1. Monthly mean values (period 1974–2000) of atmospheric downward long-wave radiation flux A vs. (1) terrestrial upward long-wave radiation flux of the Hartheim pine forest E , (2) global radiation; [W/m^2]

Fig. 2. Monthly mean values (period 1974–1991) of atmospheric downward long-wave radiation flux A , calculated vs. A measured; [W/m^2]

single trees changed. Moreover, the forest management carried out two thinnings during the observation period. In consequence we ought to observe changes in the warming rate at the surface of the canopy.

Long-term mean temperatures ($^{\circ}\text{C}$) are:

Air temperature at Bremgarten site $T_a = 10.4$,

Blackbody radiant temperature of the canopy $T_c = 9.8$ and

Equivalent temperature of the atmosphere above the pine stand $T_{\text{atm}} = 1.8$.

Unfortunately we have no precise information on the infrared emissivity ε of the canopy, nor on its changes during the 27 years of observation. Assuming ε to be 0.97, we yield a real equivalent radiant temperature of the pine canopy $T_{\text{rc}} = 12.0^{\circ}\text{C}$, which is 2.2 K higher than the equivalent blackbody radiant temperature of the canopy T_c and 1.6 K above the air temperature T_a , measured in the screen at a measuring level of 2 m over ground. The relations between the different temperatures T_{rg} (equivalent radiant temperature of the grass surface at Bremgarten), T_a , T_c and T_{rc} in our example here are hard to assess, because we have no long-term determination of the real equivalent radiant temperature of grass surfaces T_{rg} in Germany.

The close parallelism in the mean annual pattern of T_a and T_c is remarkable (Table 2 and Fig. 3). To enable a better comparison we added $+6\text{ K}$ to the T_{atm} -values before presenting them in Fig. 3. The annual pattern of T_{atm} makes clear the above mentioned temporal delay of its minimum

to the month of February and the delayed increase to its maximum in July. The cause is assumed to be the slower warming of the total air column above the pine stand in the first half-year compared to the temperature of the air layer close to the ground. Another reason is the asymmetrical annual pattern of the water vapour content close to the ground, which presents its minimum only by the end of February and the maximum in mid August (Kessler and Jaeger, 1994).

The high correlation between the air-temperature of the screen T_a and the equivalent blackbody radiant temperature of the canopy T_c based on monthly means is confirmed by the presentation in Fig. 4. The linear correlation has a correlation coefficient of $r = 0.98$. From the above, it may be concluded that the correlation between T_a and the equivalent blackbody radiant temperature of the atmosphere T_{atm} must be smaller ($r = 0.90$). This is clearly shown in Fig. 4. The relatively close interrelation between air temperature T_a and T_{atm} (or rather the long-wave atmospheric radiation A) has led to numerous formulae to estimate A using only air temperature (Sellers, 1965) and excluding other parameters, such as cloudiness, water vapour or precipitable water, or other gases.

4.3 Long-term trends

Possible long-term changes of the long-wave radiation fluxes (see Fig. 5 and Table 5) are of special interest in the context of the greenhouse discussion.

Fig. 3. Long-term monthly mean values of: T_a screen temperature Bremgarten (1974–1998); T_c equivalent blackbody radiant temperature of the pine canopy (1974–2000); T_{atm} equivalent blackbody radiant temperature of the atmosphere above the Hartheim pine stand (1974–2000); ($T_{atm} + 6$ K); T_{rc} equivalent real radiant temperature of the pine canopy (infrared emissivity $\varepsilon = 0.97$); [$^{\circ}\text{C}$]

Fig. 4. Monthly mean values (period 1974–1998) of screen temperature Bremgarten T_a vs. 1) equivalent blackbody radiant temperature of the atmosphere above the Hartheim pine stand T_{atm} , 2) equivalent blackbody radiant temperature of the pine canopy T_c ; [$^{\circ}\text{C}$]

We consider only night-time values of A and E (hourly values, when global radiation G equals zero ($G = 0$)), in order to minimise the influence of measuring errors. During daytime ($G > 0$, see Eqs. 5 and 6) calibration errors at the solarmeters influencing A and E (Philipona et al., 1995) could occur.

Linear regression yields the parameters in Table 5. All the temperature values show an increase from 1974 to 2000, which is certainly minimal and not significant. The development of T_c should be stressed. Considerable changes in the structure and geometry of the stand, the

growth of the trees and thinnings did not result in remarkable shifts in the relationship of air temperature T_a and the equivalent blackbody radiant temperature of the canopy T_c .

To demonstrate the influence of the heat advection on the long-wave atmospheric radiation A or T_c we present a comparison of the changes in wind direction and the equivalent blackbody radiant temperature of the canopy T_c at night in Fig. 6.

Describing changes of the atmospheric circulation, we used components of the resultant wind (monthly vectorial averages) at 500 hPa level of the nearest aerological station at Stuttgart

Fig. 5. Long-term variation of monthly mean values of screen temperature Bremgarten T_a , equivalent blackbody radiant temperature of the pine canopy T_c and equivalent blackbody radiant temperature of the atmosphere above the Hartheim pine stand T_{atm} ; [$^{\circ}\text{C}$]

Table 5. Linear regression coefficients $\{y = ax + b; x \text{ axis} - \text{time (monthly mean values 1974–2000), y axis} - \text{temperatures; correlation coefficients } r\}$; T_a screen temperature Bremgarten (1974–1998), T_c equivalent blackbody radiant temperature of the pine canopy (1974–2000) and T_{atm} equivalent blackbody radiant temperature of the atmosphere above the Hartheim pine stand (1974–2000)

	a	b	r
T_a	0.0037	9.87	0.048
T_c	0.0028	7.05	0.047
T_{atm}	0.0064	0.25	0.101

($48^{\circ} 50' \text{ N}$, $9^{\circ} 12' \text{ E}$) (data from NOAA). The values presented in Fig. 6 are 12-monthly running means of the original data sets from 1974 to 2000.

Wind direction ($270^{\circ} = \text{westerly wind}$) and canopy temperature T_c show long-term changes, frequently negatively correlated. A North-ward turn of the general air flow is associated with a decrease in temperature, a southward turn tends to increase temperature. The appropriate ranges are marked in Fig. 6. One should not expect

Fig. 6. Long-term variation of the wind direction at the 500 hPa level (resultant wind; $270^{\circ} = \text{W wind}$) at Stuttgart aerological station and of the equivalent blackbody radiant temperature of the pine canopy T_c at night [$^{\circ}\text{C}$]; 12-monthly running means

better agreement between wind direction as a determinant of the type of temperature and humidity advection and the magnitude of the long-wave fluxes. It would indeed prove an advection driven relationship, but it would also reduce the importance of the energy exchange processes at the outer active layer of the pine stand. As we have already shown, at the Hartheim site, it is the interannual changes of precipitation ΔP alone which relates directly to the annual magnitude of the turbulent latent energy flux $\Delta \lambda V$. This in turn controls the temperature of the energy exchange surface; as a consequence sudden alterations in the level of temperatures are possible.

Thus the long-term trend provides further confirmation of the dependence of the long-wave radiation fluxes on advection.

5. Conclusion

By analysing with a 27 year time series changes in atmospheric downward long-wave radiation flux A and upward terrestrial long-wave thermal radiation flux E above a pine forest in the southern Rhine valley plain, we have also investigated the changes of the important terms which influence A and E.

Two aspects seem to be particularly important.

- 1) There is no clear indication of a marked change in atmospheric downward longwave radiation flux A with time. Heat advection resulting from the general atmospheric circulation has a considerable influence on the magnitude of the long-wave fluxes both in annual patterns and longer periods of change. This is one of the reasons why the influence on A of the atmospheric CO₂-increase during the last quarter of the last century is not detectable. Even small changes in the direction of the general air movements can disguise the CO₂-influence perfectly. And such changes are absolutely normal in the west-wind drift at temperate latitudes. Thus, we have to conclude that the grid for monitoring long-wave fluxes has to be extended considerably. Only then is it possible to prove these kinds of effects directly.
- 2) We are not able to confirm the assumption that marked changes of the pine stand and its outer active layer by means of tree growth and forest management would influence considerably the

upward terrestrial long-wave thermal radiation. It may be that the growth of coniferous forests inhibits the upward trend in air temperatures which has been observed frequently at normal weather stations over recent decades. An inhibiting effect of this kind could also have affected the temperature level in the vicinity of the Hartheim pine forest, for air temperatures at the nearby Bremgarten climate station showed a similar pattern.

But what about changes in long-wave radiation fluxes above other slowly or unremarkably altering parts of the surface of the planet earth?

Long-wave radiation fluxes influence considerably the temperature of the earth's surface and the air temperature of the atmosphere near the ground. These effects deserve further study by analysing longer time series of air temperature in relation to the questions surrounding the anthropogenic greenhouse effect. Considerable changes in the properties of the earth's surface have taken place during the last 100 years not only in central Europe. Currently discussions tend to focus on the effects of urbanisation. Yet changes in land use and vegetation resulting from forest growth, forest clearing, changes in the cultivation of arable land etc. obviously have a greater influence because the extent of the areas affected is much more significant. Climate simulation also needs to take more account of these effects than has been the case hitherto.

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Authors' address: A. Kessler (e-mail: albrecht.kessler@meteo.uni-freiburg.de) and L. Jaeger, Meteorologisches Institut der Universität Freiburg, Werderring 10, D-79085 Freiburg i. Br., Federal Republic of Germany.