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Biogeosciences Discussions

Interactive comment on "Contrasting radiation and soil heat fluxes in Arctic shrub and wet sedge tundra" *by* I. Juszak et al.

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We thank the first reviewer for his/her positive statement and his/her interest in our results.

GENERAL COMMENTS

1. However, the information of long-wave radiation did not well presented in this manuscript, I recommend the authors can analysis the long-wave radiation balance/budget during daytime and nighttime.

   We originally focused our analysis on net radiation, albedo, and transmittance. However, we agree that the longwave radiation budget may be interesting for some readers. Outgoing longwave radiation is higher above dwarf shrubs as

   compared to above wet sedges due to higher soil temperatures at day time. We will add the corresponding diel cycles to a new figure (see Figure 1 below) replacing the former Figure 8 but appearing earlier in the manuscript.

2. I would also like to understand the diurnal course of temperature gradient between the soil and overlying air parcel to elucidate the direction of sensible heat flux.

   We agree with the reviewer and will add the information in the new figure (see Figure 1 below). We found that air temperature at $1.7\,\mathrm{m}$ above the soil surface was similar above both vegetation types, probably due to the small distance between the patches and the wind that we commonly observed. On average, the air temperature above the wet sedges was about $0.6\,^{\circ}\mathrm{C}$ colder than above dwarf shrubs. This effect reduced the gradient between air and soil temperature for wet sedges. However, at both vegetation types air temperature was warmer than soil temperature, which indicates that the sensible heat flux was on average directed towards the soil during the growing season.

3. Besides, I noticed that the authors mentioned the soil moisture condition at sedges site was always under the saturated condition, but the evapotranspiration at the sedges site was suggested to be higher than that at the shrub site. This implies that the soil moisture at sedges site was replenished/affected by lateral water flux, which could also transport heat from other regions such as upland area with the shrub vegetation cover. I recommend that the authors can cite relative studies regarding to the lateral water flux and heat transport at top soil layer over this region or the authors can add an extra analysis of soil moisture by using the soil moisture depletion approach.

   Below dwarf shrubs, soil moisture decreases during the course of the growing season. Below wet sedges, we observed that the water level decreased but remained at or above the soil surface. We agree with the reviewer that this indicates lateral water influx. Indeed the wet sedge vegetation is located about $0.7\,\mathrm{m}$ below the adjacent shrub patches. Thus lateral water fluxes can contribute to drying the shrub patch and replenish the soil water below wet sedges. In addition to lateral water fluxes, the active layer plays a key part in permafrost environments. Thawing of frozen water within the active layer depth may supply water. This water supply depends on the moisture conditions at freeze-back in the previous year.

We agree that the mentioned lateral water flux can transport energy towards the wet sedges. However, this energy is difficult to quantify and few studies measured lateral water and heat flux in patterned tundra. Boike et al. (2013) estimated that about 10% of the summer precipitation was converted to runoff at a polygonal tundra site in the Lena river delta, northeast Siberia. Helbig et al. (2013) found that lateral water fluxes were important and variable water residence times contributed to keeping a high water level in the surface drainage network. As we do not have further information on the lateral fluxes at our study site, it would be too speculative to provide a quantitative estimate for lateral heat transport. However, we will add clarifying text to indicate this possibility of lateral heat fluxes.

We investigated whether the approach by Michelakis et al. (1994) may provide additional insights at our site. This approach was developed for olive trees which is in stark contrast to vegetation growing on permafrost soils where only a shallow active layer with low temperatures (and frozen ground beneath) is available. In addition to rainfall and runoff - which is not available with the necessary accuracy and resolution for our study site - also estimates of water gains due to increasing thaw depth over the season would be required, another variable that is not available in sufficient quality for that task. Hence, although this is a welcome and relevant suggestion, we cannot offer such an additional analysis.

However, air temperature may provide an independent indication of evapotranspiration. Cooler air temperature suggests, that more energy is used for evapotranspiration as compared to sensible heat flux. Despite the close vicinity of the wet

sedges and the dwarf shrubs, the frequent wind, and the similar top soil temperatures, air temperature above the wet sedges was about $0.6\,^{\circ}\mathrm{C}$ colder than above dwarf shrubs. This finding is consistent with the hypothesis of higher evapotranspiration at the wet sedge site.

SPECIFIC COMMENTS

P1 line7 How to define the active layer thickness in this study?

The active layer thickness is the thaw depth end of summer measured from the surface of soil, mosses, or flat litter to the top of the frozen ground. We will include a description at the beginning of the methods section.

P1 line14 to 15 The authors should provide the evidence such as soil moisture information, soil albedo to support this conclusion. I can't find the approach that the authors conduct the observation of soil albedo measurement throughout the manuscript. Would you please indicate that how to measure the soil albedo? Does it also parameterize as a function of soil moisture change or solar zenith angle?

We measured soil moisture below both vegetation types and included this information in the study site description. We agree that soil albedo is a function of soil moisture and possibly solar angle. However, we do not have reliable measurements of soil albedo and are thus not able to include it quantitatively in the manuscript. An indication of soil albedo below dwarf shrubs is provided in Juszak et al. (2014). In that paper, hemispherical-conical reflectance was measured with $1\,\mathrm{nm}$ spectral resolution on plots with removed shrub cover at the same field site. Using a radiative transfer model Juszak et al. (2014) estimated a broadband soil albedo of 0.17 for conditions around solar noon (as mentioned in the discussion Section 4.3). This value is not the bare soil albedo but mostly the albedo of shrub litter and mosses. The background below wet sedges is standing water and saturated, dark litter. We do not have albedo measurements of this water and litter layer. However, wet soil and water at high sun zenith angles (when most energy reaches the ground) generally have low albedo values (Oke, 1987).

P3 line26 Please remove 'e.g.' for the consistence.

We will replace 'e.g.' with 'mainly'. 'Mainly' is necessary because several species of willows are abundant in the area.

P4 line4 Would you please also provide the information of above ground biomass at the sedges and shrub sites? It would be nice to show this information to readers for the comparison.

We will add the measured dry biomass values to the study site description.

P4 line9 & line 10, P5 line2–3; P17 line10–11 Please check the unit of the thermal conductivity and heat capacity, is it correct?

We use the unit $\mathrm{W\,m^{-1}\,K^{-1}}$ for thermal conductivity as it is commonly done. We use volumetric heat capacity in $\mathrm{MJ\,m^{-3}\,K^{-1}}$. We will add the term 'volumetric' to be more specific. The values of dwarf shrubs and wet sedges agree well with the values for dry peat and still water in Oke (1987), respectively.

P12 Figure 7 and Figure 8 The information contains in the Figure 8 which is largely repeated from the Figure 7, thus I recommend to remove the Figure 8.

The figure will be removed.

P13 line14 'Depended on soil properties', What kind of soil properties, thermal conductivity, porosity, or soil moisture?

The soil heat flux depends on several soil properties. However, we mainly meant soil thermal properties.

P13 Figure 9 Would you please apply the soil moisture depletion approach (Michelakis et al., 1994) to calculate the reference evapotranspiration rate or apply the Priestley – Taylor approach (Priestley and Taylor, 1972) to calculate the evapotranspiration rate limited by a correction function based on LAI or soil moisture conditions?

As described above in the general comments, the soil moisture depletion approach by Michelakis et al. (1994) is not applicable at our study site due to the lack of data.

The Priestley–Taylor approach (Priestley and Taylor, 1972) requires less input data. Evapotranspiration E is calculated from $E = \alpha \frac{s}{s+\gamma}(R - G)$ where s and γ are a function of surface temperature and α depends on water availability, vegetation activity and saturation deficit in the atmosphere. We measured similar net radiation (R) and surface temperatures at both vegetation types. Thus the elevated soil heat flux G below wet sedges reduces evapotranspiration as compared to the dwarf shrub patch for a constant α. However, α is different between the two vegetation types as the soil below dwarf shrubs is not saturated and the shrubs may close the stomata when they are water limited. Empirical corrections have been developed that relate the parameter α to canopy or soil characteristics (e.g. Flint and Childs, 1991; Sumner and Jacobs, 2005). However, empirical relationships can only be used in conditions which are similar to the calibration conditions. We do not know of any empirical evapotranspiration parametrisation which was calibrated for tundra vegetation. Thus, we prefer to focus the manuscript on the measured data and not include empirical models.

P15 line18 I was confused by this sentence, 'strong cloud impact on albedo masked other temporal trends within growing season ....' To my knowledge, the calculation of surface albedo (vegetation + soil background) can be separated into two parts (visible + near infrared). The reflectance (albedo) from near infrared is more sensitive to the canopy structure (Otto et al., 2014), and albedo are often parametrized as a function of solar zenith angle in the radiative transfer process.

Would you please use this concept to explain your finding in a logic way?

We will change the confusing sentence. We did not calculate the albedo from visible and near-infrared radiation, but we measured broadband shortwave incoming and reflected radiation and calculated albedo from the ratio between the two. We agree, that the effect of clouds on albedo is based on the angles of incident shortwave radiation. While most radiation comes directly from the direction of the sun under clear-sky conditions, clouds diffuse the radiation which consequently comes from all directions. Diffuse radiation commonly lowers the albedo for sun zenith angles above 55° (Oke, 1987; Yang et al., 2008).

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Figure 1 (a) Average diel cycle of above canopy shortwave (K) and longwave (L) radiation fluxes, (b) above canopy net shortwave (K_n), net longwave (L_n) and net (R_n) radiation, (c) albedo (α) and transmittance (T), (d) soil temperature (T_s) at 4 cm depth and soil heat flux (HF) at 10 cm depth, and (e) air temperature at 1.7 m above the soil surface (T_a) and gradient between air and soil temperature (ΔT) of dwarf shrubs and wet sedges during the growing season; solar noon at 14:00 local time.

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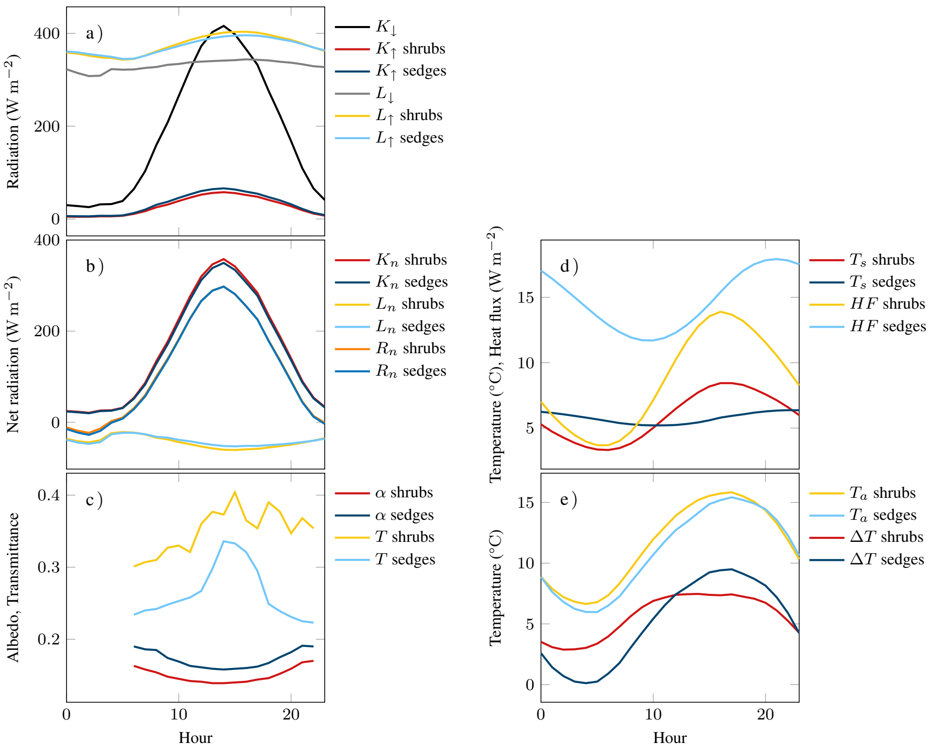

Fig. 1. For caption please see above