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Drivers of shortwave radiation fluxes in Arctic tundra across scales

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ABSTRACT

Vegetation composition and water surface area are changing in many tundra regions due to climate warming, which is twice as strong in the Arctic as compared to the global mean. Such land cover changes feed back to climate and permafrost thaw through altering the surface energy budget. We quantified the influence of vegetation type, canopy characteristics, and patchiness on the tundra shortwave radiation components. We used in situ measurements and vegetation mapping to parametrise a 3D radiative transfer model (DART) for summer conditions at the Kytalyk test site in northeast Siberia. We analysed model results assessing the most important drivers of canopy albedo, transmittance, and absorptance of photosynthetically active radiation (PAR). Tundra albedo was strongly influenced by the fractional cover of water surfaces. Albedo decreased with increasing shrub cover. However, plant area index effects on albedo were not statistically significant. Canopy transmittance and PAR absorptance (f_{APAR}) were almost entirely controlled by plant area index at the landscape scale. Only about one half of the total plant area index consisted of green leaves, while wood and standing dead leaves contributed equally to the other half. While spatial patterns and patch sizes of vegetation types and open water did not significantly influence the radiation budget at the landscape scale, it contributed to the large variability at the local scale. Such local variability of shortwave radiation may impact evapotranspiration and primary productivity at a range of scales. Therefore, the variation of radiation fluxes within single vegetation types potentially affects larger scale energy, water, and carbon fluxes.

1. Introduction

Vegetation is an important part of the climate system as it reacts to climate drivers and influences climate through changing Earth's surface properties. Arctic greening, in particular the expansion of shrubs in tundra areas, is associated with recent climate warming (Fraser et al., 2014; Myers-Smith et al., 2011; Sturm et al., 2001). This greening directly affects the surface albedo, which feeds back to climate through large scale warming (Chapin et al., 2005; Loranty et al., 2011). Vegetation effects on permafrost thaw are more complex since increased vegetation density not only leads to atmospheric warming but also partly decouples permafrost from the atmosphere through insulation and soil shading (Briggs et al., 2014; Cannone and Guglielmin, 2009; Eugster et al., 2000; Walker et al., 2003).

Encroachment of dense shrub canopies in previously graminoid or lichen dominated tundra reduces the average surface albedo and thus amplifies warming (Beringer et al., 2005; Blok et al., 2011b; Thompson et al., 2004). Furthermore, vegetation alters surface roughness and transpiration, which leads to changes in sensible and latent heat fluxes (Boudreau and Rouse, 1995). Within the canopy, transpiration strongly depends on the light regime, in particular on the small scale heterogeneity (He et al., 2014; Song et al., 2009). Thus, resolving the shortwave energy budget helps in understanding and modelling multiple land surface – climate feedback processes.

Permafrost is affected by vegetation cover in multiple ways. On the one hand, vegetation shades the ground and thus reduces the amount of shortwave radiation that is absorbed by the soil (Benninghoff, 1952; Briggs et al., 2014). On the other hand, increasing vascular plant biomass reduces moss abundance through shading and litter production (van Wijk et al., 2003). Decreased moss

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abundance affects the soil heat flux as mosses can strongly insulate the soil from air temperature (Beringer et al., 2001; Blok et al., 2011a). Additional processes, such as trapping of snow by vegetation (Pomeroy et al., 2006), further influence the interaction between vegetation and permafrost thaw.

Tundra landscapes typically show small scale patterns, such as hummocks and polygons, which are associated with small water bodies and distinct vegetation types (Walker et al., 2008). Landscape variation and associated differences in soil moisture, nutrients, and pH can lead to different vegetation composition within meters (Muster et al., 2012; Walker et al., 2011). These patterns can either remain stable over decades (Gamon et al., 2012) or change rapidly for example due to permafrost degradation (Schuur et al., 2007). Large scale vegetation dynamics are also affected by wetland area and the water budget. While an increase in lake and wetland area has been observed in the Siberian tundra (Lin et al., 2012; Smith et al., 2005), the American Arctic shows a drying trend (Carroll et al., 2011; Jones et al., 2011; Lin et al., 2012; Oechel et al., 2000). Shrubs such as dwarf birch (*Betula nana*) profit from warming and fertilisation and become increasingly dominant (Bret-Harte et al., 2001).

The radiation budget of patterned tundra landscapes is expected to vary among and within vegetation types at fine scale (few centimetres) due to variations in canopy properties and edge effects. Currently, little is known about the radiation budget of such patterned landscapes, as satellite observations are too coarse to resolve the fine scale differences (Muster et al., 2012). The aim of this study is to analyse the shortwave radiation budget of heterogeneous tundra at the Kytalyk research site in northeast Siberia by using 3D radiative transfer modelling to resolve such fine scales. The focus is on increasing the understanding of drivers of albedo, transmittance, and absorbed radiation of the canopy from patch to landscape scale in summer. Using a 3D radiative transfer model, we provide insights into typical length scales of horizontal interaction between vegetation types and the influence of local land cover variability on the radiation budget at different scales. This is the first time that such a complex 3D radiation model has been parametrised with such high detailed structural and compositional measurements for the tundra.

2. Methods

2.1. Field site

Our field site is the Kytalyk nature reserve located in the Indigirka lowlands, northeast Siberia (70.8° N, 147.5° E, Fig. 1a). According to the circumpolar Arctic vegetation map, vegetation is classified as tussock sedge, dwarf shrub, moss tundra (Walker et al., 2005). Low shrub tundra (mainly *Salix pulchra*) occurs along rivers and at lake shores. The area is dominated by continuous permafrost of several hundred meters depth (Romanovskii et al., 2004) with an active layer thickness of 12 to 50 cm (Mi et al., 2014). The Kytalyk field site is described in more detail in van der Molen et al. (2007), Nauta et al. (2015) and Juszak et al. (2016). The size of our study area is 1.4 km× 2 km (Fig. 1b).

2.2. Remote sensing data and products

We used a ground referenced orthomosaic from a UAV (unmanned aerial vehicle, eBee, senseFly), acquired with digital cameras in four spectral bands (red, green, blue, and near infra-red (NIR)) to generate a NDVI (Normalized Difference Vegetation Index) map, a DSM (digital surface model), and a land cover map of dominant vegetation types. The map products have a spatial resolution of 5 cm and an extent of 1.4 km×2 km.

2.2.1. Orthomosaic, NDVI, and DSM

The orthomosaic, which we obtained from the drone flights between 10 July and 10 August 2014, revealed some artefacts due to inhomogeneous illumination during and between flights (Fig. 2a). As these artefacts propagated to the NDVI map, spatial input variables, and the vegetation map (Fig. 2b), we chose the sub-sets for modelling in the least affected area (Section 2.4.3). We estimated the NDVI from the red (ρ_{red}) and NIR reflectance (ρ_{NIR}):

$$\mathrm{NDVI} = \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{red}}}{\rho_{\mathrm{NIR}} + \rho_{\mathrm{red}}} \quad (1)$$

The DSM was generated from the point cloud which was created during the image matching. Interpolation was performed using inverse distance weighting, minimizing artefacts (Chaplot et al. (2006); Postflight Terra 3D, Version 4.0.83). The DSM represented a level between the top of canopy and the soil surface. The uncertainty is due to variability in canopy height and not related to topography. Since the vegetation was low (<0.8 m) and mostly sparse (average LAI of all vascular vegetation types < 1.5), some of the reference points for the DSM may have been mapped at the soil surface. Thus we considered the DSM an appropriate approximation of the ground elevation and used it as topographic input for modelling. The elevation difference between the river and the highest area of the ridge was about 23 m. Fine scale drainage patterns could be detected in the

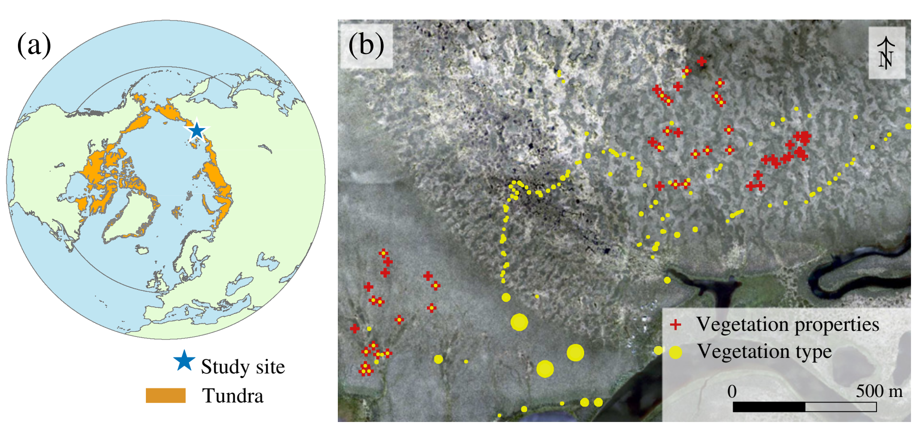

Fig. 1. (a) Location of the study site in northeast Siberia (extent of Arctic tundra from Walker et al., 2005) and (b) orthomosaic of the study site including measurement locations of vegetation properties (red) and reference points for vegetation mapping (yellow, point size indicates represented area).