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Radiation balance over low-lying and mountainous areas in south-west Germany

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With 7 Figures

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Summary

Surface radiative fluxes play a major role in the energy exchange process between the atmosphere and earth surface and are thus very crucial to climatic processes within the atmospheric boundary layer. Based on four years REKLIP (REgio-KLIma-Project) data set of measured radiative fluxes and additional supporting meteorological variables, the surface radiation regime for selected lowland site (Bremgarten 212 m a.s.l.) and mountain sites (Geiersnest at 870 m a.s.l.; Feldberg 1489 m a.s.l.) in the southern Upper Rhine valley region (south-west Germany) has been reported. Time series of radiative fluxes and surface albedo showed significant inter-site differences. Possible reasons for the observed differences have been made. Downward atmospheric radiation A_l at the study sites was parameterised in terms of air temperature, vapour pressure and cloud amount, all of which strongly govern the variation of A_l. Effective terrestrial radiation amounted to about 50% of absorbed shortwave radiation at the study sites annually. During clear sky conditions, global solar irradiance G_s constituted about 76.0% of the incident extraterrestrial solar irradiance at Feldberg mountain site but only 68.5% of that at Bremgarten lowland site. Annual cumulative of net radiative flux R_n amounted to 1722 $\mathrm{MJm^{-2}\,yr^{-1}}$ at the lowland site, while that at Geiersnest and Feldberg mountain sites constituted 84% and 73% respectively of the corresponding magnitude for the lowland site. In the same vein, annual mean of radiation efficiency (defined here as R_n/G_s) amounted to 0.32 in Feldberg, 0.37 in Geiersnest and 0.41 in Bremgarten. Consequently the annual available energy, of which net radiative flux is representative, was smaller at the mountainous sites relative to the lowland site during the study period. Inter-annual variability of net radiative flux, its constituent variables and derivatives at the study sites were generally below 10%, with longwave fluxes showing the lowest fluctuation. This renders the measured data quite suitable for modelling purposes. In winter, mean daily sums of R_n showed a slow rise with cloud amount N at the lowland site but a sharp rise with N at Feldberg mountain site. In summer however, mean daily sums of R_n declined significantly with N as well as Linke turbidity factor at the study sites.

1. Introduction

The net radiative flux R_n, which is a measure of the energy available at the ground, is the main determinant of surface climate. It is the fundamental quantity of energy at the earth's surface to drive important processes like evaporation of moisture, heating of soil, emission of heat energy to the atmosphere through turbulent heat exchange as well as other energy-consuming processes such as photosynthesis. Consequently, information about the net radiative flux is required in advance dispersion models to estimate the flux of sensible heat which regulates the boundary layer evolution and in turn determines vertical mixing of air pollutants (Berkowicz et al., 1985; Wenzel et al., 1997). In addition, studies on thermally induced local and regional wind circulation, forecasting of early and late frosts, calculation of snow melting, forecasting of Indian summer monsoon, design of solar energy systems as well as studies on climate change all require adequate knowledge of the net radiative flux and its constituent variables (Garratt and Prata, 1996; Iziomon and Aro, 1998;

Colombo et al., 1999; Gupta et al., 1999; Prasad et al., 2000).

Radiation balance close to the earth's surface is represented by the geometric sum of both downward and upward components of shortwave R_{ns} and longwave R_{nl} radiative fluxes viz:

$$R_n = R_{ns} + R_{nl} = (G_s - R_s) + (A_l - R_l - E_l) \quad (1)$$

where G_s represents global solar irradiance, R_s denotes shortwave reflected irradiance, R_l is the longwave reflected radiation, A_l represents downward atmospheric radiation while E_l denotes the outgoing longwave radiation. In Eq. (1), fluxes directed towards the earth surface were assigned positive and those directed away from it negative (with subscript s implying shortwave and l longwave component). The radiation balance equation can be further reduced to

$$R_n = G_s(1 - a_s) - E_{eff} \quad (2)$$

where $E_{eff} = -R_{nl} = E_l + R_l - A_l$ defines the effective terrestrial radiation and $a_s = R_s/G_s$ the surface albedo. In particular, R_l is negligibly small (Kessler and Jaeger, 1999), being of the order of 3 to 5% for a vegetative surface (Linacre, 1992). To be able to compare radiative transfer over various locations and to minimise effects arising from different exposure and weather conditions (Kessler and Jaeger, 1999), Eq. (2) can be normalised by global radiation to give

$$\frac{R_n}{G_s} + a_s + \frac{E_{eff}}{G_s} = 1 \quad (3)$$

The quotients R_n/G_s and E_{eff}/G_s in Eq. (3) denote the radiation efficiency R_e and the normalised effective terrestrial radiation R_{elw} of a surface respectively.

Inspite of the profound climatic information that can be derived from sustained and uninterrupted measurements of net radiative flux and its components over a surface, long-term radiative fluxes data collected at standardised radiometric observatories situated on divers terrain are still sparse (Tovar et al., 1995; Filippova and Babich, 1995; Wilks, 1999). Most radiation measurement sites cover mainly valley or lowland areas (e.g. Kasten, 1977; Jegede, 1997; Kessler and Jaeger, 1994, 1999; Sauer et al., 1998), so that most information available is inevitably biased towards lower elevations (Barry, 1992; Prudhomme and Reed, 1999). Results from radiation budget investigations conducted on lowland areas may not strictly apply to mountainous areas, which generally present a different local climate. In general, lack of adequate observations on radiative fluxes has been a persistent problem in studies of land-surface processes and in the validation of GCM results (Garrat et al., 1993; Garrat, 1994; Rosset et al., 1997).

Furthermore, a number of past studies on cloud cover and atmospheric turbidity have been applied only to solar radiation (e.g. Sahsamanoglou et al., 1991; Liepert, 1997). There is still need to investigate the seasonal effect of cloud amount and atmospheric turbidity on net radiative flux particularly for high grounds for which literature materials are still somewhat scarce. Consequently the main thrust of the present study is to compare the surface radiation budget for selected low-lying and mountainous locations in the southern Upper Rhine valley region, while also examining the seasonal effect of atmospheric turbidity index and cloud amount on the net radiative flux.

2. Experimental sites and data base

The reference experimental sites considered in this study were configured and maintained by the Meteorological Institute of University of Freiburg, Germany within the framework of REKLIP (REgio-KLIma-Projekt) aimed at investigating spatial climatic conditions and energy balance variations in the middle and southern Upper Rhine valley region. The selected sites lie in south-west Germany and are located at Bremgarten (Br) (47° 54′35″ N, 7° 37′18″ E, 212 m a.s.l.) – in the Upper Rhine lowland area, Geiersnest (Ge) (47° 55′03″ N, 7° 51′16″ E, 870 m a.s.l.) – on the west downward outskirts of the German Black forest mountains and at Feldberg (Fe) (47° 52′31″ N, 8° 00′11″ E, 1489 m a.s.l.) – within the northern area of Black forest mountains summit. In view of their elevations, these study sites shall be alternatively referred to as lowland site (Bremgarten), intermediate mountain site (Geiersnest) and upper mountain site (Feldberg). Bremgarten is situated about 20 km south-west of Geiersnest while Feldberg lies approximately 13 km south-east of Geiersnest. The surface of the three experimental sites are grasslands.

Shortwave solar irradiance was measured by means of a horizontally positioned CM11 pyranometer (Kipp & Zonen, Delft, Netherlands) installed at 2 m above ground while shortwave reflected component was measured using another horizontally positioned downward-facing CM11 pyranometer (Kipp & Zonen, Delft, Netherlands) installed at 1.9 m above ground level. Total upward (TUR) and downward radiation (TDR) were measured by a horizontally positioned LXG055 pyrradiometer (B. Lange company, Berlin) installed at 2 m above ground. The instrument has four calibration factors associated with shortwave and longwave sensitivity of the upper and lower sensors. The difference between TDR and TUR amounts to R_n. Downward atmospheric radiation and outgoing longwave radiation were determined as:

$$A_l = b_{ul}U_u + \sigma \cdot T_c^4 - \frac{b_{ul}}{b_{us}} \cdot G_s \quad (4)$$

$$E_l = b_{dl}U_d + \sigma \cdot T_c^4 - \frac{b_{dl}}{b_{ds}} \cdot R_s \quad (5)$$

where U refers to the sensor signal in volts, b is the sensitivity of the sensors and T_c is the instrument temperature in K. The indices u and d represents the upper and downward sensors, while s and l represents the short and longwave radiation component respectively.

In addition, air temperature and humidity were measured by means of wet and dry bulb psychrometer system installed at 2 m above the surface. Precipitation was measured using ARG100 type Campbell scientific ombrometer installed at 1 m above the ground. Wind direction was measured using a W 200 type Campbell scientific wind vane. The wind vane was installed at 10 m above the surface. Horizontal wind speed at the three reference sites was measured by a Type A 100R Campbell Scientific anemometer installed at 10 m above the surface. After installation, all measuring instruments were regularly inspected and maintained in line with standard guidelines (WMO, 1993).

Data acquisition system was based on a Campbell Scientific 21X micro data logger with 10 s sampling rate and 10 min integration time. Hourly mean values were determined from the integrated values. Measurement at the sites extended from January 1991 to September 1996 in Bremgarten, from August 1991 to September 1996 in Geiersnest and from July 1991 to September 1996 in Feldberg. Due to incomplete data set for 1991 and 1996 at the three study sites, only data set covering 1992 to 1995 was used here. This time scale allows for a homogenous data set for the three sites under consideration. However, it is worth-mentioning that the data set for 1994 in Feldberg is only restricted to the second half of the year. This is owing to the storm-induced collapse of the measuring tower and the consequent lack of data from January to June 1994 for this mountain site. Plausibility checks and quality control (QC) of measured variables were carried out by setting fixed high/low bounds for data elements according to Meek and Hatfield (1994) and Xia (1999) among others.

In addition to all the above mentioned meteorological variables which were directly measured at the three experimental sites, data on cloud cover and visibility for Feldberg (covering the period from January 1991 to October 1994) as well as data on sunshine duration for Feldberg (January 1991–October 1994) and Bremgarten (January 1991–February 1995) were retrieved from the German Weather Service (DWD). Furthermore, hourly cloud cover data for Bremgarten extending from January 1991 to February 1993 was provided by the German Geophysical Consultant Services.

3. Weather condition during the study period

From the point of view of climatic characteristic, the southern Upper Rhine valley region lies in the transition area from maritime to continental climate thus possessing a relatively mild and moderately humid climate. During the study period (1992–1995), annual mean of air temperature T_a amounted to $10.8 \pm 0.7\,°C$ in Bremgarten, $8.2 \pm 0.7\,°C$ in Geiersnest and $4.4 \pm 0.1\,°C$ in Feldberg, while the corresponding annual mean values of vapour pressure e were 10.7 ± 0.6 hPa (Bremgarten), 9.1 ± 0.8 hPa (Geiersnest) and 7.4 ± 0.1 hPa (Feldberg). Annual mean specific humidity amounted to $6.6 \pm 0.4\,g\,kg^{-1}$ in Bremgarten, $6.4 \pm 0.6\,g\,kg^{-1}$ in Geiersnest and $5.4 \pm 0.1\,g\,kg^{-1}$ in Feldberg.

In addition, annual mean wind speed during the period of investigation constituted $3.5 \pm 0.1\,ms^{-1}$ in Bremgarten, $4.4 \pm 0.1\,ms^{-1}$ in Geiersnest and $6.7 \pm 0.3\,ms^{-1}$ in Feldberg, with the most frequent wind direction in the study area been south-west. Annual precipitation sum for the study area, which is strongly influenced by orography, amounted to $1573 \pm 166\,\mathrm{mm\,yr^{-1}}$ and $1444 \pm 321\,\mathrm{mm\,yr^{-1}}$ in Feldberg and Geiersnest respectively, while the corresponding annual precipitation in Bremgarten totalled $704 \pm 116\,\mathrm{mm\,yr^{-1}}$. Highest monthly mean relative sunshine duration (ratio of sunshine duration to day length), which was recorded in August, amounted to 62.5% (Bremgarten) and 58.5% (Feldberg), while the lowest monthly mean relative sunshine duration was recorded in November/December (Bremgarten) and October (Feldberg), being 16.5% (Bremgarten) and 27% (Feldberg).

4. Results and discussion

4.1 Diurnal variation of net radiative flux and its constituent variables in the study area

Mean diurnal variation of R_n and its constituent variables (G_s, a_s, A_l, E_l) for June (averaged over four years) at the study sites is presented in Fig. 1, while Table 1 presents the seasonal mean diurnal (hourly) maximum values of these parameters. Diurnal variation of radiative fluxes and albedo exhibited known courses at the study sites, howbeit with marked differences in the magnitude of these parameters from one site to the other. G_s exhibited a virtually smooth course reaching a maximum between noon and 13:00 hr (Central European Time – CET). This is apparently owing to solar elevation γ, the influence of which is more pronounced during clear sky condition. The relationship between hourly values of G_s ($\mathrm{Wm^{-2}}$) and γ (°) during clear sky conditions at the lowland (Br) and upper mountain site (Fe) sites can be approximated by

$$G_s(Br)/G_0 = 0.73 - 0.03/\sin\gamma \quad (6)$$

$$G_s(Fe)/G_0 = 0.80 - 0.01/\sin\gamma \quad (7)$$

where $G_0 = I_{SC}\sin\gamma$ is a normalising factor and I_{SC} denotes the solar constant ($1367\,\mathrm{Wm^{-2}}$). Given the same clear sky conditions and solar elevation, it is apparent from Eqs. (6) and (7) that solar radiation at the upper mountain site is higher than the lowland site. This observation is of relevance to solar energy technology, since sufficiently high amount of G_s is paramount to the high efficiency of solar energy devices. In particular, measured hourly G_s constituted 76% of extraterrestrial solar irradiance at the upper mountain site but only 68.5% of that at the lowland site during clear sky condition. This is presumably owing to higher atmospheric transparency over a mountainous location as well as the shorter pathlength of sun rays at higher altitude location. With general weather conditions, G_s showed significant inter-site differences from one season to the other (see Table 1).

Mean diurnal hourly values of a_s in June were generally of the order of 20% at the three locations. Generally during summer season, mean diurnal (hourly) minimum values of a_s was about 19% at the three sites, with the corresponding diurnal hourly maximum being (24% at the

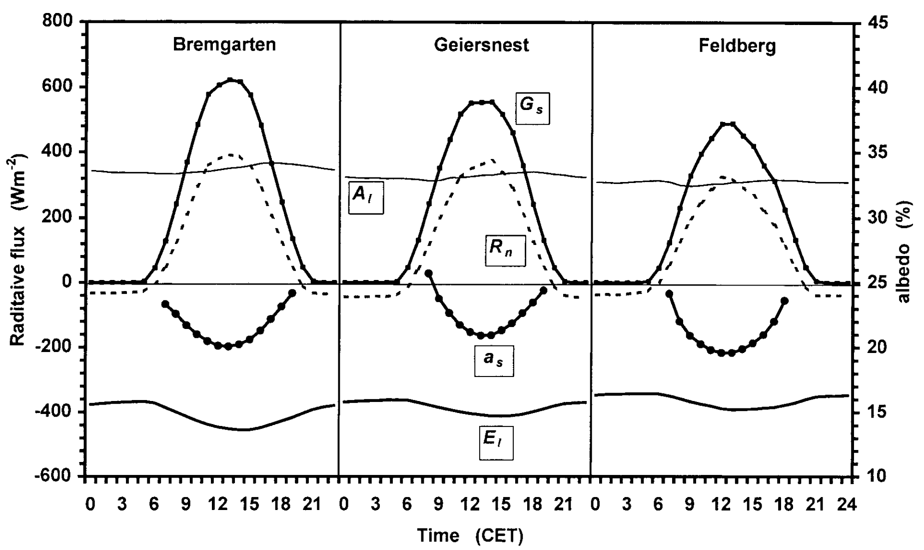

Fig. 1. Diurnal variation of short wave solar radiation G_s, surface albedo a_s, downward atmospheric radiation A_l, outgoing longwave radiation E_l and net radiative flux R_n for June at a lowland site (Bremgarten) and two mountain sites (Geiersnest and Feldberg) in southern upper Rhine Valley region (south-west Germany) averaged over four years (1992–1995)

Table 1. Mean seasonal diurnal (hourly) *maximum* values of solar radiation $G_{sh\,\max}$, albedo $a_{sh\,\max}$, downward atmospheric radiation $A_{lh\,\max}$, outgoing longwave radiation $E_{lh\,\max}$ and net radiative flux $R_{n_h\max}$ (1992–1995) at a lowland site (Bremgarten (Br)) and two mountain sites (Geiersnest (Ge) and Feldberg (Fe)) in southern Upper Rhine valley region and the intersite percentage of these quantities relative to Bremgarten (*rel. %. t. Br*)

Surface radiative fluxes (Wm^{-2}) and albedo (%)	Spring			Summer		
	Br	Ge	Fe	Br	Ge	Fe
$G_{sh\,\max}$	520	460	500	641	579	523
(*Rel. %. t. Br*)	100	88	96	100	90	82
$a_{sh\,\max}$	26	40	60	24	34	30
(*Rel. %. t. Br*)	100	154	231	100	142	125
$A_{lh\,\max}$	319	302	283	383	353	328
(*Rel. %. t. Br*)	100	95	89	100	92	86
$E_{lh\,\max}$	405	365	332	486	431	408
(*Rel. %. t. Br*)	100	90	82	100	89	84
$R_{n_h\max}$	311	247	181	395	379	340
(*Rel. %. t. Br*)	100	79	58	100	96	86
Surface radiative fluxes (Wm^{-2}) and albedo (%)	**Winter**			**Autumn**		
	Br	Ge	Fe	Br	Ge	Fe
$G_{sh\,\max}$	194	204	252	304	292	316
(*Rel. %. t. Br*)	100	105	130	100	96	104
$a_{sh\,\max}$	28	60	82	29	37	47
(*Rel. %. t. Br*)	100	214	293	100	128	162
$A_{lh\,\max}$	296	282	259	333	310	297
(*Rel. %. t. Br*)	100	95	88	100	93	89
$E_{lh\,\max}$	343	320	294	393	365	349
(*Rel. %. t. Br*)	100	93	86	100	93	89
$R_{n_h\max}$	94	74	54	170	160	167
(*Rel. %. t. Br*)	100	79	57	100	94	98

lowland site), 34% (at the intermediate mountain site) and 30% (at the upper mountain site). In winter, mean hourly values of a_s ranged from 23% to 28% at the lowland site, 38% to 60% at the intermediate mountain site and from 61% to 82% at the upper mountain site. This is supposedly as a result of the rise in snow cover occasioned by increasing elevation.

Diurnal variation of E_l exhibited marked asymmetry with a maximum at about 14:00 hr (CET) at the study sites essentially owing to a lapse in warming of the ground. The highest mean diurnal amplitude of E_l for June, which amounted to about 88 Wm^{-2}, was recorded at the lowland site, while the least (49 Wm^{-2}) was recorded at the upper mountain site. Greater magnitude of E_l obtained at the lowland site in comparison to the mountain sites could be partly attributed to the dryness of the top soil surface at the former which thus leads to higher surface temperatures. This supposition is supported by the observation of a major anticyclone continental characteristics with hot and dry weather and little convection during high and late summer particularly in the Upper Rhine plain (Czeplak et al., 1995).

Downward atmospheric radiation A_l showed a diurnal maximum between 16 and 17 hr CET for most of the months at the study sites, been mainly governed by the diurnal march of air temperature, vapour pressure and cloud cover N. Figure 2 presents the mean diurnal variation of T_a and e for June at the study sites. The small amplitude of T_a at the mountain sites relative to the lowland site could be attributed to higher wind speed at these locations which weakens warming process by day and cooling by night as well as greater cloudiness at these heights particularly during summer.

Aubinet (1994) and Crawford and Duchon (1999) have attempted to parameterise the downward atmospheric radiation in terms of clearness index (expressed as cloud fraction). However the limitation of such parameterization lies in the fact,

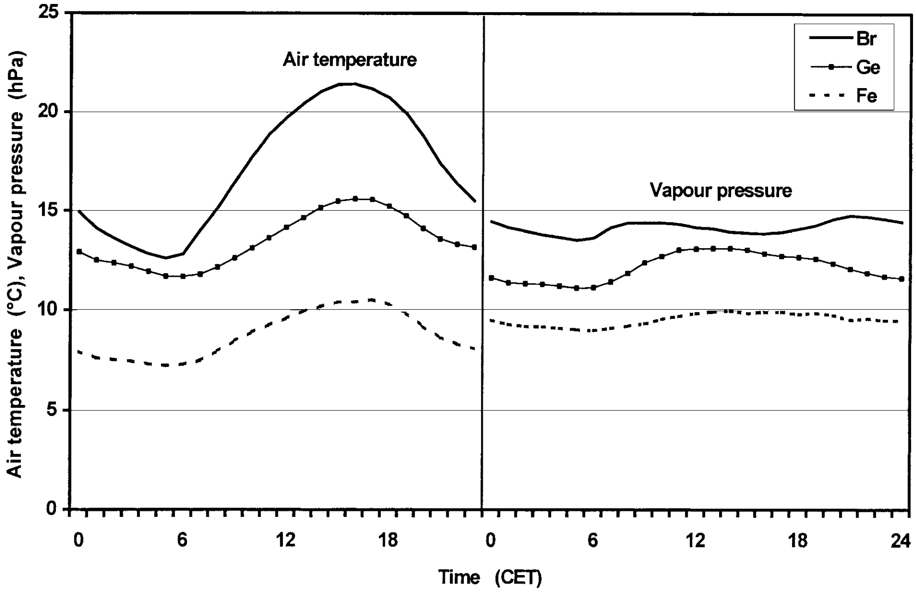

Fig. 2. Diurnal variation of air temperature and vapour pressure for June at a lowland site (Bremgarten) and two mountain sites (Geiersnest and Feldberg) in southern upper Rhine Valley region (south-west Germany) averaged over four years (1992–1995)

that they can only be used to estimate daytime downward atmospheric radiation or at best the mean daily downward atmospheric radiation. A better formulation should allow for the estimation of A_l during both day and night conditions. Consequently, the following relations for estimating hourly downward atmospheric radiation based on N (octal), e (hPa) and T_a (K) were obtained for the lowland site (Br) and the upper mountain site (Fe) with a root mean square error of 0.08 (Br) and 0.10 (Fe).

$$A_l(N, Br) = (0.582\sigma T^4 \cdot \sqrt[7]{e})(1 + 0.00238\,\mathrm{N}^2) \tag{8}$$

$$A_l(N, Fe) = (0.518\sigma T^4 \cdot \sqrt[7]{e})(1 + 0.00467\,\mathrm{N}^2) \tag{9}$$

From the commencement of dawn to the end of dusk, the diurnal course of net radiative flux followed that of G_s closely, as long as the short-wave albedo values are low and do not vary considerably. Mean summer diurnal (hourly) maximum of net radiative flux in the study area amounted to 395 Wm^{-2} in Bremgarten, 379 Wm^{-2} in Geiersnest and 340 Wm^{-2} in Feldberg, while the corresponding winter values constituted 24% (Bremgarten), 20% (Geiersnest), 16% (Feldberg) of the respective summer values. Mean hourly lower limits of night values of R_n for the winter month of January amounted to -33.6 Wm^{-2} (Bremgarten), -35.3 Wm^{-2} (Geiersnest) and -34.0 Wm^{-2} (Feldberg), while those for the summer month of June were -34.4 Wm^{-2}, -45.1 Wm^{-2} and -38.8 Wm^{-2} respectively.

4.2 *Running mean of radiative fluxes and albedo*

Figure 3 presents five days running mean of G_s, A_l, E_l, a_s and R_n for the study sites. Daily values of a_s were obtained as ratio of the daily totals of R_s to daily totals of G_s. Running mean of G_s and R_n attained their highest values between the 181$^{\mathrm{st}}$ and 183$^{\mathrm{rd}}$ calendar days (i.e. between the end of June and the beginning of July) at the study sites, with G_s varying more irregularly in spring than autumn. The sudden increase in the fluxes of G_s and R_n in April could probably be attributed to weather conditions with cyclonic character which often lead to Föhn in northern Alps area and the east side of the French Vosges (Hess and Brezowsky, 1977; Kessler and Jaeger, 1994; Czeplak et al., 1995). Through this Föhn effect, clouds in the lee side of the Vosges are broken up. This mainly south-west air flow is dissolved from an increasing meridional circulation, which leads to strong cloudiness at the northern side of the Alps.

Running means of A_l reached a peak between the 199$^{\mathrm{th}}$ and 202$^{\mathrm{nd}}$ calendar days (in mid July) at the study sites while E_l reached a peak value between the 218$^{\mathrm{th}}$ and 219$^{\mathrm{th}}$ calendar days (early August). Furthermore, running means of A_l showed an annual variability of 9.1% in Brem-

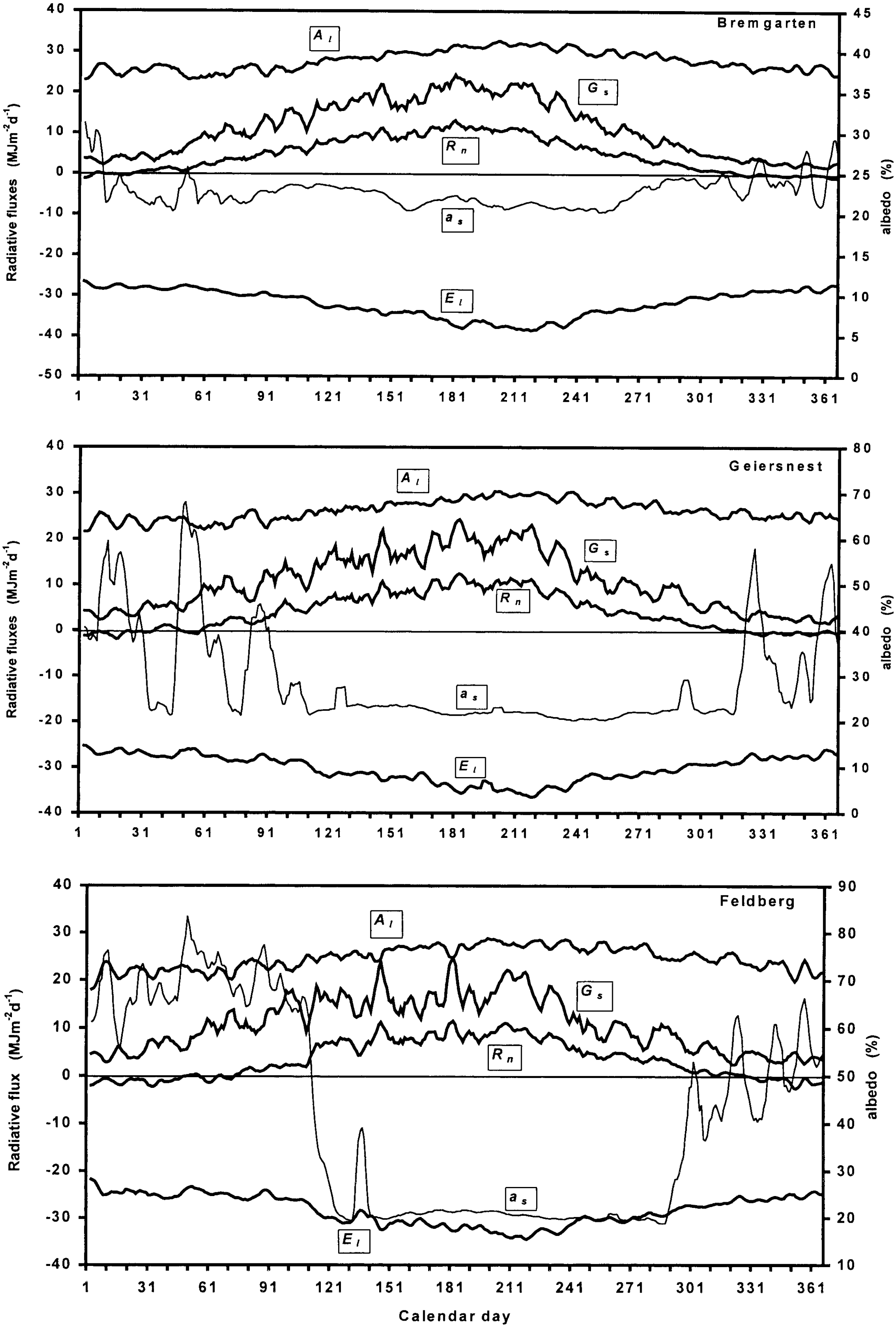

Fig. 3. Five days running mean of short wave solar radiation G_s, surface albedo a_s, downward atmospheric radiation A_l, outgoing longwave radiation E_l and net radiative flux R_n for a lowland site (Bremgarten) and two mountain sites (Geiersnest and Feldberg) in southern upper Rhine Valley region (1992–1995)

garten, 8.4% in Geiersnest and 9.7% in Feldberg, while those of E_l showed a variability of 10.6% (Bremgarten), 9.5% (Geiersnest) and 11.1% (Feldberg). Apart from relatively few days in autumn and early winter, running means of a_s for the lowland site showed an annual variability of about 9%.

4.3 Monthly mean of radiative fluxes and albedo at the study area

Figure 4 presents monthly mean of daily average of G_s, R_{ns} and R_n at the lowland site, as well as the inter-site difference in these parameters at the mountain sites relative to the lowland site. As indicated in Fig. 4, monthly mean values of G_s and R_{ns} are greatest at the lowland site and least at the upper mountain site from late spring till the end of summer period. The lower monthly mean values of G_s obtained at the mountain site at this time is mainly a consequence of convective cumulus clouds. Average monthly mean cloud amount at Feldberg during this period ranged from 54% to 70%. On the other hand, during autumn and winter months, the highest magnitude of monthly mean G_s was recorded at the upper mountain site and the least at the lowland site. The higher values of G_s recorded at the former during this period was basically owing to clear sky conditions and hence high clearness index. At the lowland site however, surface inversion, foggy conditions and stratus clouds gave rise to lower monthly mean G_s during autumn and winter months.

Monthly mean of R_n was negative from December to January at the lowland site, November to February at the intermediate mountain site and from December to February at the upper mountain site. Thus energy is lost from the Earth-atmosphere interface during this period at the study sites. The highest monthly mean of R_n amounted to 128 Wm^{-2} (Bremgarten), 123 Wm^{-2} (Geiersnest) and only 106 Wm^{-2} (Feldberg). Except for October and November, monthly mean magnitude of the daily average of R_n was greatest at the lowland site and least at the upper mountain site. The greatest inter-site difference in the monthly mean values of R_n and R_{ns} occurred in March while that for G_s occurred in June.

Monthly mean of a_s at the lowland as well as the inter-site difference in albedo at the mountain sites relative to the lowland site is presented in Fig. 5. From May to September, monthly mean of a_s was generally low at all three sites ranging from 19% to 24%. The low values of surface albedo at all locations during this period could be attributed to high solar height as well as soil moisture. From November to April, considerably high reflectance are recorded at the upper mountain site and to a lesser extent at the intermediate mountain site, mainly due to snow cover.

Monthly mean of E_{eff} attained a maximum in August (see Fig. 5) at all three locations due to considerable temperature difference between the ground and the atmosphere during this time. Compared to R_{ns}, E_{eff} showed only minor seasonal variations, being less than 50% of the corresponding monthly mean absorbed shortwave radiation

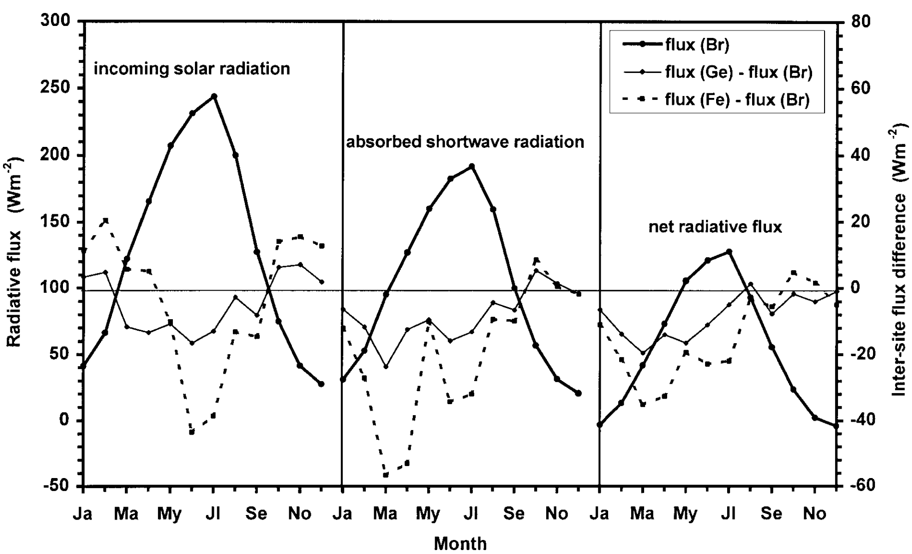

Fig. 4. Monthly mean of incoming solar radiation, absorbed shortwave radiation and net radiative flux at a lowland site (Bremgarten (Br)), as well as the inter-site difference in these parameters at two mountain sites (Geiersnest (Ge), Feldberg (Fe)) relative to the lowland site in southern Upper Rhine valley region (1992–1995)

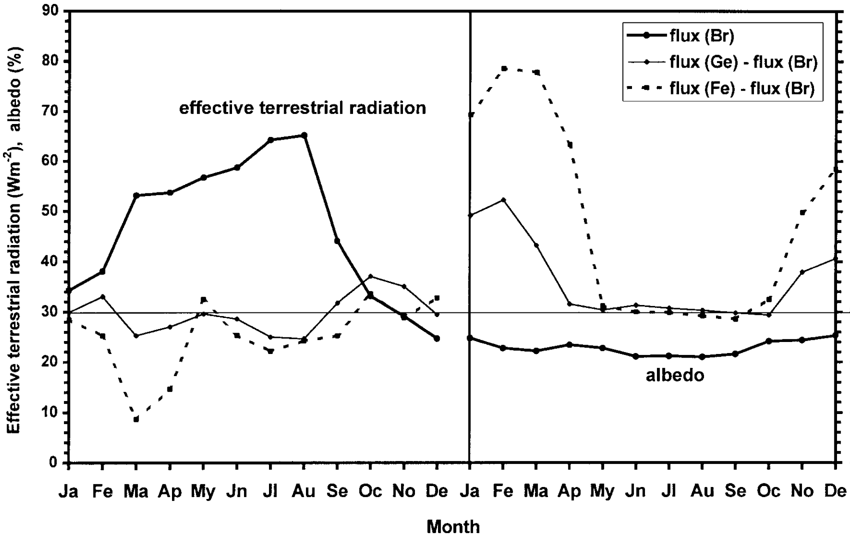

Fig. 5. Monthly mean of effective terrestrial radiation and surface albedo at a lowland site (Bremgarten (Br)), as well as the inter-site difference in these parameters at two mountain sites (Geiersnest (Ge) and Feldberg (Fe)) relative to the lowland site in southern Upper Rhine valley region (1992–1995)

from April to September. On an annual mean, E_{eff} constituted about 50% of the absorbed shortwave radiation R_{ns} at the three sites so that R_{ns} assumes a more dominant role in the overall surface radiation budget. Mean annual cumulative of daily sum of R_n for all three locations over 1992–1995 amounted to $1722\,\mathrm{MJm^{-2}\,d^{-1}}$ at the lowland site, while that at the mountain sites constituted approximately 84% (Geiersnest) and 73% (Feldberg) of the value for the lowland site.

4.4 *On radiation efficiency and normalised effective terrestrial radiation*

Figure 6 presents monthly mean of radiation efficiency and normalised effective terrestrial radiation at the study sites. R_e was about 0.5 at all sites for most of the summer period. The uniformity of monthly mean of R_e at all three sites for the summer months is most probably owing to the near-constant value of the surface albedo ($\approx 22\%$) during this period. However, R_e for lowland and mountain sites vary significantly from January to May. Low R_e in winter and autumn months are indications of reduced magnitude of available energy at the surface necessitated in part by shorter period of daylenght as well as higher reflection coefficient of the underlying surface (both of which lowers R_n significantly). Annual march of R_{elw} varied inversely as R_e. This can be attributed to the dominance of monthly mean of G_s over the effective terrestrial radiation. Mean R_{elw}, which ranged from 0.25 to about 0.30 from June to August at the study sites, attained

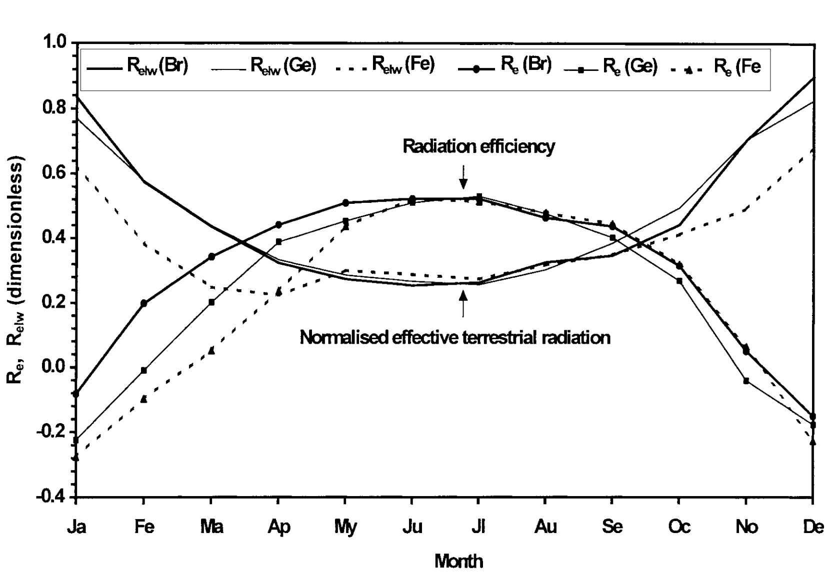

Fig. 6. Monthly mean of radiation efficiency R_e and normalised effective terrestrial radiation R_{elw} at a lowland site (Bremgarten) and two mountain sites (Geiersnest and Feldberg) in southern upper Rhine Valley region (1992–1995)

highest values in January and December when G_s reached its minimum. Annual mean of R_e over four years (1992–1995) amounted to 0.32 (Feldberg), 0.37 (Geiersnest) and 0.41 (Bremgarten) with a variability of 6.2%, 9.6% and 7.9% respectively. Similarly, annual mean R_{elw} amounted to 0.32 (Feldberg), 0.37 (Geiersnest) and 0.36 (Bremgarten) with a variability of 2.1%, 3.3% and 9.5% respectively.

4.5 Inter-annual variability of mean radiative fluxes and albedo

Annual mean and variability of radiative fluxes and albedo at the study sites from 1992 to 1995 are presented in Table 2. Annual mean values of radiative fluxes and albedo for Feldberg for the year 1994 was omitted in Table 2 (indicated by double asterisks) due to the incompleteness of data set for this particular year at the site (see section 2 above). Besides a_s and R_n for Feldberg, whose inter-annual variability exceeds 8%, the inter-annual variability of mean radiative fluxes and albedo was generally less than 7% within the study area. This implies that the year to year fluctuation of the fluxes were relatively small, a factor that is essential for the modelling of these parameters. In particular, mean longwave fluxes A_l and E_l exhibited the least inter-annual variability (being less than 2%) at the study sites.

4.6 Seasonal effects of cloud amount on net radiative flux

Figure 7 presents mean daily sums of R_n ($MJm^{-2}\,d^{-1}$) as function of cloud amount (octal) in winter and summer season for the lowland and upper mountain sites studied here. Daily sum of R_n declined with N during summer at the study sites. This is supposedly owing to the depleting effect of cloud on G_s. In winter however, R_n increased slightly with N at the valley site, but quite significantly at the mountain site. The increase in the daily sum of R_n with increasing N in winter at both sites could be attributed to the observed increase in A_l with N resulting from mostly warmer longer winter nights with cloudy conditions. This rise in A_l with N overcompensated the decline of G_s with N as well as the slight increase of E_l with N observed in winter at these sites.

Turbidity of air results from the absorption and scattering (extinction) of visible light by aerosols as well as various gases. Particulate, whose diameter is of the size range of 0.1 μm to about 1 μm are particularly significant in the extinction of visible radiation. Mean hourly net radiative flux declined with Linke's turbidity factor (estimated from hourly visibility data) in Feldberg during summer and winter seasons. With Linke turbidity factor rising in summer from 1.6 to about 4.1 at Feldberg, mean net radiative flux at high solar

Table 2. Annual mean and variability of radiative fluxes and albedo at a lowland site (Bremgarten (Br)) and two mountain sites (Geiersnest (Ge) and Feldberg (Fe)) in southern Upper Rhine valley region (south-west Germany)

Radiative fluxes (Wm^{-2}) and a (%)	Site	Year 1992	1993	1994	1995	1992–1995	Inter-annual variability (%)
G_s	Br	132.8	130.4	124.4	129.2	129.1 ± 3.5	2.7
	Ge	128.5	127.6	114.8	122.8	123.4 ± 6.2	5.1
	Fe	129.4	132.0	**	122.5	128.0 ± 4.8	3.8
a_s	Br	22.0	21.6	22.1	23.2	22.2 ± 0.7	3.2
	Ge	25.8	25.8	25.1	26.5	25.8 ± 0.6	2.3
	Fe	38.3	32.6	**	37.1	36.0 ± 3.0	8.3
A_l	Br	314.6	318.9	328.2	323.9	321.4 ± 5.9	1.8
	Ge	296.5	302.1	309.6	305.8	303.5 ± 5.6	1.8
	Fe	282.2	284.4	**	289.5	285.4 ± 3.7	1.3
E_l	Br	368.3	364.2	370.8	366.3	367.4 ± 2.8	0.8
	Ge	344.9	347.2	353.1	351.4	349.2 ± 3.8	1.1
	Fe	323.5	327.1	**	328.0	326.2 ± 2.3	0.7
R_n	Br	49.9	56.9	54.3	56.8	54.5 ± 3.2	5.9
	Ge	47.0	49.6	42.5	44.6	45.9 ± 3.0	6.6
	Fe	38.5	46.2	**	38.7	41.1 ± 4.4	10.7

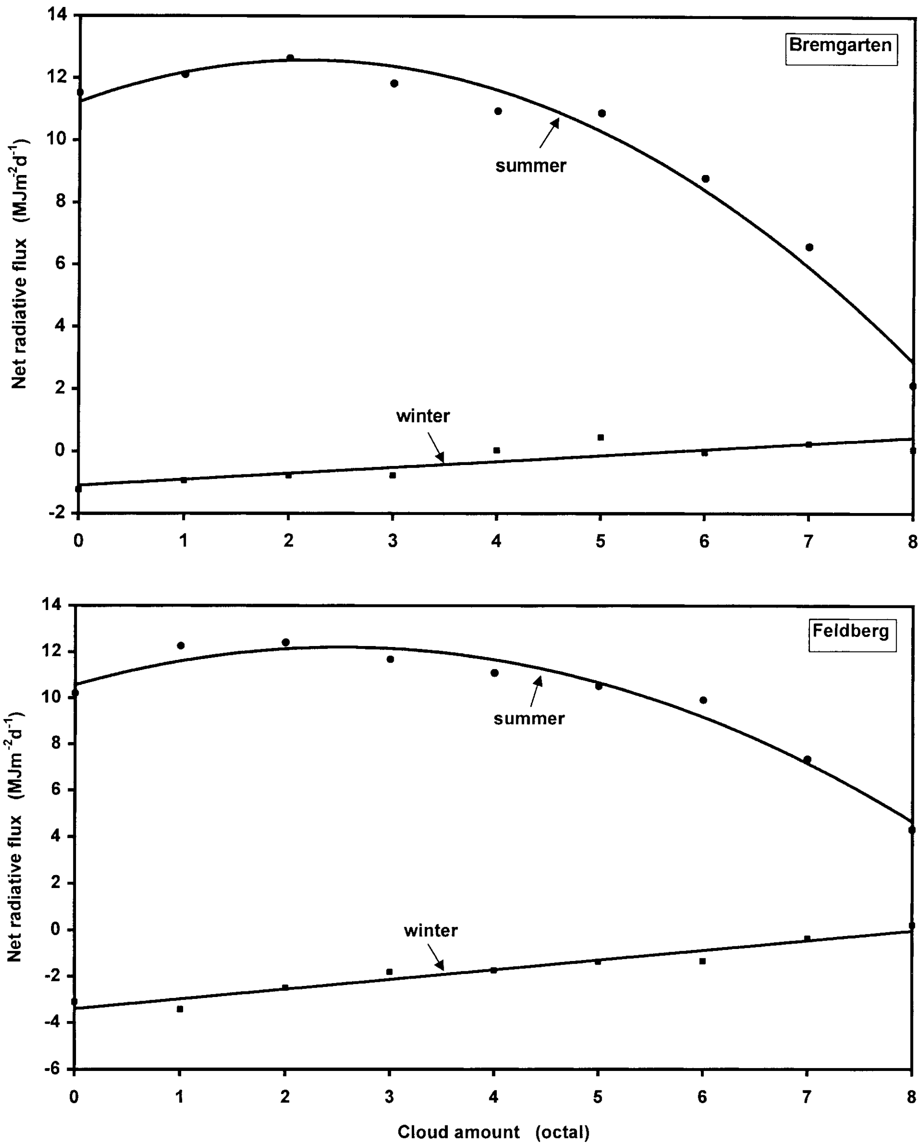

Fig. 7. Mean daily sum of net radiative flux as function of cloud amount in summer and winter for a lowland site (Bremgarten) and a mountain site (Feldberg) in southern upper Rhine Valley region (south-west Germany)

elevation (between 12 and 14 hrs (CET)) declined from 530.0 Wm^{-2} to 175.6 Wm^{-2}. Similarly in winter, for Linke turbidity factor ranging from 1.4 to about 2.5, mean net radiative flux (averaged between 12 and 14 hrs (CET)) dwindled from 92 Wm^{-2} to 28.5 Wm^{-2}.

5. Conclusion

Experimental measurement and investigation of radiative fluxes and albedo for regions with marked orographical features are still rare. In view of local conditions and phenomena (such as mountain cumulus, lenticular clouds, Föhn effect) pertinent to high grounds, surface radiation budget observed for lowland areas cannot be generalised. In addition to promoting the understanding of radiative processes in the atmospheric boundary layer, the investigation of the radiation budget of high grounds (in addition to lowland areas) is significant to the improvement of radiative transfer models. Although the time series of radiative fluxes and albedo for selected lowland and mountain sites examined in this study exhibit known courses, the seasonal inter-site difference in the magnitude of these parameters at one site relative to the other presents an interesting problem.

The fluctuation of annual mean values of radiative fluxes and surface albedo for the lowland site and the mountain site (Geiersnest) are satisfactorily low, being less than 7%. With this low variability, modelling of radiative parameters for these sites would be highly facilitated. For the upper mountain site (Feldberg: 1489 m a.s.l.) however, net radiative flux and albedo showed higher inter-annual variability amounting to 10.7% and 8.3% respectively. Annually, R_n was least at the upper mountain site and greatest at the lowland site. Since R_n is the governing parameter in the energy balance model, it should therefore be expected that the sum of sensible and latent heat fluxes would equally be lower at the upper mountain site relative to the valley site.

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