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Long-term changes in net radiation and its components
above a pine forest and a grass surface in Germany

LONG-TERM CHANGES IN NET RADIATION AND ITS COMPONENTS ABOVE A PINE FOREST AND A GRASS SURFACE IN GERMANY¹

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ABSTRACT

Long-term measurements (1974–1993 and 1996, respectively) of the net radiation (Q), global radiation (G), reflected global radiation (R), long-wave atmospheric radiation (A) and thermal radiation (E) of a pine forest in Southern Germany (index p) and of a grass surface in Northern Germany (index g) are compared. The influence of changes in surface properties is discussed. There are, in the case of the pine stand, forest growth and forest management and in the case of the grass surface, the shifting of the site from a climatic garden to a horizontal roof. Both series of radiant fluxes are analyzed with respect to the influences of the weather (cloudiness, heat advection). To eliminate the different influence of the solar radiation of the two sites, it is necessary to normalize by means of the global radiation G , yielding the radiation efficiency Q/G , the albedo $R/G = \alpha$ and the normalized long-wave net radiation $(A + E)/G$. Furthermore, the long-term mean values and the long-term trend of yearly mean values are discussed and, moreover, a comparison is made of individual monthly values. Q_p is twice as large as Q_g . The reason for this is the higher values of G and A above the pine forest and half values of α_p compared to α_g . E_p is only a little greater than E_g . The time series of the radiation fluxes show the following trends: Q_p declines continuously despite a slight increase of G_p . This is mainly due to the long-wave radiation fluxes. The net radiation of the grass surface Q_g shows noticeably lower values after the merging of the site. This phenomenon is also dominated by the long-wave radiation processes. Although the properties of both site surfaces alter, E_p and E_g remain relatively stable. A_p and A_g show a remarkable decrease however. The reason for this is to be found in a modification of the heat advection, showing a more pronounced impact on the more continentally exposed site (pine forest). Compared to α_g , α_p shows only a small variability. The changes of α_p can be easily explained as resulting from the influence on the albedo of alterations in cloudiness and the changes in the water storage in stand and soil produced by varying weather conditions. The influence of the forest management is only small and short-termed. α_g reacted with a leap on site merging, followed by a continuous drop. The drop of the grass surface albedo α_g on top of the observatory is probably related to the gradual development of the newly sown lawn there and the resultant change in the specific hydrological balance of the soil. A decreasing radiation efficiency Q/G at both sites is observed, which is principally due to an increase in $-(A + E)/G$.

The investigation discovered changes in the long-wave radiation processes. Its influence in Q should lead to more attention to the long-wave radiation processes in routine monitoring of radiation. Copyright © 1999 Royal Meteorological Society.

KEY WORDS: net radiation; grass surface; pine forest

1. INTRODUCTION

Net radiation Q is a specific property of any surface. It is dependent on the short-wave albedo of this surface α , on the long-wave radiation emissivity ϵ of the specific surface and its energy budget. The energy budget determines the surface temperature and consequently the long-wave emission. A particular influence is forced indirectly by the turbulent latent heat flux λV , which is dependent on the availability

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¹ Dedicated to Manfred Hendl, Berlin, on the occasion of his 65th birthday.

of soil water. In addition, surfaces with vegetation are capable of regulating their temperatures by active control of stomatal conductance and transpiration.

Routinely, measurements of net radiation and its components have been carried out in the world radiation network (Kessler, 1985a), only above the following:

- (i) grass surfaces in the common climatic gardens;
- (ii) low vegetation and above snow and ice surfaces in cold climatic regions;
- (iii) bare soil in dry regions and;
- (iv) a few oceanic locations by means of fixed weather ships.

Long-term measurements of Q above arable land, above shrub surfaces, coniferous and deciduous forests and above anthropogenically altered surfaces (streets, buildings, etc.) are lacking. All these surface types cover large areas of the solid earth surface and are not subject to routine monitoring. It would certainly be valuable from now on to install measuring devices for the net radiation and its components above the widely distributed types of terrestrial forests in addition to the existing monitoring above grass surfaces.

Forest canopies in particular differ from the other above mentioned surfaces. They change gradually and over long periods, because of their continuous growth, whereas the other surfaces present approximately similar conditions from year-to-year (the lawn of climatic gardens is mown frequently). Thus, we regret the lack of routine measurements of Q and its components above forest canopies, especially in the light of aspects and problems of Global Change.

The lack of measurements obstructs any validation of GCM results by means of observation (Garratt *et al.*, 1993). Recent classifications of the climate which also use the energy balance of the vegetation still use auxiliary parameters in general (Lauer *et al.*, 1996). Regional climatologies (like the regional volumes of World Survey of Climatology and Weischet, 1996) are still using climatic data predominantly which came from standard sites above grass surfaces. Thus, there exists a great need for energy and radiation balance data for individual surface types of the earth. The deficiency is particularly pronounced with regard to data of long-wave radiation fluxes, as already mentioned by Miller (1981) and Garratt and Prata (1996). Stanhill and Cohen (1997) recently showed by analyzing long-term time series of radiation measurements in the Antarctic that changes in surface temperature cannot be explained satisfactorily without data for the long-wave radiation components of Q .

The objective of this paper is to present results of radiation measurements which have been carried out continuously above a pine forest (*pinus silvestris*) (Kessler, 1985b; Keding, 1989; Lehn, 1991; Kessler and Jaeger, 1994; Jaeger and Kessler, 1996a). Trees grew *ca.* 8 m during the observation period (Figure 1). Thus, the components of the energy budget and the hydrological conditions changed. The authors have already presented a detailed report about that elsewhere (Jaeger and Kessler, 1996b).

The measurements above the pine forest were compared with the measurements above a grass surface, carried out simultaneously at the Hamburg observatory of the German Weather Service (Deutscher Wetterdienst, 1978, Met. Obs. Hamburg, 1978 ff). The measurements at Hamburg above a grass surface were conducted at two different locations, so that different heat and water balances caused an alteration of net radiation also.

2. MEASURING DEVICES, CALIBRATIONS, RADIATION REFERENCES, ERROR ANALYSIS

Both sites were equipped with measuring devices of the same type: pyranometers (solarimeters) of type Moll-Gorczyński CM6 and CM11, respectively (Hamburg), CM5 and CM6, respectively (Hartheim); net radiometer, type Schulze-Däke (Däke, 1972).

The net radiometer is ventilated. Each of the up- and downward-facing thermopiles is calibrated separately in the long-wave and in the short-wave range. Halldin and Lindroth (1992) pointed out the advantages of the Schulze-Däke radiometer compared to other net radiometers.

The quality of the measurements above the grass surface shows the high standard of a radiation observatory. The sensors exposed above the pine forest were changed every 1–3 years. Calibration of the

sensors above the Hamburg grass surface was done by the observatory itself. Calibration of the sensors used in Hartheim was performed either by the manufacturers (Kipp and Zonen, Delft/Netherlands and Dr. Lange, Berlin/Germany) or was kindly done by the observatory at Hamburg (Director Dr. F. Kasten). Thus optimal conditions for comparing both datasets can be assumed.

The long-term stability of the Kipp and Zonen solarimeters is satisfactory. A long-term variability of the CM6 sensor of 1% can be assumed (Fröhlich and London, 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). The Lange company in Berlin uses similar calibration routines to those of the Hamburg observatory. Thus, the data from the grass surface and the pine canopy are satisfactorily comparable in this respect. They are, so to speak, related to a similar relative reference level. Measuring accuracy of the long-wave radiation fluxes is assumed to be *ca.* 4% (Schmetz *et al.*, 1986; Keding, 1989).

All the radiation data, from both the pine and the grass surfaces reported here are related to the World Radiometric Reference, 1981 (WRR, 81).

3. NET RADIATION, ITS COMPONENTS AND THE ENERGY BALANCE

The net radiation equation is formulated as follows:

$$Q = Q_s + Q_l \quad (1)$$

$$Q_s = G + R \quad (2)$$

$$Q_l = A + E \quad (3)$$

with the following radiant flux densities in W m^{-2} . The direction of the radiant flux vectors is defined as positive if radiation energy is transported to the reference level (outer active layer of the pine stand and of the grass surface) and *vice versa*: Q is the net all-wave radiation; Q_s , the net short-wave radiation; Q_l , the net long-wave radiation; G the total downward solar radiation (global radiation) on the horizontal reference plane; R the reflected solar radiation (reflected global radiation); A is the downward atmo-

Figure 1. Development of the Hartheim pine forest. The triangles give the mean stand height, the solid line shows the stand density and indicates the thinnings

spheric long-wave radiation (counter radiation); and E is the total of the upward terrestrial long-wave thermal radiation and the atmospheric long-wave radiation reflected at the surface. However, this reflected amount is negligibly small.

Measurement of both components of Q_s is carried out directly as mentioned above. A was calculated as:

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

with $(G + A - \sigma T^4)$ being the signal output of the pyr radiometer (Schulze/Däke) 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:

$$E = (|R| + |E| - \sigma T^4) - |R| + \sigma T^4 \quad (5)$$

with, similar to A , the signal output in parentheses.

To describe the other energy flux terms, the following energy balance equation is used. The directions of all energy flux densities are defined in the same way as the radiant fluxes:

$$Q + (S + J) + H + \lambda V = 0 \quad (6)$$

with Q again the net radiation, S the soil heat flux, J the energy storage change in the stand (per unit of ground area), which is negligible in the case of the grass surface, H is the sensible turbulent heat flux into the atmosphere and *vice versa* and λV is the evaporative heat or turbulent latent heat flux, where λ is the latent heat of vaporization of water.

Indices of the letters denote the following: p, pine forest at Hartheim; and g, the grass surface at Hamburg.

4. THE EXPERIMENTAL SITES

4.1. The pine forest (*pinus sylvestris*)

4.1.1. The site. The experimental site is located in the lower part of the Upper Rhine valley near the village of Hartheim, 20 km southwest of Freiburg. Geographical coordinates are 47°56'N, 7°37'E, the altitude is 201 m above sea level. The area is a highly uniform flood plain. The approximate dimensions of the forest here are 10 km (north–south) and 1.5 km (east–west).

The site is considered to be an ideal place to conduct a radiation experiment. The view of the horizon is reduced by values of just less than 3°. It is fortunate that the data from the hourly monitoring of cloudiness at the Bremgarten Airbase (in the area until 1992, when the airport was closed) was available.

The radiation sensors were installed on a number of measuring towers. The thermopiles are always exposed *ca.* 2 m above the canopy. Comparing measurements taken at higher levels above the canopy did not yield any significant differences. Data recording was carried out by means of stripchart recorders during the first years of observation. Then two generations of process computers followed (Jaeger, 1980). Now the data are collected by means of data loggers.

In 1997, the trees (*pinus sylvestris*) were 38 years old. Figure 1 presents the development of the pine stand and the work of the forest management (stand density, solid line). The mean stand height (triangles) more than tripled from the beginning of the monitoring up to the present. The best-investigated biometrical dataset at Hartheim site consists of the mean stand heights. Eight pilot trees have been measured twice per year yielding the mean stand height. The forest management carried out three thinnings in the years 1970/1971, 1981/1982 and 1991/1992. The resulting stand density reductions are indicated by means of the solid line in Figure 1.

At the first thinning (1970/1971), every third row of the pine plantation was removed. The following thinnings can be characterized as light ground thinnings (1981/1982 and 1991/1992). Here the over-topped trees in the vicinity of the dominant elite trees (final crop trees) were cut. The maximum difference in height between the suppressed and the dominant trees is *ca.* 1 m. The impact of the forest management

Figure 2. Yearly means of soil temperature (— 40 cm) and of the equivalent blackbody temperature of the canopy of the pine forest at Hartheim

can be detected in the growth of the trees. In addition, the dry period at the end of the 1980s reduced the increase in height.

4.1.2. The climate. The climate of the central part of the southern Rhine rift valley is characterized by relatively high temperatures and low precipitation. The average yearly means (Bremgarten, Geophysical Service of the German Army, period 1951–1980) of temperature and precipitation are 9.8°C and 667 mm, respectively. Most precipitation is observed in the summer season as well as a minimum of cloudiness (Kessler and Jaeger, 1994). The number of days with more than 0.1 mm precipitation is 170. Further details of the regional climate can be found in Hendl (1966).

The temperature regime of the ecosystem *pine forest* shows a long-term change during the operation period as follows (Figure 2). The soil temperature increased slowly despite the fact that the growing stand progressively weakened the incoming short-wave radiation reaching the forest floor. Simultaneously, however, there was a smaller loss of long-wave radiation energy on the forest floor. The oscillations of the soil temperature are certainly a result of the changing weather which almost completely obscures the influence of the forest management. The equivalent blackbody temperature of the canopy,

$$T_c = (E/\sigma)^{0.25}, \quad (7)$$

shows no significant long-term trend in contrast to the soil temperature. This is remarkable, considering the fact that the distance between forest floor and canopy surface increased continuously. The variations of this curve are also affected mainly by the dynamics of the weather.

4.2. The grass surface

4.2.1. The site. The site of the measurements above the grass surface is situated in the lower plains of Northern Germany close to the sea. Reduction of the horizon is only slight. The station was installed at the Hamburg airport Fuhlsbüttel in a standard climatic garden till in December 1978 (53°38'N, 10°00'E, 14 m a.s.l.). In January 1979, the radiation measuring unit was merged with the grass topped flat roof of the Hamburg Observatory (DWD), 53°39'N, 10°07'E, 49 m a.s.l. Both positions are influenced by different heat and hydrological budgets. Thus, different radiation budgets must be taken into account.

4.2.2. The climate. The average yearly means of temperature and total precipitation (period 1961–1990) at Hamburg are 8.4°C and 770 mm, respectively. The amplitude of the yearly variation in temperature is smaller at Hamburg than at Hartheim due to the Hamburg's proximity to the coast. The influence of the

Table I. Average yearly mean values of daily means (W m^{-2}), S.D. (σ), highest and lowest yearly mean values (maximum, minimum) of: global radiation G , reflected global radiation R , atmospheric long-wave radiation A , upward thermal radiation E and net radiation Q of a grass surface at Hamburg and a pine forest at Hartheim, period 1974–1993

	Hamburg grass				Hartheim pine			
	Mean	σ	Maximum	Minimum	Mean	σ	Maximum	Minimum
G	107.6	6.8	123.6	99.9	131.5	9.6	144.7	112.7
R	−24.2	1.7	−27.1	−20.3	−13.3	1.4	−16.1	−11.0
A	322.2	11.9	349.3	308.9	327.9	10.2	346.8	306.9
E	−364.8	8.8	−385.1	−351.4	−365.9	3.7	−372.7	−356.4
Q	40.8	9.7	63.4	25.5	80.2	7.4	102.1	66.1

West European summer monsoon on the radiation caused by a higher amount of overcasting is more pronounced at Hamburg than at the more southerly and continentally situated site Hartheim. The yearly maximum of the global radiation G in the north is observed in general in May already and at the beginning of the month of June, before Hamburg is influenced by the monsoon. At Hartheim, in the south, the maximum occurs only in July (Kasten and Golchert, 1981; Kessler and Jaeger, 1994; de Bruin *et al.*, 1995).

5. RESULTS

5.1. Long term mean values of net radiation and its components

Tables I, II and III present the longtime mean values (1974–1993) of the months June and December as well as the yearly average. The mean albedo (α_m) is given by:

$$\alpha_m = \Sigma R / \Sigma G, \quad (8)$$

with ΣR and ΣG being the temporal integration of the radiant flux densities of R and G within the entire observation period yield the following values:

Site	June	December	Year
$\alpha_{m,p}$ Hartheim, pine forest	0.094	0.121	0.101
$\alpha_{m,g}$ Hamburg, grass surface	0.213	0.282	0.225

Table II. Average monthly mean values of daily means (W m^{-2}) for June, S.D. (σ), highest and lowest monthly mean values (maximum, minimum) of: global radiation G , reflected global radiation R , atmospheric long-wave radiation A , upward thermal radiation E and net radiation Q of a grass surface at Hamburg and a pine forest at Hartheim, period 1974–1993

	Hamburg grass				Hartheim pine			
	Mean	σ	Maximum	Minimum	Mean	σ	Maximum	Minimum
G	204.4	39.8	265.4	146.9	234.4	28.0	296.6	185.9
R	−43.5	8.8	−62.3	−29.7	−22.0	2.8	−26.7	−16.7
A	351.3	14.1	381.5	332.2	358.2	22.2	397.3	320.8
E	−404.9	14.5	−441.4	−381.0	−403.4	7.8	−424.3	−392.4
Q	107.3	24.9	160.0	66.0	167.2	19.2	217.9	130.1

Table III. Average monthly mean values of daily means (W m^{-2}) for December, S.D. (σ), highest and lowest monthly mean values (maximum, minimum) of: global radiation G , reflected global radiation R , atmospheric long-wave radiation A , upward thermal radiation E and net radiation Q of a grass surface at Hamburg and a pine forest at Hartheim, period 1974–1993

	Hamburg grass				Hartheim pine			
	Mean	σ	Maximum	Minimum	Mean	σ	Maximum	Minimum
G	15.2	2.9	21.6	9.6	31.6	4.2	40.9	24.3
R	−4.3	2.2	−11.5	−2.4	−3.8	0.8	−5.4	−2.3
A	302.0	15.5	338.9	262.5	294.9	5.8	303.1	286.0
E	−327.7	13.3	−355.2	−294.2	−323.0	10.8	−340.5	−308.0
Q	−14.8	6.6	−3.1	−31.3	−0.3	7.4	16.3	−14.0

The following facts in particular should be stressed:

- (i) the yearly net radiation Q above the pine forest is twice as much as above the grass surface. The reasons for this are the higher (by a value of 23.9 W m^{-2}) global radiation G_p of the more southerly and more continentally situated pine forest, a 5.7 W m^{-2} higher long-wave atmospheric radiation A_p of the atmosphere over the forest, which is 1.4 K warmer, the smaller (by an amount of 10.9 W m^{-2}) reflected short-wave radiation R_p of the pine forest which is due to an albedo, $\alpha_{m,p}$, half as big as that of the grass surface. With regard to the long-wave emission E , not much difference between the two surfaces can be detected. As expected, it is slightly higher from the pine forest. The annual mean of $(S + J)$ and its totals arrive more or less at zero (Jaeger and Kessler, 1997). Hence, the pine stand is able to invest twice as much energy into the total of $(H + \lambda V)_p$, according to Equation (6). This results in a double gain of turbulent energy fluxes to the atmosphere above the pine forest;
- (ii) the net radiation Q_p is almost zero in December. Furthermore, the pine forest shows a loss of water by evapotranspiration (Jaeger and Kessler, 1996a). The energy required must be provided by $(S + J)_p$ and H_p , which is a sensible heat flux directed downward from the atmosphere to the canopy surface. The energy loss of the grass surface caused by radiative processes is much greater in winter;
- (iii) the yearly variation, V_Y , (June minus December values) of all radiation fluxes, except R , is greater above the pine forest than the grass surface. V_Y of Q_p is 1.4 times greater than V_Y of Q_g . The reasons are principally the values of the global radiation G , which is less reduced by the cloudiness in June of the more continentally influenced south and the higher yearly oscillation of temperature there which affects A_p . V_Y of R yields $2.2 R_p = R_g$. The reason is the very small V_Y of $\alpha_{m,p}$, which is a result of the rough canopy surface of the pine forest, the higher southern solar elevations and the rare occurrence of a snow cover in Hartheim (Kessler, 1985b; Lehn, 1991).

5.2. Monthly values of net radiation, short-wave and long-wave net radiation

Figures 3–5 present the individual monthly values of Q , Q_s and Q_l of both times-series from the years 1974–1993. Firstly, it can be detected that the same facts about the mean yearly values can be recognized in the individual monthly values in general. The scattering indicates the influence of different weather at both stations in the individual months. Factors influencing these indefinite elements are the different cloudiness conditions and the different large scale heat advection (HA) at both sites. HA first of all influences Q_l . Regarding the dataset of the 240 monthly values, it can be seen that only with 1.3% $Q_p < Q_g$, with 2.1% $Q_{s,p} < Q_{s,g}$, but 39.6% $Q_{l,p} < Q_{l,g}$.

Figure 3. Comparison of monthly values of daily means of measured net radiation above a pine forest Q_p to the measured net radiation of a grass surface Q_g (1974–1993)

5.3. Trend of yearly values of net radiation and its components

During the period of operation the pine forest grew by 8–9 m. In 1981/1982 and 1991/1992 the forest management carried out thinnings. This should be taken into account when analyzing the trends of the radiation fluxes R_p and E_p directed upwards from the canopy. When interpreting the trend analysis of the grass surface it must be noted that, beginning at January 1979, the measurements were carried out on the grass covered flat roof of the observatory. This lawn only acquired its present deep root system and its consequently balanced water supply over a number of years, just as these were developed at the old site in the climatic garden over decades.

Figure 6 shows the trend of G_p , R_p and Q_p above the pine forest at Hartheim. The slight increase in G_p of *ca.* 11.5 W m^{-2} (daily mean) can be explained by a decreasing trend in cloud overcasting (see Figure 9), which amounts to *ca.* 0.5 eighths. The slight increase in R_p is due to the increase of G_p . The parallel

Figure 4. Comparison of monthly values of daily means of measured short-wave net radiation above a pine forest $Q_{s,p}$ to measured short-wave net radiation of a grass surface $Q_{s,g}$ (1974–1993)

Figure 5. Comparison of monthly values of daily means of measured long-wave net radiation above a pine forest $Q_{l,p}$ to measured long-wave net radiation of a grass surface $Q_{l,g}$ (1974–1993)

course of G_p and Q_p is obvious; admittedly, Q_p decreases slightly, which cannot be mainly a result of the short-wave radiation fluxes.

Except the G_g values of 1975 and 1976 (Figure 7), the negative trend of global radiation at Hamburg cannot be distinctly detected from 1974 to 1993 which is reported by Grabbe and Grassl (1994) and Liepert *et al.* (1994) for the period 1948–1988 (for further trend analyses of global radiation in Central Europe, see Baumgartner and Gietl (1975), Ohmura and Gilgen (1991) and Dirmhirn *et al.* (1992)).

The greater variability of R_g is discussed with the albedo below. The lower values of Q_g since 1979 must be attributed chiefly to the changes in the long-wave fluxes.

Long-term changes in the long-wave radiation fluxes are presented in Figure 8. E_p at Hartheim site (see also Figure 2) remains quasi-stable during the period of observation, despite the changes of the radiating medium pine forest. The amplitude of oscillation, *ca.* 11.5 W m^{-2} (daily mean), corresponds to the

Figure 6. Yearly values of daily means of measured net radiation Q_p , global radiation G_p and reflected global radiation R_p above a pine forest

Figure 7. Yearly values of daily means of measured net radiation Q_g , global radiation G_g and reflected global radiation R_g above a grass surface

temperature oscillation of a blackbody radiator of *ca.* 2 K. This agrees well with the observed changes in the yearly mean of the air temperature. Leaving aside again the exceptional years 1974–1976, the analysis of E_g of the grass surface in Hamburg bears similar results.

Both the long-wave atmospheric radiation A_p and A_g show a change on a higher level from 335.6 W m^{-2} in the early years to 318.3 W m^{-2} in the present. At the Hamburg site, the alteration is observed *ca.* 5 years earlier. A_p at Hartheim site was checked with respect to be a possible reduction in cloudiness. On the basis of radiation and cloud cover data during the individual months of 1974 values of atmospheric radiation for the following years were simulated ($A_{p,\text{sim}}$). With this, yearly values were calculated assuming only a changing influence of really observed cloudiness on the long-wave atmospheric radiation (Figure 9). $A_{p,\text{sim}}$ was computed by means of the following equation:

Figure 8. Yearly values of daily means of measured long-wave atmospheric radiation A_p and A_g and terrestrial long-wave thermal radiation E_p and E_g of a pine forest (p) and a grass surface (g)

Figure 9. Yearly mean values of the cloud cover at Hartheim, yearly values of daily means of measured long-wave atmospheric radiation A_p of the pine forest and simulated values $A_{p,sim}$ (see text)

$$A = A_o(1 + aC^b) \quad (9)$$

where A is atmospheric long-wave radiation depending on cloudiness; A_o , atmospheric long-wave radiation without cloud cover; C , cloudiness in tenths and $a = 0.153$, $b = 2.1826$ (following Keding, 1989).

Figure 9 indicates a slight decrease in long-wave atmospheric radiation due to a reduction in cloudiness. The oscillation of A_p is not parallel to $A_{p,sim}$ and is very much greater. The only reason can be found in temperature changes of the large scale advection of air masses. It is not possible to detect a different tropospheric aerosol load on A_p and A_g because of the lack of data. But it would be quantitatively in the range of the influence of cloudiness and cannot explain the observed changes in reality. An assumed increase of the CO_2 concentration and the measured increase of water vapour pressure by an amount of 1.5 hPa in the atmospheric surface layer at Hartheim during the period 1974–1993 resulted in an increase of atmospheric long-wave radiation. But its quantity is lower than the influence of changing cloudiness (Kessler and Jaeger, 1994).

5.4. Yearly values of the radiation efficiency, the short-wave albedo and the long-wave radiation budget normalized by means of the global radiation

Solar radiation is the forcing function of all the radiation and energy processes at the earth surface. Equation (1) is divided by G to obtain a better comparison between the measured values of both surface types. Thus, the differences in exposure and alterations of the solar radiation due to the weather are eliminated (Kessler, 1985a), yielding the following equation:

$$Q/G + \alpha_m - (A + E)/G = 1, \quad (10)$$

with Q/G , the radiation efficiency; $\alpha_m = -R/G$, the short-wave albedo; and $(A + E)/G$, the normalized long-wave radiation budget.

Equation (10) applied to the yearly values in Table I yields surface specific values, as per Table IV.

The high radiation efficiency of the pine forest Q_p/G_p , which is almost twice as great as Q_g/G_g of the grass surface is due to the low albedo and the relatively small specific energy loss caused by the long-wave radiation. The deeply differentiated surface of the pine forest is less heated by means of the short-wave insolation than the more plane grass surface despite the lower albedo. So it shows a smaller heat loss due to the long-wave emission E_p compared to the grass surface.

Table IV. Yearly mean values of the radiation efficiency Q/G , the short-wave albedo $-R/G = \alpha_m$ and the long-wave radiation budget normalized by means of the global radiation $-(A+E)/G$ and S.D.s, σ

Yearly mean values (1974–1993)	Pine forest, Hartheim	Grass surface, Hamburg
Q/G	0.610 $\sigma = \pm 0.055$	0.379 $\sigma = \pm 0.072$
α_m	0.101 $\sigma = \pm 0.009$	0.225 $\sigma = \pm 0.017$
$-(A+E)/G$	0.289 $\sigma = \pm 0.051$	0.396 $\sigma = \pm 0.062$

Furthermore, the relationship of the radiation efficiency to the normalized turbulent energy fluxes can be specified by means of the long-term measurements of the components of the energy budget Equation (6) at the Hartheim pine forest (Jaeger and Kessler, 1996b).

As the annual mean of $(S+J)$ approaches zero, it yields the simple relation from Equation (6):

$$Q/G + H/G + \lambda V/G = 0 \quad (11)$$

and combined with Equation (10):

$$-R/G - (A+E)/G - H/G - \lambda V/G = 1 \quad (12)$$

The long-term annual mean values (1974–1988) of the pine forest are: $Q/G = 0.62$, $H/G = -0.22$, $\lambda V/G = -0.40$, $R/G = -0.10$ and $(A+E)/G = -0.28$.

Looking at the normalized energy losses in Equation (12), it was found that the highest long-term mean value was the latent heat flux. Second position is taken by the loss through long-wave radiation processes. Therefore, more attention should be dedicated to this component in future investigations.

5.5. Trend of the yearly values of the radiation efficiency, the short-wave albedo and the long-wave radiation budget normalized by means of the global radiation

Earlier analyses at the Hartheim pine forest (Kessler, 1985b; Lehn, 1991) dealt with the dependence of the albedo on elevation of the sun, azimuth of the sun, cloud cover, soil moisture and geometries of the stand. The long-term trend is represented by Figure 10. The following characteristics should be stressed:

Figure 10. Yearly mean values of the albedo α of the pine forest and the grass surface

Figure 11. Yearly mean values of the radiation efficiency Q_p/G_p , the albedo R_p/G_p and the long-wave radiation budget, normalized by means of the global radiation $(E_p + A_p)/G_p$ of the pine forest

- (i) the albedo of the pine forest shows only small variations from year-to-year compared to the grass surface. The low values in 1988 and 1989 are not real, they are related to a gradual destabilization of one of the sensors. To demonstrate the influence of such effects, the erroneous values were not corrected. The values at the beginning, 1974–1977, are likewise not so reliable as the later values. The hourly values of G_p and R_p are the result of the processing of strip chart records during these years. So the variations from year to year are even smaller than indicated by the curve;
- (ii) thinnings carried out by the forest management during the years 1981/1982 and 1991/1992 caused only a short and very small decrease of the albedo;
- (iii) the statistical analysis produced a slight (but not significant ($r=0.177$) on the 95% level of significance) increase of the albedo. According to this, α_p rose only by 0.006 from 1974 to 1996. This is remarkable, given the strong growth of the forest during the observation period;
- (iv) an increasing of α_p can be due to several causes: e.g. the decrease in cloudiness (Figure 9 and Kessler, 1985b, his Figure 6) or a rising specific water consumption of the growing pine forest (Kessler, 1985b, Figures 6 and 7)

The big jump in the grass surface albedo α_g from 1978 to 1979 is the result of a movement of the site. The strong decreasing trend since then is best explained by the slowly developing newly seeded lawn on the flat roof top of the Hamburg observatory.

It should be stressed that the given situation of the grass surface is leading to a much greater dynamic in the development of the albedo compared with the slowly growing pine forest despite considerable changes in the tree canopies.

Both surface types show a decrease in the radiation efficiency Q/G during the 20- and 23-year observation periods, respectively (Figures 11 and 12). The bulk of this is caused by the long-wave radiation processes, as can be seen in the increasing incline of the $-(E + A)/G$ curves of the pine forest. The dislocation of the grass site produced a leap of the $-(E + A)/G$ value. The strong decreasing trend in the radiation efficiency of the pine forest observed during the first years until 1984 was weakened later. Above the grass surface, even a slight increase in Q_g/G_g , due to the decrease in the albedo α_g after the abrupt increase in 1979 is observed.

Figures 13 and 14 present the normalized long-wave radiation fluxes E_p/G_p , A_p/G_p , E_g/G_g and A_g/G_g . Here, a phenomenon in the longtime series can be recognized (see Figure 8 in addition), which is also valuable for other periods (daily and yearly pattern of E and A ; the case of Hartheim see Kessler and

Figure 12. Yearly mean values of the radiation efficiency Q_g/G_g , the albedo R_g/G_g and the long-wave radiation budget, normalized by means of the global radiation $(E_g + A_g)/G_g$ of the grass surface

Jaeger, 1994 and Czeplak *et al.*, 1995): a highly correlated parallel course of E and A and their derived terms. The reasons are known. E and A 's magnitude differ only slightly. They are present continuously, without interruption, at night or in winter and they are directed inversely. The result is a steady approximation of both fluxes in magnitude.

This assimilation process is disturbed most strongly by an advection of air masses of different enthalpy due to general atmospheric circulation. The consequence is stronger alterations at sites in more continental climatic situations (the climate at Hartheim is more continental) than at stations subject to maritime influence (e.g. Hamburg). This fact is confirmed by the curves at both sites in Figures 13 and 14.

Therefore the influence of changes in surface properties on the individual fluxes (Figures 13 and 14) shows no stronger impact than the changes in atmospheric circulation.

Figure 13. Yearly mean values of daily means of terrestrial long-wave thermal radiation E_p , atmospheric long-wave radiation A_p and long-wave radiation budget $(A_p + E_p)$, normalized by means of the global radiation G_p of the pine forest

Figure 14. Yearly mean values of daily means of terrestrial long-wave thermal radiation E_g , atmospheric long-wave radiation A_g and long-wave radiation budget ($A_g + E_g$), normalized by means of the global radiation G_g of the grass surface

6. CONCLUSION

At present, the question as to which effect on the long-term increase in $(E + A)/G$ over both surface types is unclear and may be attributable to either:

- (i) influences of atmospheric circulation on the atmospheric counter radiation of air masses with different enthalpy; or
- (ii) surface specific effects (with regard to the pine forest: forest management with thinnings 1981/1982 and 1991/1992 and the forest growth in particular; with regard to the grass surface: merging the site in 1979 and the long-term development of the lawn).

In general, more attention needs to be paid to the monitoring of the long-wave radiation fluxes of different types of surfaces and in different climatic regions than is the case at present. Furthermore these investigations have shown that it will take a long time before measurements at a single site can demonstrate the influence of increasing CO_2 concentration in the atmosphere on long-wave counter radiation A .

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