Wind directional dependency of surface energy fluxes over north-eastern Siberia and its implications

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Abstract

In order to better understand the water cycle over tundra, micro-meteorological and hydrological observations were carried out over tundra near Tiksi, North-eastern Siberia and seasonal variations of energy budget components were estimated for two years. As an average, net radiation was partitioned for sensible heat flux 25-30%, for latent heat flux 50-55% and for soil conductive heat flux 20%. Those ratios were changed by wind direction. The southwesterly winds were warm and dry, made the sensible heat flux small or its direction changed towards ground surface, and the northeasterly winds were cold, gave the sensible heat flux to the atmosphere from the tundra surface. The southwesterly winds were associated with cyclone intrusions to this area and the northeasterly winds with anti-cyclones. More frequent intrusions of cyclones would decrease the sensible heat flux and increase the latent heat flux. A simple air temperature increase experiments using a simple heat balance model showed that the sensible heat flux decreased, the latent heat flux unchanged and conductive heat flux in soil increased.

Keyword: tundra, energy budget, wind direction, heat flux

1. Introduction

As a part of GAME-Siberia project, hydrological and meteorological observations for a basin water/energy balance have been carried out in Siberian tundra region near Tiksi, Sakha Republic, Russian Federation from 1997 to 2001. The tundra area has a unique water cycle due to the existence of frozen ground, drifting snow and tundra vegetation. The frozen ground limits the subsurface flow and the subsurface storage and its change is small. The low vegetation and strong wind redistributes the snow once fallen on the ground and forms snow drifts at the leeward of ridges and the depression. The meltwater from the snowdrifts becomes a resource of the summer runoff for the tundra watershed, where liquid precipitation is small. The low vegetation distribution, such as lichen, moss and sedge, also play an important role in the evaporation over the tundra watershed, although the soil water content in turn determines the vegetation distribution. The mosses and lichens do not have stomata, and behave like a sponge. When the surface is totally wet, evaporation is substantial, but when the surface becomes dry, the evaporation becomes small and the surface temperature becomes high, even though a few centimeters below the surface is very wet and cool. These energy/water fluxes are also dependent on the atmospheric conditions. In this paper, the annual water balance and seasonal variation of heat balance at the tundra surface are reported, with particular emphasis on the wind direction dependency.

2. Observation site

An experimental watershed of 5.5 km^2, 7 km south of Tiksi, Sakha Republic, Russia has been selected for analysis in this study (71^{o}N, 129^{o}E) (Fig. 1). It is a tributary of the Suonannav River and the elevations range from 40 m to 360 m m.s.l.. We have initiated monitoring of snowmelt and summer heat and water balance of patch and basin scales, installation of full meteorological station, monitoring the variation of soil moisture, evaluating the variation of one-dimensional vapor and energy flux, and monitoring the variation of active layer (thickness, temperature, moisture) over a 1 km^2 grid.

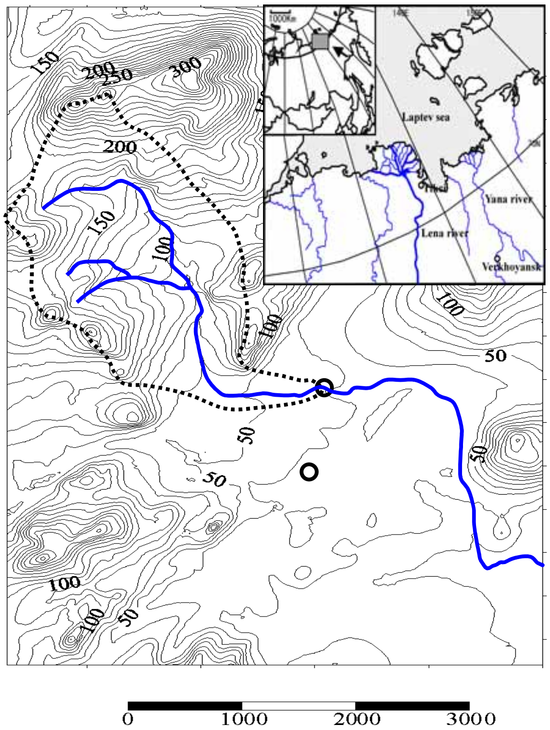

Fig.1: Observation site

The climatic data have been collected at the nearby Polyarka Hydrometeorological Station since 1932. The climatic (30 year mean of the period from 1955 to 1984) annual mean air temperature is –13.5 ^{o}C and the highest air temperature recorded was 32.6^{o}C and the lowest –53.6^{o}C. The annual mean wind speed is 5.0

ms^{-1}, with the prevailing wind direction of northeast in summer and southwest in winter. The annual mean precipitation is 345 mm.

3. Heat balance

Micro-meteorological observations have been carried out in the flat plain of the tundra region (Fig.1) using 10 m tower as well as soil temperature and water contents in the active layer.

In order to estimate the heat balance components, heat balance equation (Eq.1) was solved for the surface temperature, T_s, by iteration.

$$S\downarrow - S\uparrow + L\downarrow - \sigma T_s^4 + Hs + lE + G = 0 \tag{1}$$

$$Hs = \rho C_p D(T_a - T_s) \tag{2}$$

$$LE = 0.622 \beta \rho L_V D(e_a - e_{ss})/P \tag{3}$$

$$G = K(T_s - T_z)/z = 0 \tag{4}$$

S↓ and S↑ are the incoming and outgoing short wave radiation, respectively, L↓ the incoming long wave radiation, σ the Stefan-Boltzman constant, T_s the surface temperature, Hs the sensible heat flux, lE the latent heat flux, G the heat flux in soil, ρ the density of air, C_p the specific heat capacity of air, D the turbulent transfer coefficient, T_a the air temperature, β the evaporation efficiency, L_V the latent heat of vaporization, e_a the vapor pressure of air, e_{ss} the saturation vapor pressure at the surface temperature T_s, P the barometric pressure, K the heat conductivity of soil and T_z the soil temperature at the depth of z. The turbulent transfer coefficient D is changeable with the stability of the atmosphere as shown by Thom (1975). The heat conductivity of soil is changed linearly with the soil moisture at the depth of 0.05m. To solve Eq. 1, first an arbitrary surface temperature is given, then the transfer coefficient is calculated, and the surface temperature is obtained iteratively by Newton-Lappson method. Using the newly obtained surface temperature, new transfer coefficient is calculated again and the same method is repeated until the surface temperature does not change. When the surface temperature is obtained, the heat balance components are calculated.

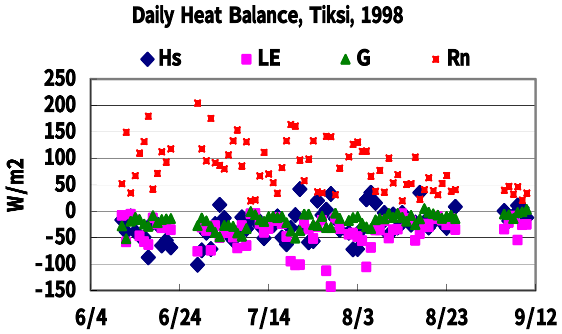

Fig. 2: Daily heat balance in 1998.

The results of the daily values of the heat balance components for 1998 are shown in Fig.2. The similar result was obtained for 1999. The net radiation has a maximum in the end of June and then gradually decreased. The heat flux in soil is the smallest in the components and does not change much. The sensible heat flux is large in the end of June but doe not show a clear seasonal variation, but sometimes show positive values. This coincides with the large latent flux. These are all connected to a wind direction, which will be discussed later. The 10 day mean heat balance components and their ratio to the net radiation for the period from June 10 to September 10 in 1998 are shown in Fig. 3. The net radiation was the largest in the end of June for the both year. The latent heat flux is larger than the sensible heat flux most of the periods. The heat flux in soil is smallest among the components and decreasing gradually towards fall.

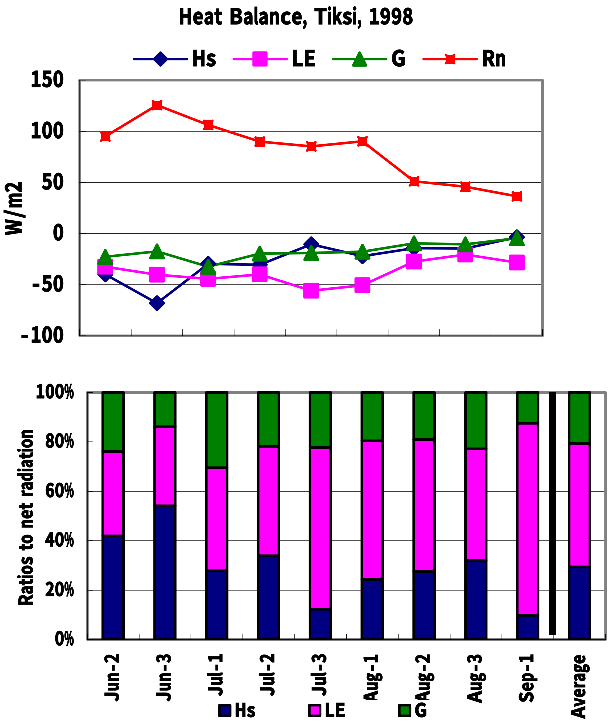

Fig. 3: 10 day mean heat balance components and the ratios to the net radiation for 1998.

When the sensible heat flux is positive (towards ground), the latent heat flux usually becomes large. Net radiation is partitioned to sensible, latent and soil conductive heat fluxes. The ratios of these components to the net radiation are shown in the second and forth figure in Fig. 3. The mean ratios are 25-30% for sensible heat flux, 50-55% for latent heat flux and 20% for soil conductive heat flux.

4. Wind direction dependency

We have seen that the positive value (towards ground) of sensible heat flux and large latent heat flux at the same time. This is closely connected to the wind direction. Fig. 4 shows the wind directional dependency of heat balance and meteorological components in 1998. From the top, frequency of wind direction, ratio of net radiation, ratio of sensible heat flux, ratio of latent heat flux, ratio of soil conductive heat flux, average air temperature and average vapor deficit. The “ratio” means the ratio of total heat flux in the specific wind direction to the total heat flux for all wind direction.

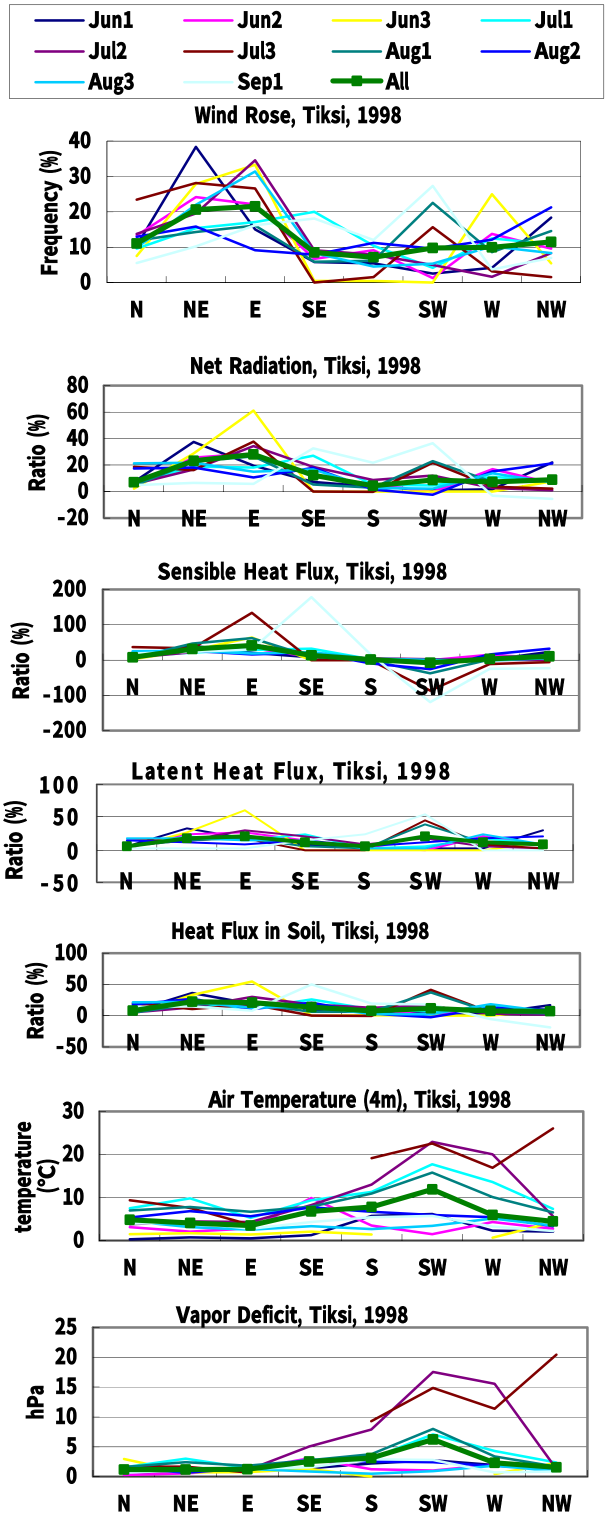

Fig. 4: Wind directional dependency of heat balance and meteorological components.

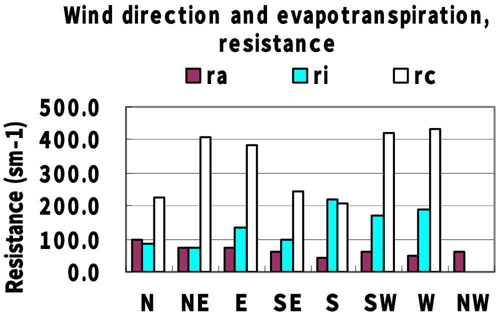

Fig.5: The ratio of evapotranspiration and the diffusion resistances for each wind direction

The most frequent wind direction is east and northeast, which are the same as the climatic prevailing wind direction of Poliarka Hydro-meteorological station in summer. Easterly and northeasterly winds are onshore winds, and oppositely southwesterly and westerly winds are offshore winds. The sensible heat flux is large and positive for onshore wind but mostly small or negative for offshore wind. This is obvious for the most of the periods, especially in the end of July (Jul3). The latent and soil conductive heat fluxes do not clearly depend on the wind direction. For the offshore wind, air temperature is high and the vapor deficit is large, whereas onshore wind is cold and has smaller vapor deficit. The wind direction dependency of the heat balance components was also found in Alaska and Northern Canada (Yoshimoto et al. 1996, Rouse et al. 1987, Rouse 1984).

In order to discuss the effect of the difference in microclimate on the vegetation activity and the energy partition, diffusion resistance to vapor transfer for each wind direction was calculated in daytime between 0900 and 1500, local time, and shown in Fig. 5, where r_a is the aerodynamic resistance, r_i the isothermal (or climatological) resistance and r_c the canopy resistance. The equations for the resistances are written in, for example, Harazono et al. (1998). The aerodynamic resistance r_a did not show strongly the wind directional dependency. This is mainly due to the wind speed: the mean wind speed for the each wind direction did not show preference in wind direction. The climatological resistance, r_i, which is the ratio of the water vapor deficit and the available energy at the canopy, showed larger values for southerly, southwesterly and westerly winds. This is due to the large water vapor deficit for the southerly and westerly air mass (see the bottom figure in Fig. 4). The canopy resistance, r_c, which is a function of r_i and Bowen ratio, showed the larger values for the west and southwest wind directions as well as the east and northeast wind directions. This is quite different from the result of Harazono et al. (1998) in Northern Alaska, where canopy resistance as well as the other two resistances showed small for onshore winds and large for offshore winds. The large r_c for the offshore winds in this study are mainly due to the large water vapor deficit of the westerly and southwesterly air masses. The large r_c also for the onshore wind could be explained by the low temperature of the air mass: low air temperature gives large sensible heat flux towards atmosphere and large Bowen ratio. Although the water vapor deficit is small for this onshore wind, the large Bowen ratio, which might be the results of dryness of the ground surface, gives the large r_c.

Figures 6 show the examples of the synoptic weather conditions for the case of north-easterly wind (left) and south-westerly wind at Tiksi. Most of the south-westerly winds associate with the cyclone

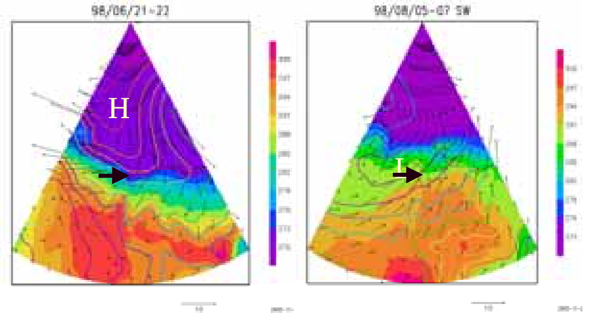

Fig.6: Synoptic atmospheric conditions for north-easterlies (left) and south-westerlies (right). Contour lines show the isobars, thin arrows wind direction and speed and colored contours air temperature. Thick arrow indicates the location of Tiksi.

intrusion from southwest, and the north-easterly winds with the anti-cyclones. Further analysis showed the wind direction change in Tiksi is not strongly influenced by land-see breeze.

According to the global change scenario (IPCC,1996), the air temperature at the Arctic area will increase by 3-4 ℃ with an increase in atmospheric greenhouse gas concentrations. If the warmer and drier air mass would be coming from west and southwest more frequently by global warming, the tundra surface would become drier and the surface air temperature would further become higher, giving a positive feedback. If the temperature difference between continent and Arctic Ocean would become larger by the global warming, the opposite trend could be found. If global warming would make the continent warmer but would not warm the ocean surface relatively, giving a larger temperature difference between the continent and the ocean, the onshore winds would be more frequent and the tundra surface would be colder, resulting in a negative feedback effect. However, further study is warranted.

Fig. 7 shows the results of the warming simulations by simply adding –2°C, -1°C, 0°C, +1°C, and +2°C to the air temperature and recalculate the surface heat balance equation (1) by iteration as mentioned above. The ordinate in Fig.7 shows the anomaly of fluxes from those of the zero-warming situation normalized by the mean fluxes. When the warming increases, the sensible heat flux decreases, soil conductive heat flux increases and the latent and radiative heat fluxes do not change much. The increase of air temperature decreases the temperature difference between air and land surfaces, on which net radiation absorbed is not much changed. This is the reason the sensible heat flux decreases by the warming. Since the relative humidity is not changed, the increase in air temperature keeps the air moister, therefore the latent heat fluxes is not changed by warming. The soil conductive heat flux is increased by the warming. This means the warming of the ground temperature and eventually increasing of the active layer thickness.

5. Summery

We have studied the summer heat balance for a tundra watershed near Tiksi, Sakha Republic, Russia. Strong wind direction dependency on sensible heat fluxes were observed: southerly and southwesterly winds

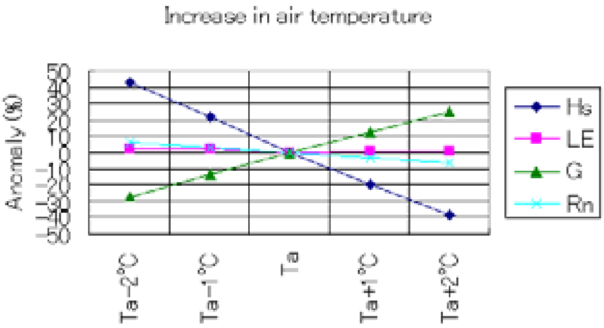

Fig. 7: The results of in the cases of the simply changing the air temperature.

increasing the are warm and dry, giving sensible heat flux towards the ground surface and the larger latent heat flux, easterly and northeasterly winds are cold and smaller vapor deficit, giving a large sensible flux to the atmosphere from the tundra surface. Those wind directions were caused the by the synoptic atmospheric conditions, not by the local wind like sea-land breezes. Global warming due to green house effect gas increase is expected in these tundra area, however, further studies is warranted to determine future tundra conditions.

Acknowledgments

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