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Spatio-temporal sensitivity of MODIS land surface temperature anomalies indicates high potential for large-scale land cover change detection in Arctic permafrost landscapes

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ABSTRACT

The accelerated warming of the Arctic climate may alter the local and regional surface energy balances, for which changing land surface temperatures (LSTs) are a key indicator. Modeling current and anticipated changes in the surface energy balance requires an understanding of the spatio-temporal interactions between LSTs and land cover, both of which can be monitored globally by measurements from space. This paper investigates the accuracy of the MODIS LST/Emissivity Daily L3 Global 1 km V005 product and its spatio-temporal sensitivity to land surface properties in a Canadian High Arctic permafrost landscape. The land cover ranged from fully vegetated wet sedge tundra to barren rock. MODIS LSTs were compared with in situ radiometer measurements from wet tundra areas collected over a 2-year period from July 2008 to July 2010 including both summer and winter conditions. The accuracy of the MODIS LSTs was −1.1 °C with a root mean square error of 3.9 °C over the entire observation period. Agreement was lowest during the freeze-back periods where MODIS LST showed a cold bias likely due to the overrepresentation of clear-sky conditions. A multi-year analysis of LST spatial anomalies, i.e., the difference between MODIS LSTs and the MODIS LST regional mean, revealed a robust spatio-temporal pattern. Highest variability in LST anomalies was found during freeze-up and thaw periods as well as for open water surface in early summer due to the presence or absence of snow or ice. The summer anomaly pattern was similar for all three years despite strong differences in precipitation, air temperature and net radiation. Summer periods with regional mean LSTs above 5.0 °C showed the greatest spatial diversity with four distinct 2.0 °C classes. Summer anomalies ranged from −4.5 °C to 2.6 °C with an average standard deviation of 1.8 °C. Dry ridge areas heated up the most, while wetland areas and dry areas of sparsely vegetated bedrock with a high albedo remained coolest. The observed summer LST anomalies can be used as a baseline against which to evaluate both past and future changes in land surface properties that relate to the surface energy balance. Summer anomaly classes mainly reflected a combination of albedo and surface wetness. The potential to use this tool to monitor surface drying and wetting in the Arctic should therefore be further explored. A multi-sensor approach combining thermal satellite measurements with optical and radar imagery promises to be an effective tool for a dynamic, process-based ecosystem monitoring scheme.

1. Introduction

Arctic land surface temperatures are increasing twice as rapidly as global temperatures, as has been indicated by measurements both on the ground (ACIA, 2005; AMAP, 2011; Hinzman, Bettez, & Bolton, 2005; Parry, 2007) and from space (Comiso, 2003, 2006). Land surface warming results in associated changes in land surface properties, especially in areas underlain by permafrost. The thawing of ground ice in permafrost soils causes the ground to subside and lake shorelines to erode. As a consequence, surface wetting is observed due to the expansion of lakes and the formation of new ponds (Jorgenson, Racine, Walters, & Osterkamp, 2001; Jorgenson, Shur, & Pullman, 2006; Smith, Sheng, MacDonald, & Hinzman, 2005; Watts, Kimball, Jones, Schroeder, & McDonald, 2012). The thawing of ground ice may also lead to surface drying as a result of lake drainage (Carroll, Townshend, DiMiceli, Loboda, & Sohlberg, 2011; Smith et al., 2005; Yoshikawa & Hinzman, 2003). Current climate projections of the Arctic predict even more dramatic changes in land surface properties. This includes the spread of shrub and forest at the expense of tundra (Matthes et al., 2012) with associated changes in albedo (Chapin, Sturm, & Serreze, 2005; Sturm, Racine, & Tape, 2001) that are expected to amplify temperature changes over land (Euskirchen et al., 2007; Hinzman et al., 2013). Such land cover changes also affect other biogeophysical surface

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properties, such as soil moisture, emissivity, and surface roughness, all of which regulate the surface energy balance, i.e., the partitioning of the available net radiation into the sensible and latent heat flux and the ground heat flux (Hinzman et al., 2013). Radiometric land surface temperatures (LSTs) are dependent on the surface energy balance and reflect the combined effects of land surface properties and atmospheric conditions, which together control the transfer of energy into either the atmosphere or the ground (Dickinson, 1983; Friedl, 2002; Jin & Dickinson, 2010; Mannstein, 1987). LST is therefore a key parameter for both modeling and monitoring the surface energy balance.

Satellite-borne thermal sensors provide access to LSTs over large areas. This is especially invaluable in the vast and remote Arctic landscapes, where ground-based observations of LSTs are sparse. Sensors such as the Landsat and ASTER sensors provide medium resolutions of 90 m, but are limited in both areal coverage and temporal resolution. Sensors with global coverage, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) have a limited spatial resolution of 1 km or more but a high temporal resolution, with several measurements per day in the Polar Regions. MODIS LSTs provide a versatile tool that can be used for both modeling and monitoring applications which are essential for assessing and anticipating changes in the hydrology, ecology, and climatology of Arctic ecosystems. The use of MODIS LSTs for permafrost modeling in the Arctic has been demonstrated by Langer, Westermann, and Boike (2010), Westermann, Langer, and Boike (2011), and Langer, Westermann, Heikenfeld, Dorn, and Boike (2013). Other studies successfully used MODIS LST to monitor changes in vegetation and land cover (Bhatt et al., 2013; Coops, Wulder, & Iwanicka, 2009; Zhang, Friedl, Schaaf, & Strahler, 2004).

The interpretation of LST changes in Arctic environments in terms of the surface energy balance requires an understanding of the relationship between the measurement uncertainty in LSTs and their spatio-temporal sensitivity. Efforts have recently increased to quantify LST uncertainty in the high latitudes by consolidating LST data sources (Soliman, Duguay, Saunders, & Hachem, 2012) and by comparing LSTs to ground and air temperatures over large regions, including herbaceous and shrub tundra sites in northern Quebec, Canada, and on the North Slope of Alaska, USA (Hachem, Duguay, & Allard, 2012). Comparisons have also been made with in situ radiometer measurements at a polygonal tundra site in Siberia (Langer et al., 2010), at a barren site (Westermann, Langer, & Boike, 2011, 2012) and an Arctic ice cap on Svalbard (Østby et al., 2014). Few case studies have attempted to elaborate the specific relationship between land surface characteristics and remotely sensed LSTs in Arctic environments, where permafrost plays a crucial role in the surface energy balance. Those that have were conducted at diverse temporal and spatial scales. Regional surface thermal patterns have been investigated in relation to the Normalized Difference Vegetation Index (NDVI), land cover, and elevation in boreal and tundra landscapes of northern Canada, but only for single snapshots in summer (Bussières, 2002; Gota, Royer, & Bussières, 1997). Langer et al. (2010) and Westermann et al. (2011) discussed the effect of net radiation and surface soil moisture on MODIS LSTs over the course of a summer season in Siberian ice-wedge polygonal tundra and at a barren site on Svalbard, but their investigations were spatially restricted to a single MODIS pixel.

In this study we have evaluated the use of MODIS LSTs to detect large-scale land surface changes in an Arctic permafrost tundra landscape. To this end, a two year record of MODIS LSTs for Bathurst Island, in the Canadian High Arctic, has been evaluated. The study area includes a broad range of typical Arctic land cover types, ranging from fully vegetated wet sedge tundra to barren rock areas. Specific objectives of the study were (i) to validate the performance of the MODIS LST/Emissivity Daily L3 Global 1 km V005 product against in situ radiometer measurements, (ii) to investigate the spatial and temporal relationships between MODIS LSTs and land surface properties, and (iii) to assess the sensitivity of MODIS LSTs with regard to land cover change detection.

2. Study area

Bathurst Island (98°30′W, 75°40′N) is located in the central zone of the Canadian Arctic Archipelago in Nunavut, Canada (Fig. 1a). It has a typical polar desert climate with long, cold winters and short, cool summers (Young & Labine, 2010). The climate does not significantly differ from the climate at Resolute Bay on Cornwallis Island, which lies about 145 km to the southeast, where long-term climate records are available dating back to 1948. The mean January air temperature is −32.2 °C in Resolute Bay and the mean July air temperature is 4.3 °C (downloaded from http://climate.weather.gc.ca/). The mean annual precipitation for the years 1948 to 2007 is about 159 mm (Mekis & Vincent, 2011). Air temperatures have been warming at both Resolute Bay and Polar Bear Pass over the last decade (Woo & Young, 2014).

In low-lying areas the underlying permafrost impedes drainage which results in poorly drained, highly saturated soils (Woo & Young, 2006). These wetland and wet sedge tundra areas support unusually productive habitats with a plant cover of 65% or more in the otherwise dry and barren environment. One of the largest continuous areas of wetland on the island is Polar Bear Pass (PBP), which has a surface area of about $94 * 10^6$ m^2 and is located in the study area (Fig. 1c). PBP has been designated a National Wildlife Area by the Canadian Wildlife Service as well as a waterfowl habitat of international importance according to the Ramsar Convention (http://www.ramsar.org/). It is a crucial staging area for migratory birds and also a bird breeding area. It serves as a key travel route for polar bears during spring and summer and is a vital habitat for muskoxen and caribou. The PBP wetland area is bordered by hills that reach about 240 m above sea level; runoff from these hillslopes supplies both water and sediment into the adjacent wetland area (Woo & Young, 2006). Within the wetland zone, moss, grass, and sedge meadows alternate with sparsely vegetated dry ridges and numerous small ponds and lakes, creating a patchy land cover pattern. Plant growth is limited to the short snow-free season which typically lasts from mid-June to the end of August. Soil conditions and plant communities reflect the local water supply (Edlund & Alt, 1989; Nettleship & Smith, 1975; Sheard & Geale, 1983). Uplands and plateaus are comparatively dry with a low total plant cover; plant communities in these areas consist of scattered herbaceous perennials with varying amounts of lichen (Sheard & Geale, 1983).

3. Methods

3.1. Measuring in situ LST and climate data

In situ LST measurements were recorded using a Precision Infrared Temperature Sensor (IRTS-P, Apogee Instruments) over wet sedge tundra (Fig. 2). The sensor was mounted 0.83 m above the canopy, with a field of view of about 0.28 m in diameter. The IRTS-P had an accuracy of ±0.5 °C in the range of −40 to 80 °C. In situ LST measurements were recorded from July 2008 to July 2010. Battery failure led to a measurement gap between July 13 and July 21, 2009, July 17 and July 21, 2010 as well as between December 23, 2009 and April 27, 2010.

An automatic weather station was set up a few meters from the radiometer station and recorded net radiation, incoming short-wave radiation, and air temperature over the same time period as the in situ LST measurements. Net radiation and incoming short-wave radiation were measured with a NR Lite (Kipp & Zonen) with an accuracy of 0.01 MJ m^{-2}. The air temperature was measured with a CS215 temperature probe (Campbell Scientific, Inc.), which had an accuracy of ±0.2 °C. The total daily precipitation was recorded from the beginning of June to the end of August, using a tipping bucket rain gauge (Campbell Scientific, Inc.) with an accuracy of ±0.25 mm. During summer, sky condition was classified visually twice daily and served as a qualitative measure with which to characterize distinct synoptic periods. We distinguished between snow-covered and snow-free