Remote Sensing of Environment 114 (2010) 2059–2069

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Spatial and temporal variations of summer surface temperatures of wet polygonal tundra in Siberia - implications for MODIS LST based permafrost monitoring

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ARTICLE INFO

Article history:
Received 21 October 2009
Received in revised form 16 April 2010
Accepted 17 April 2010

Keywords:
Permafrost
Polygonal tundra
Thermal imaging
Land surface temperature
MODIS

ABSTRACT

The surface temperature of permafrost soils in remote arctic areas is accessible by satellite land surface temperature (LST) detection. However, the spatial resolution of satellite measurements such as the MODIS LST products is limited and does not detect the heterogeneities of the wet polygonal tundra landscape where surface wetness varies over distances of several meters. This paper examines the spatial and temporal variability of summer surface temperatures of a polygonal tundra site in northern Siberia using a ground based high resolution thermal imaging system. Thermal infrared images were taken of a 1000 m^2 polygonal tundra area in 10 min intervals from July to September 2008. Under clear sky conditions, the individual measurements indicate temperature differences of up to 6 K between dry and wet tundra surfaces and which can exceed 12 K when dry tundra and water surfaces are compared. These differences disappear when temperature averages are considered for intervals longer than the diurnal cycle; for weekly averages the spatial temperature variability decreases below 1 K. The exception is the free water surface of a shallow polygonal pond where weekly averaged temperature differences of 2.5 K are sustained compared to the tundra surface.

The ground based thermal infrared images are upscaled to MODIS sized pixels and compared to available MODIS LST data for individual measurements and weekly averages. The comparisons show generally good agreement for the individual measurements under clear sky conditions, which exist during 20% of the studied time period. However, several erroneous measurements and large data gaps occur in the MODIS LST data during cloudy conditions, leading to biased weekly temperature averages inferred from the satellite observations. Based on these results the following recommendations are given for future permafrost temperature monitoring based on MODIS LST products: (i) high resolution surface water masks for the quality assessment in landscapes where lakes and ponds are frequent and (ii) reliable cloud cover detection in conjunction with a gap filling procedure for accurate temporal averages.

1. Introduction

The land surface temperature (LST) is the manifestation of the energy balance partition at the soil-atmosphere interface and is therefore a crucial parameter for the energy budget of permafrost environments. The sensitivity of permafrost towards degradation and the potential activation of a massive carbon source is directly associated with the energy exchange processes occurring at the soil-atmosphere interface. Especially wet tundra landscapes, where large quantities of carbon are stored in frozen organic soils, may become a massive source of green house gases under a warmer climate (Davidson & Janssens, 2006). A number of studies revealed a sustained large scale warming of the Arctic during the last decades (e.g. Comiso, 2002; Serreze et al., 2003; Stroeve et al., 2005; Overland et al., 2008; Rothrock et al., 1999), which is also reported by Comiso (2003, 2006) using long term satellite LST measurements. The satellite observations indicate strong warming trends of LST during summer over the entire Arctic, which is essential for the summer thaw depth of permafrost soils. Hence, the monitoring of LST can be an important tool to assess the effects of climate change in the usually remote and inaccessible permafrost environments. Land surface temperatures are currently accessible by various remote sensing platforms e.g. Terra/Aqua-MODIS, Terra-ASTER, NOAA-AVHRR, Meteosat-MVIRI, ERS-ATSR and Landsat. Since they are available on a global scale with high overpass frequencies, these products have a great potential for two major applications in permafrost regions.

1. The LST provides access to atmospheric boundary layer processes in regions where climate data are sparse. Efforts have been initiated to synthesize surface-based meteorological data with satellite observations and numerical models in arctic regions (Martin & Munoz, 1997; Rigor et al., 2000). In addition, several projects in non-arctic regions, such as FIFE (Sellers et al., 1992),

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doi:10.1016/j.rse.2010.04.012

BOREAS (Sellers et al., 1995) and SEBAL (Bastiaanssen et al., 1998), examined surface energy balance models based on satellite products. A detailed overview of LST derived energy balance models is given by Friedl (2002).

2. Land surface temperatures can serve as upper boundary condition in permafrost models, calculating the annual thaw depths and the thermal stability of permafrost soils. Hachem et al. (2008) introduce satellite derived land surface temperatures for permafrost detection, while essential issues such as data gaps due to cloud cover and the decoupling of soil and surface temperatures due to snow cover are addressed. A proposed scheme of satellite based permafrost modeling is given in Marchenko et al. (2009), which makes use of a MODIS LST product in combination with the analytical permafrost model GIPL-1.1. to calculate permafrost active layer dynamics for the entire Arctic.

The spatial resolution of satellite LST products typically ranges from 60 meters (Landsat) to one kilometer (MODIS). Temperature differences on smaller scales are therefore not resolved, but are nevertheless critical when they occur systematically over long time periods. In such cases, they result from sustained differences in the surface energy balance and might indicate differences in the thermal state of the subjacent permafrost, potentially triggering processes such as initial thermo karst erosion. Previous studies in non-arctic regions have outlined the effect of surface heterogeneity on satellite based energy balance detection (Brunsell & Gillies, 2003; Friedl, 1996; Hall et al., 1992; Humes et al., 1994). In particular, sub-resolution LST variations are expected to occur in highly fractionated landscapes. This is especially true for permafrost environments, such as the wet polygonal tundra, where a sharp contrast between wet and dry surface patches occurs on scales of several meters. Hence, it is desirable to elucidate the sub-resolution surface temperature variability and its impact on the accuracy of satellite permafrost monitoring schemes.

In this paper, we present summer surface temperature observations using a tower-mounted high resolution thermal imaging system at a Siberian polygonal tundra site. This surface type is characteristic for a large area of circumpolar wet tundra landscapes. At first, the spatial and temporal variability of surface temperatures obtained with the thermal camera is analyzed for the snow free period. Secondly, the MODIS L2 (collection 5) LST product (Wan, 2008) is compared to up-scaled LST data from the thermal camera and evaluated with respect to its applicability for the monitoring of permafrost active layer dynamics in wet polygonal tundra landscapes.

2. Site characteristics

The study was performed on Samoylov Island (72° 22' N; 126° 30' E), which represents a typical Siberian wet tundra landscape in the zone of continuous permafrost (Fig. 1a). Samoylov Island is located in the upper plain of the Lena River Delta, close to one of the main river channels (Fig. 1b). The region is characterized by an arctic continental climate. The mean annual air temperature (MAAT) at Samoylov Island is -14.7 °C and the total annual precipitation is around 250 mm, showing high inter-annual variations (Boike et al., 2008). Snow melt and Lena ice drift typically start in the beginning of June and the snow free season lasts from mid-June to mid-September. The regional permafrost reaches depths of 500-600 m (Grigoriev, 1960) and is characterized by a very low temperature of -9.2 °C at the depth of zero annual amplitude approximately 10 m beneath the surface. Samoylov Island covers an area of 4.3 km^2. While the western part of the island is characterized by a recent flood plain, the eastern part consists of an elevated terrace 10-16 m a.s.l. (Fig. 1c). This terrace is characterized by wet tundra showing the typical polygonal micro-relief, which features elevation differences of 0.2 to 1.0 m. The size of the polygons typically ranges from 5 to 10 m. The depressed polygonal centers

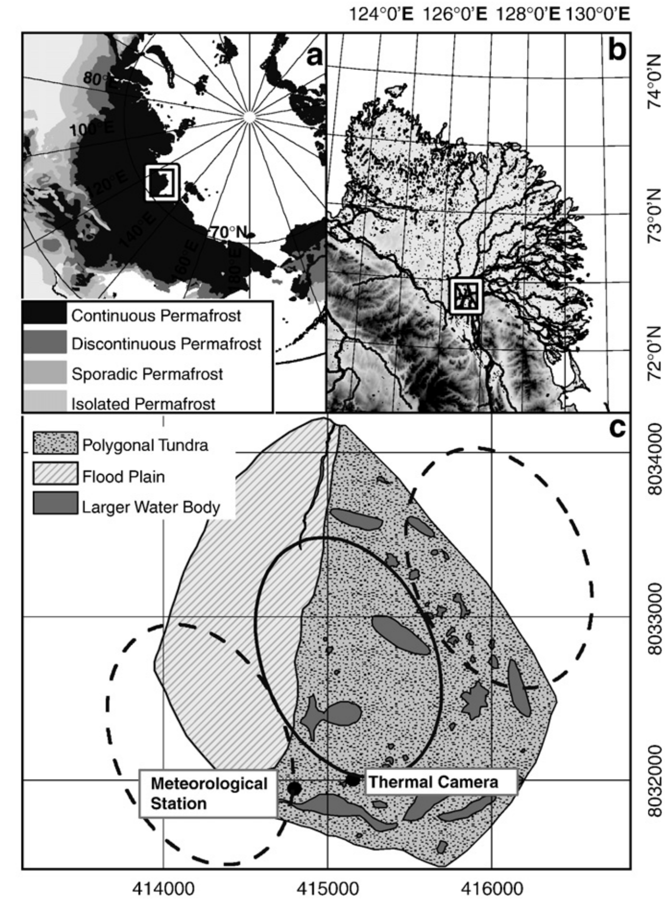

Fig. 1. (a) Location of the Lena River Delta in northern Siberia, the map shows the permafrost boundaries (Brown et al., 1997). (b) Location of Samoylov Island in the upper plain of the Lena River Delta close to one of the main river channels. (c) Measurement site on Samoylov, the ellipses show typical footprint areas of the MODIS scanner swath; the dashed ellipses indicate footprint areas which do not fit the 80% overlap criterion with the island (see Section 3.6).

consist of water saturated peat soils or they constitute shallow ponds. The vegetation at these wet locations is dominated by hydrophilic sedges and mosses (Kutzbach et al., 2004). The lowered centers are surrounded by elevated dry polygonal rims, which are dominated by mesophytic dwarf shrubs, forbs and mosses (Kutzbach et al., 2004; Sachs et al., 2008).

The experimental plot is located on the elevated terrace. It consists of three low center polygons and one polygonal pond surrounded by elevated dry rims (Fig. 2). Polygon (a) (Fig. 2) is characterized by a wet peaty center, which is dominated by hydrophilic mosses such as *Limprichtia revolvens*. Vascular plans are only sparsely distributed, while some mosses (pillows of *Aulacomium turgidum*) occur at the transition of the dry rim and the wet center. The vegetation of polygon (b) (Fig. 2) is characterized by sedges (*Carex aquatilis*) with a growth height of 20 cm. The sedge canopy is underlain by hydrophilic mosses. Polygon (c) (Fig. 2) is comparable in shape to polygon (a). It shows a similar vegetation cover, but is characterized by an increased number of isolated moss pillows (*Aulacomium turgidum*) occurring in the transition zone and in the polygon center. Polygon (d) (Fig. 2) contains a shallow pond, about 1.5 m deep. The edge of the pond is covered by sedges. The dry polygon rims are generally dominated by mesophilic mosses, such as *Hylocomium splendens*. Considerably more vascular plants occur at the dry locations. The elevation differences of the investigated polygons vary between 0.2 to 0.5 m. The water level is mostly located directly underneath the surface of the wet polygonal centers, resulting in a patchy structure of puddles and moss agglomerations. During the