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Mean long-term surface energy balance components in Finland during the summertime

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The long-term, 1961–1990, mean summertime surface energy balance components in Finland were estimated by making use of earlier published studies for the estimation of the global radiation, surface albedo and latent heat flux. The net long-wave radiation was estimated with the help of synoptic cloud observations, and the sensible heat flux was calculated as the remainder in the energy balance equation. The results are presented both on a 10 km × 10 km grid and as climate-zone averages. The lowest values of global radiation, about 170 W m^{-2}, were found in north-eastern Lapland. There was also a local minimum of about 190 W m^{-2} over the Suomenselkä divide and southern Ostrobothnia. The maximum values of about 220 W m^{-2} were found along the coast of the Baltic Sea. The cooling of the surface due to net long-wave radiation was smallest in northern Lapland, about –35 W m^{-2}, elsewhere the spatial variation was very small, and the net long-wave radiation was from –40 to –45 W m^{-2}. The highest values of evaporation occured in southern Finland, where the latent heat flux was about –80 W m^{-2}, and the minimum in Lapland with a value of about –35 W m^{-2}. The highest sensible heat fluxes were located along the coast and in Lapland, and the smallest in the inland areas of southern Finland. The difference in the sensible heat flux between the climate zones was small.

Introduction

The surface energy balance is one of the key factors determining a particular area's climatological conditions. Complicated feedback mechanisms exist between the surface energy balance and the surface characteristics: the energy balance modifies the surface characteristics and vice versa. For example, the vegetation is dependent on the available energy, but on the other hand vegetation has an influence on the surface albedo and thus on the available energy. Sensitivity studies made with GCMs also indicate major surface influences on the atmospheric and hydrologic processes. The feedback between land-surface processes and the atmosphere is more complex than that over the oceans, and is still far from being fully understood (IPCC 1995).

Due to its importance, the estimation of the surface energy balance has long traditions. Dines

(1917) published the first realistic estimate of the earth's surface energy balance on a global scale. Budyko (1963) published the geographical and seasonal distribution of the energy balance components and his global energy balance atlas is still regarded as the standard work in this field. Ohmura and Gilgen (1993) continued the work of Budyko. Kiehl and Trenberth (1997) published a very recent estimate of the global energy balance, also utilising data obtained from satellites. Details on a scale of tens or a few hundreds of kilometres cannot all be depicted on global scale maps, and thus smaller-scale studies are also needed.

Energy balance studies at high latitudes were carried out by e.g. Ohmura (1982). He examined the energy balance on the arctic tundra, and compared the obtained values of energy balance components with results from other areas in the arctic and boreal forest regions. A recent study of the conditions over a boreal forest can be found e.g. in Grelle *et al.* (1997). They studied latent heat flux based on eddy-correlation measurements over a coniferous forest in Sweden.

Finnish scientists also have a long tradition in surface energy balance studies and, according to Brutsaert (1982), the Finnish scientist Hómen (1897) probably carried out the first quantitative and detailed analysis of the energy budget at the earth's surface. Hómen's work has been followed by that of several other scientists. Franssila (1936) analysed the energy balance of the earth's surface for a few days in the summer of 1934, Kulmala (1970) studied the energy balance for the summer of 1968 at Jokioinen Observatory in South-western Finland and Laitinen (1970) estimated the spatial and temporal variation of the surface energy balance over the whole of Finland. Virta (1971) studied the energy balance of Pääjärvi, a lake in southern Finland, and Elomaa (1977) and Elo (1994) continued his work. The spatial variation of the long-term mean global radiation in Finland was studied by Venäläinen and Heikinheimo (1997). Long-term mean values for the latent heat flux were published by Solantie and Ekholm (1984), and Hyvärinen *et al.* (1995). The surface albedo was investigated by Solantie (1988) who used a low-flying aircraft, and by Laine and Heikinheimo (1996) who used NOAA satellite data. Solantie (1990) studied the interaction between the atmosphere and the underlying surface and how surface characteristics affect local climate and also the surface energy balance.

In this study, estimates of long-term, 1961–1990, mean values for the summer-time surface energy balance components in Finland are presented. The results given here were obtained by combining the "best" estimates available for the different energy balance components. Values for global solar radiation are based on work by Venäläinen and Heikinheimo (1997), the albedo was obtained from Laine and Heikinheimo (1996), and the latent heat flux from Hyvärinen *et al.* (1995). The long-wave radiation balance was calculated with the help of synoptic cloud observations, and air temperature and air humidity measured at a height of two metres, while the sensible heat flux was then estimated as the remainder in the energy balance equation.

The values of the various energy balance components have been collected from several sources, and the accuracy of the estimates will vary from one component to another. This especially has an influence on the values of the sensible heat flux, as this is estimated as a residual term.

The purpose of this study is to increase our understanding of the spatial variation of the surface energy balance in the Boreal zone by providing some kind of "normal" values for these components. Hopefully these values can be used, for example, in the verification of atmospheric model results or in applications such as agriculture and forestry.

Material and methods

The surface energy balance is defined by the incoming solar global radiation (Rg), surface long-wave radiation balance (Rl), albedo (α), latent heat flux (LE), sensible heat flux (H) and the heat flux to/from the soil (G) (Eq. 1).

$$\mathrm{Rg}(1 - \alpha) + \mathrm{Rl} + \mathrm{LE} + H + G = 0 \quad (1)$$

The values for the various energy balance components presented here were collected from several sources. The results are presented both on a 10 km × 10 km grid, and as climate-zone averages. The quasi-latitudinal climate zones used here were defined by Solantie (1990) mainly on the basis of conditions during the vegetation period.

These climatic zones are based on the vegetational zones of Ahti *et al.* (1968). Climate-zone averages were calculated as an average of the grid-square values situated inside each of these zones.

Global radiation

Global radiation onto a 10 km × 10 km grid in Finland was analysed by Venäläinen and Heikinheimo (1997), who used both direct measurements of global radiation and indirect methods, i.e. measured sunshine hours and synoptic cloud observations. They used altogether 37 observing stations and the data was interpolated onto the grid using a kriging interpolation method. According to Venäläinen and Heikinheimo (1997), the accuracy of the global radiation in any randomly selected grid square can be expected to be better than 5 W m^{-2}, and as there was no bias in the estimates, the climate-zone average values can be expected to be even more accurate.

Venäläinen and Heikinheimo (1997) published global radiation values for January, April, July and October only. In this work the same method and data set is used for the calculation of summertime mean global radiation.

Surface albedo

The broadband surface albedo is defined as the ratio of the vertical component of the reflected radiation flux density to the incoming solar irradiance. A method for determining the surface albedo from routine daily NOAA AVHRR satellite data was described and tested for applicability under high latitude conditions in a boreal-subarctic region by Laine and Heikinheimo (1996).

The spatial resolution of AVHRR data is 1.1 km at the nadir. The spatial scale of the albedo images is however largely dependent on the relative positioning accuracy of individual images, determined to be on average about five pixels. The albedos initially calculated for each pixel were averaged spatially to minimise noise caused by the positioning error. In practice, spatial averaging was carried out over squares of 24 × 24 pixels giving a spatial scale of 700 km^2 at the satellite nadir. In this study, all parameters are presented on 10 km × 10 km grid squares, and the 24 km × 24 km albedo values were interpolated onto this finer grid. As a result of the study of Laine and Heikinheimo (1996), the July 1994 mean albedo as obtained from satellite data was available, and was used as the surface albedo in this study.

In the middle of summer, the albedo lay in the range of 15%–18% for agricultural areas mixed with patches of forest, 11%–13% for mainly forest-covered terrain, 15%–16% for open bogs, and about five percent for large lakes and sea areas. The monthly average of the albedo in July can be expected to represent the average albedo of the whole summer, because from June to August only small changes in the forest and crop leaf cover occur. The surface albedo as obtained from satellite data also correlates well with that obtained from surface classification. Compared with the Solantie (1988) measurements made from a low-flying aircraft, the satellite albedo was a little higher in southern Finland. July 1994 was warm and dry, and this may have caused early ripening of crops, which in turn could explain this difference. There have been some changes in the land characteristics over the period 1961–1990 that obviously have an influence on the albedo values. However, it is reasonable to expect that these changes have relatively little influence in the case of climate-zone averages, though conditions in some 10 km × 10 km grid squares may have changed.

In recent years satellite albedos for Finland have only been calculated occasionally. A one-month average value cannot fully describe the variation of surface albedo during the 30-year period but it is the best estimate available at the present time, and was therefore used in this study.

Latent and sensible heat fluxes

For estimation of the seasonal mean values of the latent heat fluxes over large areas such as river basins or climatological zones, the value can be estimated as a remainder term in the water balance equation. Hyvärinen *et al.* (1995) presented evaporation values basin-wise using the water balance equation for basins having the required precipitation and run-off data. For areas with insufficient data, the evaporation values were calculated with a help of a regression equation that was verified using the evaporation values obtained from areas where the use of the water balance method was possible. The regression equation was originally developed by Solantie (1974) and was also used by Solantie and Ekholm (1984). In the equation, the basin-wise evaporation (E_B) is calculated from

$$E_B = C_1X_1 + C_2X_2 + C_3X_3 + C_4X_4 + C_5X_5 + C_0 \quad (2)$$

where C_0–C_5 are empirical constants, X_1 is the basic evaporation from land areas and explained with the help of the temperature sum, X_2 is the influence of the amount of growing vegetation on evaporation i.e. the more growing trees there are in a forest the higher is the evaporation, X_3 is the reduction of evaporation due to shortage of available water i.e. on areas where the land surface evaporation was higher than the precipitation in July the evaporation was reduced, X_4 is the excess evaporation from wet peat-lands and X_5 the lake evaporation. A detailed description of how X_1–X_5 are defined is given in Hyvärinen *et al.* (1995).

Hyvärinen *et al.* (1995) estimated the mean error of corrected regional precipitation estimates to be about 15 mm/year, the accuracy of the run-off data being very good, with a mean error of only one or two mm/year. This leads one to the conclusion that the mean error in the evaporation estimate is between 15 and 20 mm/year for areas where precipitation and run-off data are available. An error of 15 mm/year for regional precipitation sum is rather low, but even if we assume that the error is double, the error in the evaporation sum would still remain below 50 mm/year. With a mean annual evaporation of about 400 mm, this error corresponds to an error of about 10%. Solantie and Ekholm (1984) estimated the accuracy of evaporation estimates that were based on the regression equation (Eq. 2), by comparing the evaporation values so obtained with values obtained from the water balance equation. In the case of the mean annual evaporation, the mean difference between the two estimates was two millimetres, with an RMS difference at river basin level of 18 mm.

Interpolation of the latent heat fluxes onto the 10 km × 10 km grid was done subjectively by taking into account the properties of the grid boxes. Interpolation is yet another error source, but as it was done by a very experienced climatologist, the climate-zone averages can be regarded as accurate, although for single 10 km × 10 km grid boxes the errors can be significant.

The weakness inherent in the latent heat estimates is that the formulae used by Hyvärinen *et al.* (1995) were empirical, and comparison with latent heat fluxes as obtained from a more physical approach would be of great interest. However, the estimates used here are the "best" estimates available at the moment.

The soil heat flux is significantly smaller than either the latent heat flux or the global radiation and thus the term (–Rg)(1– α) – LE – Rl in Eq. 1 describes most of the spatial variation of the sensible heat flux.

Long-wave radiation

The surface long-wave radiation balance (Rl) is dependent on the surface and air temperature, the cloudiness and the humidity of the air. Radiative cooling in cloudy and humid conditions is small compared with that in dry clear-sky conditions. Several expressions were published for estimation of the long-wave radiation balance. The formula for estimation of the net long-wave radiation under a clear sky (RL_{nc}) used in this study was adopted from Brutsaert (1982).

$$RL_{nc} = \varepsilon\sigma T^4(1.28(e/T)^{1/7} - 1) \quad (3)$$

where ε is the surface emissivity, σ is the Stefan-Boltzman-constant, and e and T are the water vapour pressure (hPa) and air temperature (Kelvins), respectively at a height of 2 metres. A constant value (0.98) was used for the surface emissivity. The influence of cloudiness was estimated using a widely-used formula that can be found in e.g. Sellers (1965) (Eq. 4).

$$Rl = RL_{nc}(1 - kn^2) \quad (4)$$

where k is an empirical constant whose value depends on cloud type, and n is the total cloudiness. According to Sellers (1965) k in the case of low and medium clouds is 0.85 and for high clouds 0.25.

Values for the long-wave radiation balance were calculated for the same 37 stations that were used for the estimation of global radiation. Calculations were based on all synoptic observations made at those stations during the summer months of 1961–1990. The interpolation onto the grid was

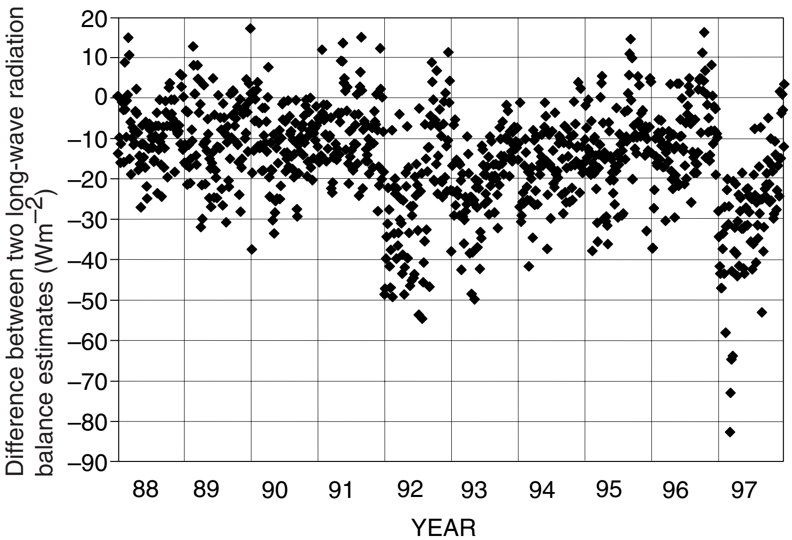

Fig. 1. The difference between two different net long-wave radiation estimates. The first estimate is based on measurements of downward and reflected short-wave radiation and net radiation while the other estimate is based on the parameterization by Brutsaert (1982) utilising synoptic cloud observations and air temperature and humidity measurements. The plotted values are 1988–1997 June–August daily mean values (measurements — Brutsaert parametrization) for Jokioinen Observatory (60°49´N, 23°30´E, W m^{-2}).

done using the same kriging method that was used in the case of global radiation.

An estimate of the long-wave radiation balance can be obtained as a residual term for stations measuring the components of short-wave radiation (downward and reflected) and the overall radiation balance. Ten years (1988–1997) of daily June–August radiation data were used to calculate net long-wave radiation values for Jokioinen Observatory (60°49´N, 23°30´E), and these values were compared with estimates of the long-wave radiation balance as obtained from the parameterization.

According to this comparison, the parameterization was able to predict the day-to-day variation in the long-wave radiation balance and the correlation between the estimated and parameterized values was 0.97, the standard error of the estimate being 10.9 W m^{-2}. Unfortunately, the parameterization underestimated the radiative cooling. The mean estimate based on measurements was 58 W m^{-2}, while that based on the parameterization was 43 W m^{-2}.

The estimate of long-wave balance based on measurements of global, reflected and net radiation may have systematic errors too, because the measurement of the radiation balance is especially problematic, the accuracy of these measurements being estimated to be about 10% (L. Laitinen pers. comm.). One can assume that the cloud observations were made similarly during the whole verification period, so that the parameterized long-wave radiation values are comparable between the different years; a time series of the difference between the two different estimates for the long-wave radiation balance then shows, how radiation measurements changed during the period studied (Fig. 1). During 1988–1991, the difference between the values of long-wave radiation balance obtained with two different methods was on average about 10 W m^{-2}. In 1992, the difference suddenly increased to about 35–40 W m^{-2}. From 1993 until 1996, the difference was again about 10 W m^{-2}, but in 1997 the difference increased to about 30 W m^{-2}. In 1992, the net pyrradiometer used for measuring the radiation balance at Jokioinen was adjusted by eight percent, and in 1993 it was renewed. This may explain some of the sudden changes in the difference seen in Fig. 1. Beside difficulties in net radiation measurements, changes in surface characteristics also influence reflected radiation and thus also the estimated long-wave radiation balance.

According to this small verification, the parameterized radiative cooling due to net long-wave radiation is too small, with the difference being about 10 W m^{-2} if only the "stable" years, when there were obviously no major changes in measuring conditions, are considered. If all years are taken into account then the difference is about 15 W m^{-2}. Even if the values of the long-wave radiation balance obtained from the parameterization

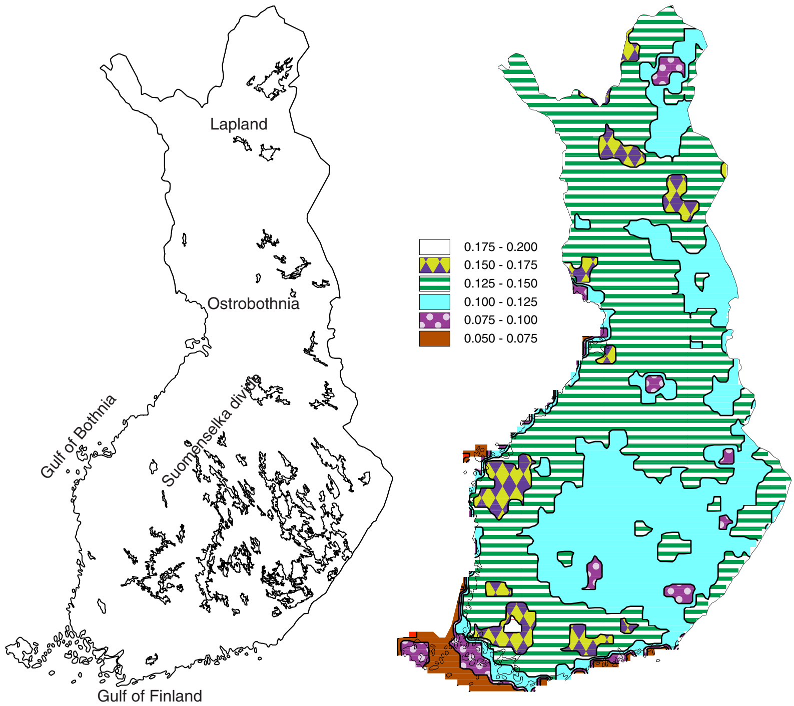

Fig. 2. Inland waters and surface albedo in Finland. The albedo is based on NOAA AVHRR data (Laine & Heikinheimo, 1996). The data was collected in July 1994.

were not exactly correct, the spatial variation could be obtained from the values calculated using this method, as the same formula was used for all stations. One also has to remember that surface characteristics, such as the emissivity of the surface, influence long-wave balance but were not taken into account. Thus the values given describe the spatial variation in the long-wave radiation balance brought about by the spatial variations in cloudiness, air temperature and air humidity.

Results and discussion

The differences between the characteristics of land and water covered surfaces can be seen in the surface albedo values (Fig. 2). In Fig. 2, the largest lakes can be seen as areas of smaller albedo. The highest albedo values in southern and western Finland are due to the large areal proportion of agricultural land. Fig. 2 also shows the location of the districts whose names are used later in the text.

The lowest values of global radiation were found in north-eastern Lapland and over the Suomenselka divide and southern Ostrobothnia (Fig. 3). The maximum values occured along the coast of the Baltic Sea, and in south-eastern Finland. The longitudinal variation in global radiation was caused by the variation in cloudiness. Convective clouds in particular tend not to be formed over cold water surfaces and thus the coastal regions are regions of negative anomaly in cloudiness. The large number of lakes in eastern Finland may also be a factor causing less cloudiness and higher radiation values there. On the other hand a local area of negative anomaly in global radiation was situated over the Suomenselkä water divide region, which is characterised by a large number of bogs. These are poor heat conductors, and may intensify the sensible heat flux, and thus also the formation of convective clouds.

The cooling of the surface due to net long-wave radiation was smallest in northern Lapland (Fig. 3; the energy flux tending to cool the surface is shown as negative). Elsewhere the spatial variation was very small. The total cloudiness in Lapland had higher values than in areas further south (e.g. Kolkki 1969). Cold air outbreaks from the Barents Sea associated with thick stratocumulus clouds occur frequently in Lapland also during the summer, and this is one explanation for the smaller values of radiation cooling in Lapland.

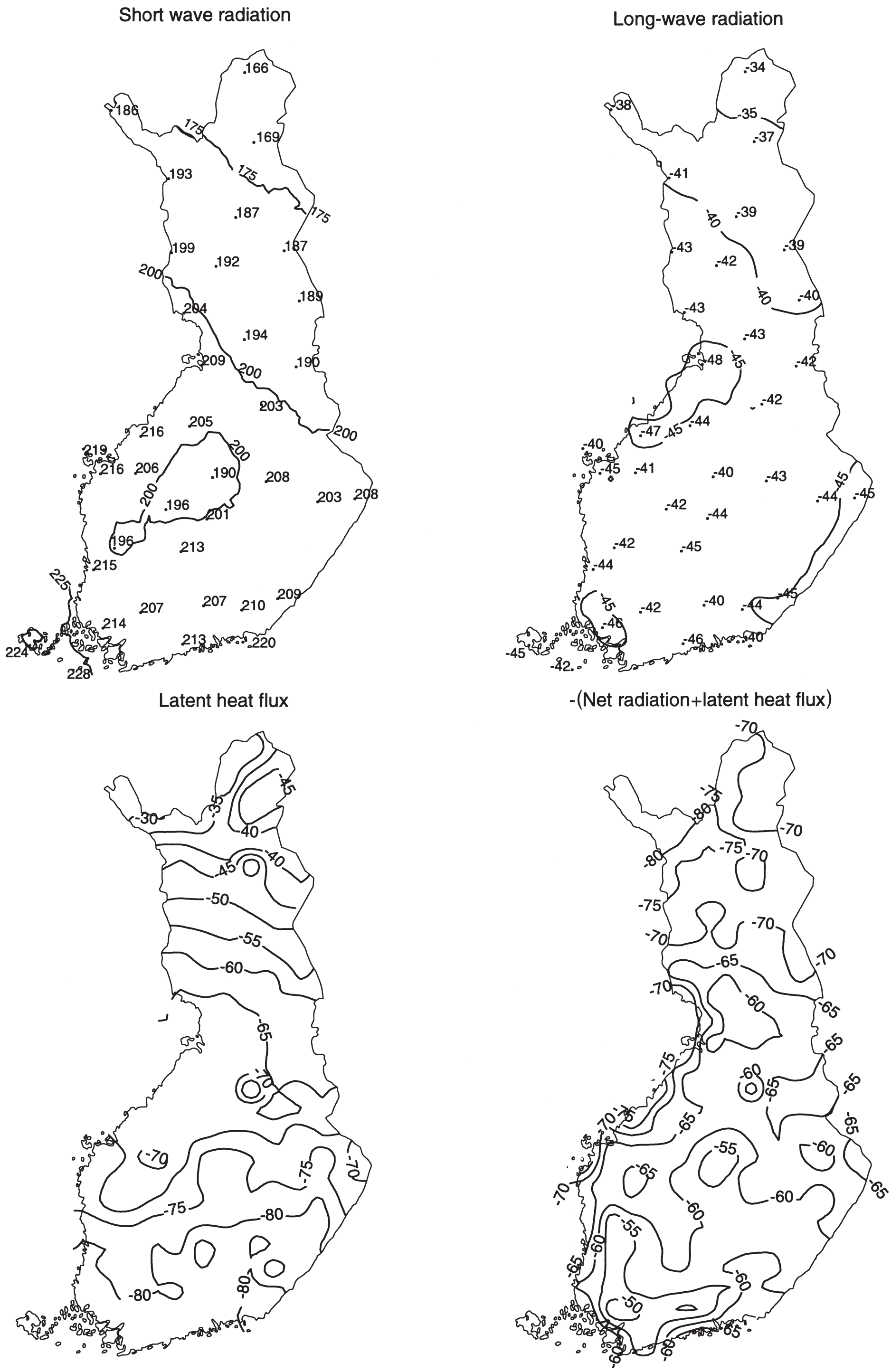

Fig. 3. The spatial variation of summertime (June–August) long-term (1961–1990) mean values of the surface energy balance components in Finland. Global radiation values were obtained from Venäläinen and Heikinheimo (1997), the latent heat flux from Hyvärinen *et al.* (1995), and the surface albedo from Laine and Heikinheimo (1996). The long-wave radiation balance was calculated with the help of synoptic cloud observations. Fluxes that tend to warm the surface are positive. The unit is W m^{-2}.

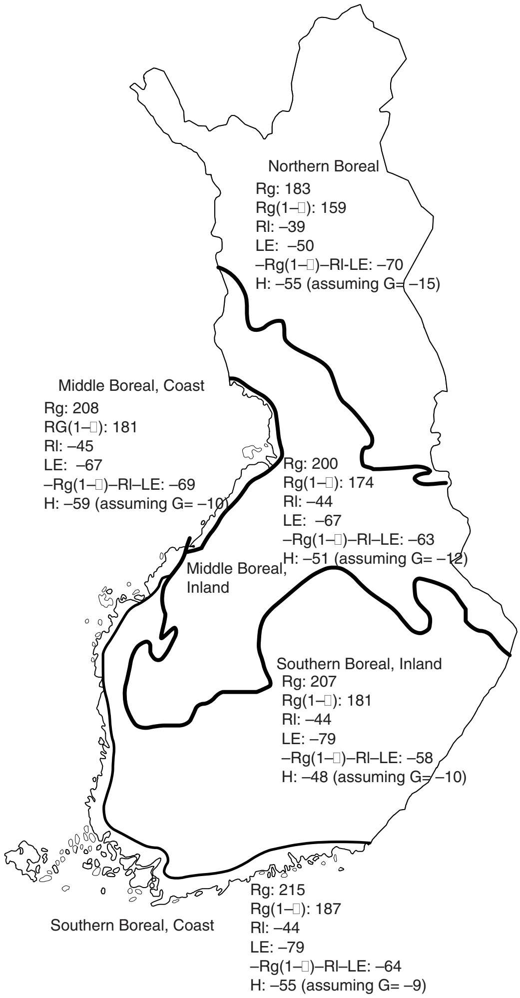

Fig. 4. The summertime (June–August) long-term (1961–1990) mean values of the surface energy balance components in Finland given as climate-zone averages. Global radiation (Rg) values were obtained from Venäläinen and Heikinheimo (1997), the latent heat flux (LE) from Hyvärinen *et al.* (1995), and the surface albedo (α) from Laine and Heikinheimo (1996). The long-wave radiation balance (Rl) was calculated with the help of synoptic cloud observations and the sensible heat flux was calculated as a residual term in the energy balance equation, and the ground heat flux (*G*) is from Laitinen (1970). Fluxes that tend to warm the surface are positive. The unit is W m^{-2}.

Maximum values of latent heat flux of about 80 W m^{-2} were found in southern Finland and a minimum of about 35 W m^{-2} in Lapland (Fig. 3). Large lakes can be distinguished as local maxima.

The spatial variation of the sensible heat flux was calculated as the remainder of the other energy balance components (Fig. 3). Because the soil heat flux was not included in the calculation, the values given in Fig. 3 are not exactly the sensible heat flux but are too high. According to Laitinen (1970), the average soil heat flux during the summer months is between –9 W m^{-2} in southern Finland and –15 W m^{-2} in Lapland. In northern Finland, the energy consumption was higher due to soil frost at the beginning of summer. The upward sensible heat fluxes were thus about that much smaller than those given in the figure. However, most of the spatial variation of the sensible heat flux can be seen in the figure. The highest upward fluxes can be found in Lapland and smallest in South-western Finland. Coastal areas could be distinguished as areas of higher sensible heat fluxes compared with nearby inland regions. If the soil heat fluxes are taken into account, the difference between southern and northern Finland becomes smaller.

The energy balance components were also calculated as climatological zone averages (Fig. 4). In the middle and northern Boreal zones, the characteristic vegetation is xeromorfic or xerophilous even at wet sites. On the other hand, coniferous forests that have high transpiration rates are rarer than in the southern Boreal zone. This can be seen as a result of the interaction between vegetation and climate (Solantie 1990). As a result of surface characteristics the northern Boreal zone is slightly more effective in producing sensible heat than inland areas of the middle and southern Boreal.

The sensible heat flux in coastal areas is higher than inland because the cold sea inhibits the formation of convective clouds. The large values of available solar radiation lead to correspondingly large values of sensible heat flux that compensate the unfavourable effect the cold sea has on vegetation. Due to the large sensible heat fluxes, the air warms rapidly when brought inland by the sea breeze. In coastal areas the difference between the southern and middle Boreal zones is of the same magnitude as inland.

The Bowen ratio, i.e. the ratio of the sensible and latent heat fluxes, was 0.6–0.7 for the southern Boreal zone, 0.8–0.9 for the middle Boreal zone and about 1.1 for the northern Boreal zone. The increase of Bowen ratio from south to north indicates that in the northern Boreal zone a larger portion of the available energy is used for heating of the lower atmosphere than in southern Finland. The values of Bowen ratio of 0.7–1.0 are typical of those found in a forested landscape (e.g. Oke 1987).

Comparison with previous studies

Ohmura's (1982) results for the energy balance components for arctic tundra (79°20´N, 90°30´W) and for boreal forest (63°N, 120°W) offer an interesting comparison with the results presented in the present study. According to Ohmura, the June–August mean global radiation over the tundra was 196 W m^{-2} and the net long-wave radiation –50 W m^{-2}. Correspondingly, over the forest the global radiation was 223 W m^{-2} and the net long-wave radiation –35 W m^{-2}. Over the tundra the albedo was 0.3 and over the forest 0.16. The high albedo value over the tundra was due to partial snow cover in June. The sensible heat flux over the tundra was –29 W m^{-2} and the latent heat –40 W m^{-2}. Over the forest the values were –69 W m^{-2} and –76 W m^{-2}, respectively. The soil heat flux was –12 W m^{-2} on the tundra and –7 W m^{-2} in the forest. The largest difference between Ohmura's study and present one may be the high sensible heat flux found in this study in Lapland compared with the conditions over the tundra. The explanation may be that in the present study the surface was estimated to be snow free in June. However, there are summers in Finnish Lapland when there is still snow cover over large areas at the beginning of June, and during such summers energy is also consumed in melting the snow; this would have an influence on the other energy balance components.

Laitinen (1970) presented values for the main energy balance components over Finland on a coarse 17-point grid. The short-wave radiation balance as estimated by Laitinen agrees well with the results of the present study, but Laitinen estimated values for the long-wave radiation of from –71 W m^{-2} to –60 W m^{-2} from south to north. Laitinen estimated latent heat as –61 W m^{-2} in southern Finland and –45 W m^{-2} in Lapland. He also calculated the sensible heat flux as a residue and found that the sensible heat flux was about the same, –45 W m^{-2}, over the whole country. If we assume that the soil heat flux is the same as in Laitinen's study then the sensible heat flux in the present study would vary between –40 and –65 W m^{-2}. If we look at the mean values for inland areas of climate zones, the sensible heat flux would vary from –55 Wm^{-2} in the Northern Boreal zone to –48 Wm^{-2} in the Southern Boreal zone; the difference between the different climate zones is thus relatively small and agrees with Laitinen's results.

According to Kiehl and Trenberth (1997), the mean values for energy balance components on a global scale are: global radiation 198 W m^{-2}, albedo 15%, long-wave radiation balance –66 W m^{-2}, sensible heat flux –24 W m^{-2} and latent heat flux –78 W m^{-2}. During summertime the mean short-wave radiation balance and latent heat flux in Finland seem to be near the global averages. An estimate obtained from Budyko's (1963) atlas gives the following values for the summertime energy balance components in Finland: global radiation 193 W m^{-2}, radiation balance 137 W m^{-2}, latent heat flux –53 W m^{-2} and sensible heat flux –32 W m^{-2}. Budyko's work covers the whole globe and gives broad-scale features of the spatial variation of the energy balance components. Taking into account the coarse resolution of Budyko's work, his results and those of the present study are comparable.

Conclusions

The accuracy of the long-term mean energy balance components found in the present study varies from one component to another. Mean values for the incoming solar global radiation and albedo can be estimated accurately with errors of less than 5%. The error in the latent heat flux estimate is judged to be about 10%. The more problematic energy balance components regarding their accuracy were found to be the long-wave radiation balance and the sensible heat flux. When compared with estimates based on measurement of the radiation balance components, the long-wave radiation balance estimate used in this work was found to be biased by 10–20 W m^{-2}. However, the comparison also revealed that there are inaccuracies in the routine radiation measurement records and the measurement of the overall radiation balance in particular seems to be problematic. The sensible heat flux was calculated as a remainder term, and errors in the other terms of the energy balance equation lead to inaccurate sensible heat flux values. However, this study does provide the spatial variation of the various energy balance components; in the case of the short-wave radiation, albedo and latent heat flux, the actual numeric values can also be regarded as accurate.

The results of this study support Laitinen's (1970) conclusion that even though there is a clear difference in global radiation values between the different parts of the country, the difference in the sensible heat flux is small.

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