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GIS-based modelling of the energy balance of Tarfala Valley, Sweden using Landsat-TM data

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Abstract

Landsat-TM-data was used to model the spatial distribution of all terms of the energy budget equation for Tarfala Valley, a small subpolar area of 67 km² in northern Sweden. The digital elevation model in conjunction with the shortwave irradiance model (SWIM) facilitated producing a data layer of short-wave irradiance. Landsat-TM multispectral satellite data was used for a supervised maximum-likelihood classification of the region. Albedo was estimated in respect of surface type. Atmospheric downward radiation was computed from air temperature, humidity and condensation level of local convective clouds. Surface temperature and terrestrial emission of the surface were derived from the combined information from Landsat-TM band 6 and the estimated emissivities for each surface type. Since TM band 6 has a pixel resolution of 120·120 m² only, a multiple regression analysis was carried out to calculate a synthetic thermal image with 30·30 m² pixel resolution. Storage heat flux under vegetation and bare soils was modelled from net radiation and the normalized difference vegetation index (NDVI). Turbulent heat fluxes were estimated from the temperature difference between the surface and the atmosphere. For that purpose temperature and humidity measurements at the Tarfala Research Station of Stockholm University were extrapolated to different elevations using radio sounding profiles.

Introduction

Most natural processes at the earth's surface are determined by the amount of available energy. Therefore, research on energy transfer phenomena at the surface is an important topic in many geoscientific disciplines. The cartographic representation of energy transfer processes is desireable, because these transfers influence to a great extent geomorphological, climatological, hydrological and biological processes (Gryzybowski, 1986). Furthermore, a profound knowledge of spatial and temporal variability and vulnerability of the study area is a prerequisite for the detailed studying of the impact of global change or local anthropogenic influences at specific sites (Parlow & Scherer, 1991a).

Regions that are not easily accessible or have very complex topographical conditions like mountainous areas cannot be evaluated representively by operating a few stations collecting point data. For that reason we suggest combining remote sensing techniques and ancilliary point data in a geographical information system (GIS). Although calculations based on remotely sensed data often serve as estimates only, they reveal the spatial variability in more detail than any other method. On the other hand calculations based merely on one satellite image do not show any temporal dynamics. Therefore, the conclusions have to be drawn very carefully and with respect to the actual meteorological conditions.

Study area

The study area is a subpolar region located in northern Sweden at 67°56' n. lat. and 18°35' e. long., including the Kebnekaise massif, with summits at about 2100 m a.s.l.

It covers the Tarfala drainage basin and parts of the main valley Ladtjovagge including glaciers, a small lake, tundra vegetation and small areas of birch forest at lower altitudes (600 m a.s.l.). A wide

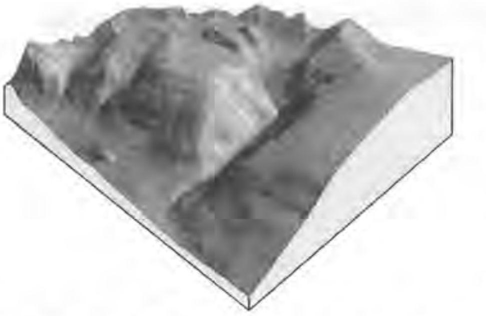

Fig. 1: 3D-plot from digital terrain model, view to Tarfalavagge from SE.

Tab. 1: Albedo and emissivities of surface types.

Surface type	albedo	emissivity
Lake	0.07 ± 0.02	0.98
Forest	0.15 ± 0.03	0.97
Fjeld (moist)	0.14 ± 0.03	0.97
Fjeld (dry)	0.15 ± 0.03	0.97
Alpine heath	0.20 ± 0.03	0.96
Debris, rock	0.20 ± 0.04	0.95
Moraine deposits	0.18 ± 0.04	0.94
Glacier	0.44 ± 0.08	0.96
Snow	0.55 ± 0.10	0.96
Snow edges	0.45 ± 0.10	0.06
Rivers	0.12 ± 0.05	0.97

range of localities with different climatic features have to be considered reaching from subpolar birch forest to glaciated areas. The three-dimensional plot of the digital elevation model (DEM, Fig. 1) gives an impression of the study area.

The meteorological recordings at the Tarfala Research Station, which is located in the Tarfala Valley at an altitude of 1130 m a.s.l. almost in the centre of the study area, show an annual mean temperature of -4.3 °C. In summer daily averages reach +5.5 °C with extremes on sunny days of up to +20 °C (Jahn, 1991).

Data sets

The Landsat-5 Thematic Mapper (TM) satellite image used in this study was acquired on July 20, 1986 at 10.32 a.m.

At that time the synoptic chart showed an anticyclone centering 700 km northwest of the study area. Only a marginal wind speed of approximately 2 ms^{-1} was measured at Tarfala Research Station that day, while cloud coverage declined constantly during the day. Temperature and humidity measurements from a radio sounding at Luleå/Kallax on the shore of the Baltic Sea revealed a layer of discontinuity at 2650 m a.s.l.

The DEM (Fig. 1) was produced from a topographical map of the area. The DEM and the satellite image were coregistered and a multispectral supervised maximum-likelihood classification was carried out after adjusting the bands individually for different illumination angles (Parlow, 1991; Scherer et al., 1994).

The Energy Budget Equation

At any time the energy budget equation at the surface is given by

$$R_n + L + H + S = 0 \qquad (1)$$

where R_n is net radiation, L is latent heat flux, H is sensible heat flux and S indicates storage heat flux. Energy fluxes due to biochemical processes can be neglected as long as meteorological phenomena are being investigated.

Net radiation as the major input term into the energy budget during daytime controls the energetic settings at the earth's surface to a great extent. It can be written as

$$R_n = (I_{dir} + I_{dif})(1 - \alpha) + R_a + R_s \qquad (2)$$

with I_{dir} the direct short-wave solar irradiance, I_{dif} the diffuse short-wave sky radiance, α the short-wave albedo, R_a the longwave atmospheric radiation and R_s the longwave terrestrial emission.

Shortwave Irradiance and Reflexion

Using SWIM (Short Wave Irradiance Model) (Parlow, 1988; Parlow & Scherer, 1991b) the spatial pattern of I_{dir} and I_{dif} were calculated for the time of the satellite passing over. SWIM recommends a digital elevation model as input data set. Atmospheric transmissivity and altitudinal effects are taken into consideration. For this purpose a standard atmosphere for clear sky conditions and polar latitudes is assumed. The position of the sun, the variation of the solar constant, slope and aspect of the surface are also parameters for the computation.

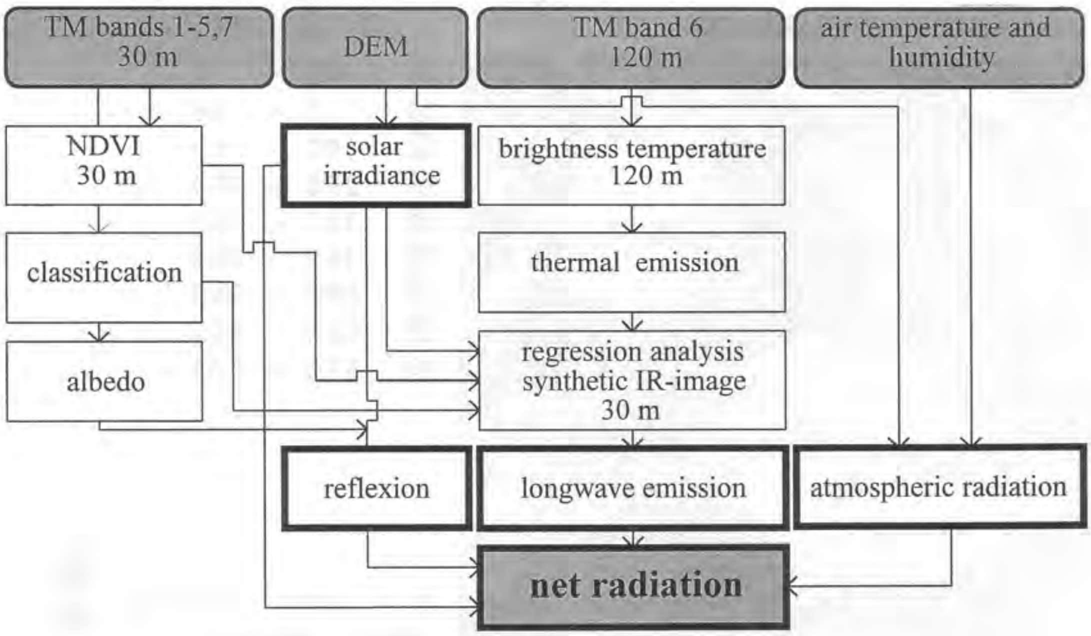

Fig. 2: Methodological concept of the computation of radiation fluxes.

Albedo α (Tab. 1) was estimated for each surface type based on quoted values from different authors: (Blüthgen & Weischet, 1980; Brutsaert, 1982; Greenland, 1991; Kontratyev, 1972; Ohmura, 1981; Oke, 1978; Weller & Holmgren, 1974).

Atmospheric Longwave Radiation

The atmospheric radiation is mainly a function of temperature and water vapour of the atmosphere. A simplified parametrization (Brutsaert, 1982) is given by

$$R_a = 0.552\sqrt[7]{e}\sigma T_a^4 (1 + s_c p_c^2) \qquad (3)$$

with e the water vapour pressure (hPa) and T_a the air temperature (K) at screen level, σ the Stefan-Boltzmann-constant, s_c a coefficient referring to cloud types and p_c the percentage of cloud coverage.

A linear function between e respectively T_a and the altitude z is assumed. The gradients were calculated from measurements at the Tarfala Research Station and the values at the layer of discontinuity derived from the radio sounding of the Swedish Meteorological Service (SMHI) at Luleå. The parametrization is in good agreement with the gradients retrieved from the radio sounding.

Longwave Terrestrial Emission

The terrestrial emission can be calculated from the radiation temperature T_{rad} using the Law of Stefan-Boltzmann. T_{rad} can be determined from TM-band 6 (Wucelic et al., 1989 and Parlow, 1991) using a calibration formula suggested by Schott & Volchok (1985).

The signal measured at the satellite sensor had to be corrected for atmospheric effects. Price (1980) proposed a method using temperature and water vapour values from a nearby radio sounding to calculate a correction term depending on elevation. This procedure was implemented.

Since band 6 of the TM has a pixel resolution of $120 \cdot 120$ m² only, a synthetic picture of R_s with a pixel resolution of $30 \cdot 30$ m² was simulated by using a regression model (Scherer & Parlow, 1990). The assumption is that in first order there is a linear correlation between R_s on the one hand and solar irradiance, altitude and surface type on the other hand (Scherer, 1989).

Net radiation

After all radiation fluxes were spatially modelled, the spatial pattern of the net radiation was computed

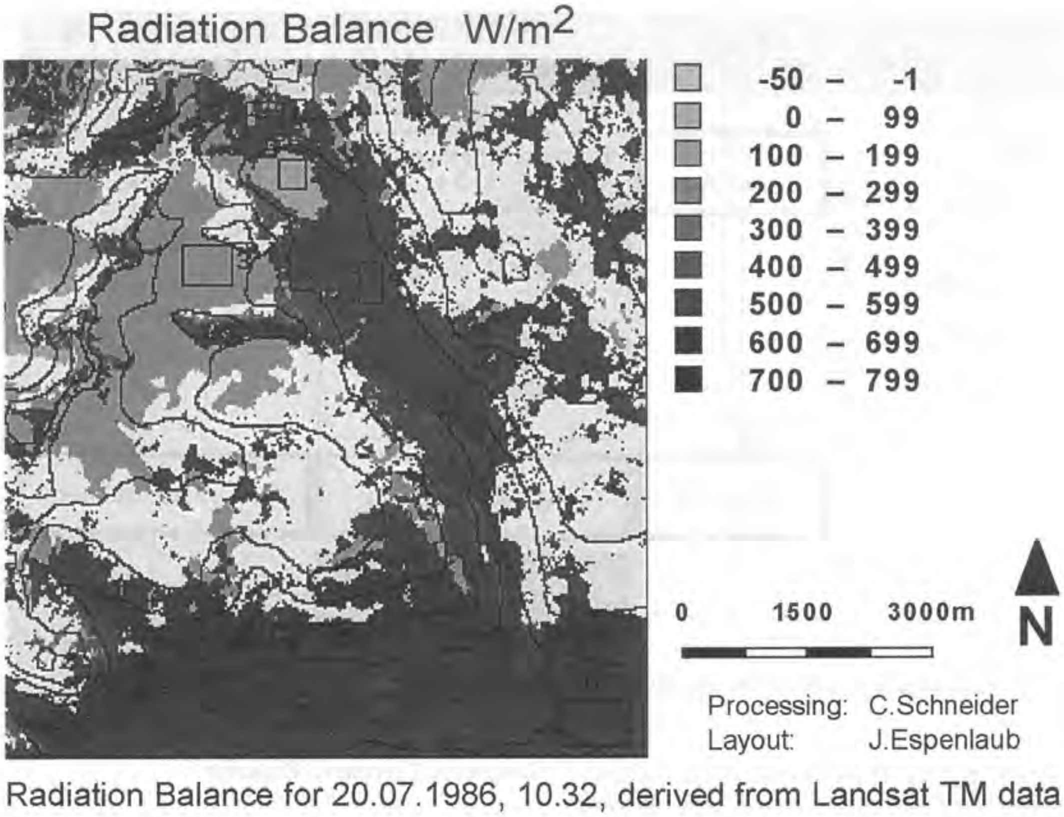

Fig. 3: Net radiation of Tarfalavagge, 20.7.1986, 10.32 hours. The contour lines give 200 m intervals of altitude. The rectangles numbered from 1 to 6 mark areas that are used later for site specific interpretation. White areas were not considered as they were obscured by clouds.

according to (2). The methodological concept is summarized in Fig. 2.

The resulting image (Fig. 3) shows a mean value of 472 Wm^{-2}, ranging from -79 Wm^{-2} to 799 Wm^{-2}. The negative values were modelled in cirques facing north with only little diffuse sky radiation and high albedo because of snow coverage. South-facing slopes and the lake surface show the highest values, because here the low albedo leads to a high rate of absorption and low surface temperatures are responsible for low terrestrial emission. The high albedo of glaciers and snow patches is responsible for a rather low overall net radiation.

Storage Heat Flux

The storage heat flux depends first of all on the energy supply and the surface cover serving as insulation. Therefore, this term was modelled according to an expression given by Daughtry et al. (1990)

$$S = (0.325 - 0.208 \cdot N) R_n \tag{4}$$

that makes use of the NDVI as calculated from bands 3 and 4 of the TM image. The mean value of S is 29 % of R_n which seems to be rather high. On the other hand Scherer (1992 & 1994) found similar results during micro-meteorological measurements under similar conditions on Svalbård. The storage heat flux under snow and ice and the warming of the lake water were calculated as remainder in the energy budget equation (1) because the NDVI is not applicable on these surfaces.

Latent and Sensible Heat Flux

Turbulent heat fluxes were estimated employing the so-called equilibrium evaporation (Brutsaert, 1982)

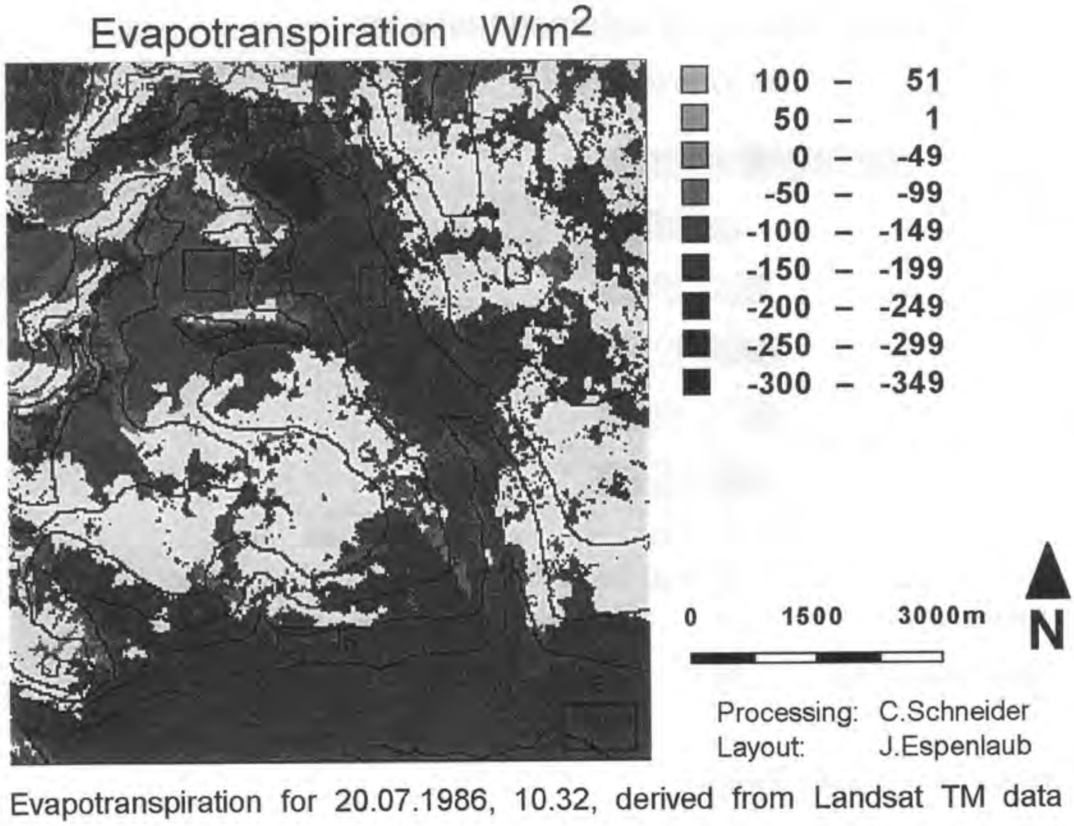

Fig. 4 : Evapotranspiration at Tarfalavagge, 20.07.86, 10.32 hours. The rectangles numbered 1 to 6 mark areas used for site specific interpretation.

$$L = \frac{R_n + S}{1 + \gamma(\frac{\Delta T}{\Delta e})} \tag{5}$$

with the psychrometric constant γ. Here the profiles $e(z)$ and $T(z)$ are assumed to be similar and the gradients of temperature and humidity are replaced by measurements at two different heights. Based on the measurements at Tarfala Research Station we assumed a nearly saturated atmosphere with $e_a \approx e^*_a$, the saturation vapour pressure. At a sufficiently wet surface the water vapour pressure at the surface e_s approximately equals e^*_s. Therefore the ratio can be transformed to

$$\frac{\Delta e}{\Delta T} = \frac{e^*(T_s) - e^*(T_a)}{T_s - T_a} = \Delta \tag{6}$$

This leads to the equations

$$L = \frac{\Delta}{\Delta + \gamma}(R_n + S) \tag{7}$$

for potential evapotranspiration and

$$H = \frac{\gamma}{\gamma + \Delta}(R_n + S) \tag{8}$$

for sensible heat flux. These equations were successfully used by Rouse & Stewart (1972) and Wilson & Rouse (1972) at different sites in Canada.

Using this set of mathematical expressions it is possible to calculate turbulent heat fluxes almost entirely from remotely sensed data. The classification enables the substitution of relevant emissivities for different surface types (Tab. 1), according to quoted values from Albertz (1991), Arya (1988), Gossmann (1982) and Mannstein (1989). The image of brightness temperatures now is transformed to a data layer of surface temperatures. Air temperature T_a can be computed in respect to the elevation in the same way as shown for the computation of the atmospheric emission.

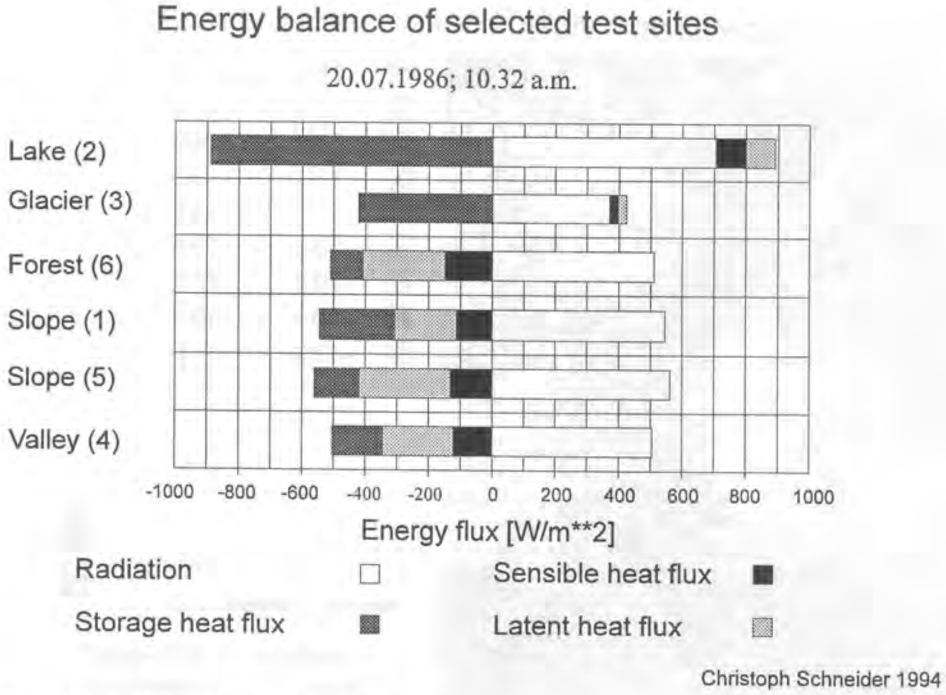

Fig. 5: Energy balance at specific test sites.

Turbulent Heat Fluxes over Cold Surfaces

It was not possible to estimate storage heat flux into ice, snow and the lake water using the remotely sensed data. Thus the concept given by (7) and (8) could not be applied for modelling turbulent heat fluxes over these surfaces.

For that reason, empirical approaches making use of the humidity and temperature differences between the surface and the air had to be considered. Formulas from Brutsaert (1982) for evapotranspiration from the water body and Blöschl et al. (1987) for sensible heat flux from snow and ice recommend windspeed as a further variable. This was derived from measurements at Tarfala Resarch station located in the vicinity of the lake and the glaciers. The Bowen ratio as derived from (7) and (8) was used to calculate the remaining turbulent flux. The storage heat flux was compiled as the remainder according to (1).

By now all fluxes given in (1) were spatially modelled and available as GIS data layers for further interpretation. Evapotranspiration is given in Fig. 4 as an example. Data values had to be combined into a rough classification for the presentation. Nevertheless, it can be shown that maximum values of energy loss due to evapotranspiration occur on south-facing slopes and over dense vegetation in Ladtjovagge. Energy input from condensation on cold surfaces was retrieved for the water body, snow patches and glaciers. In spite of the rough classification, the flux varies remarkably with exposition, slope and surface type.

Site Specific Interpretation

Different localities numbered from {1} to {6} were selected to give a site specific interpretation of the results. They are localized in Fig. 3 and Fig. 4. The modelling results of the components of the energy budget of these localities are summarized in Fig. 5.

Most striking is the enormous storage heat flux into the lake {2} due to the low albedo. Furthermore the low temperature of the lake surface leads to low rates of longwave emission.

In comparison to the lake, the glacier surface {3} has a high albedo and therefore net shortwave radiation as well as ground heat flux are characterized by low flux rates.

The smallest ground heat flux is found in the birch forest {6} as a result of the high insulation effect of the canopy.

As a consequence of exposition the south facing slopes north of the lake {1} and along Ladtjovagge {5} receive more than 700 Wm^{-2} of shortwave irradiance. Since the surface of {1} consists mainly of soil and rock the ground heat flux is very high. The bare soil heats up fast, giving rise to reasonably high values of surface temperature and longwave radiation. At locality {5}, the latent heat flux is higher than the ground heat flux on account of the vegetation cover. The high surface temperature indicates a water deficit. Therefore, we assume that the bowen-ratio was not modelled correctly in that area. The latent heat flux seems to be overrated in comparison to the sensible heat flux.

The differences between the fluxes in the Tarfala Valley {4} and the birch forest {6} show that the modelling approach has led to significant results: The forest has higher evapotranspiration rates due to the active transpiration of its denser vegetation cover. On the other hand, the thin alpine meadow in the Tarfala Valley heats up fast and shows high values of longwave emission.

Conclusion

The purpose of this study was to investigate the potentials of obtaining good estimates of the energy fluxes and their spatial variability when the satellite passes over without having to set up an intensive and expensive field campaign.

The spacial patterns of the components of the energy budget equation were modelled successfully from Landsat TM satellite imagery. The results reflect the momentanous micro-meteorological conditions at different localities in the study area. Since these conditions can be taken as representative for a number of summer situations, the pattern found helps to improve the knowledge about the spatial variability of climatic settings in the region.

Nevertheless, it is expected that the integration of further parametrizations, e.g. for surface roughness and wind speed, will improve the results. The computation of actual bowen ratio from remotely sensed data especially should be improved.
Although the results can only be taken as estimates, they reveal a significant spatial pattern of the components of the energy budget, describing appropriately the different climatological settings in the study area.

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