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Satellite-based modeling of permafrost temperatures in a tundra lowland landscape

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ABSTRACT

Remote sensing offers great potential for detecting changes of the thermal state of permafrost and active layer dynamics in the context of Arctic warming. This study presents a comprehensive feasibility analysis of satellite-based permafrost modeling for a typical lowland tundra landscape in the Lena River Delta, Siberia. We assessed the performance of a transient permafrost model which is forced by time series of land surface temperatures (LSTs) and snow water equivalents (SWEs) obtained from MODIS and GlobSnow products. Both the satellite products and the model output were evaluated on the basis of long-term field measurements from the Samoylov permafrost observatory. The model was found to successfully reproduce the evolution of the permafrost temperature and freeze-thaw dynamics when calibrated with ground measurements. Monte-Carlo simulations were performed in order to evaluate the impact of inaccuracies in the model forcing and uncertainties in the parameterization. The sensitivity analysis showed that a correct SWE forcing and parameterization of the snow's thermal properties are essential for reliable permafrost modeling. In the worst case, the bias in the modeled permafrost temperatures can amount to 5 °C. For the thaw depth, a maximum uncertainty of about ±15 cm is found due to possible uncertainties in the soil composition.

1. Introduction

Satellite-based earth observation has become an indispensable tool for the investigation of climate change especially in remote areas such as the polar regions (Hall, 1988). For most of the cryosphere components such as glaciers, ice sheets, sea ice, and snow cover satellite monitoring and change detection has been established for several decades (e.g. Armstrong & Brodzik, 2001; Rignot & Thomas, 2002; Stroeve et al., 2007). Although permafrost is one of the largest components of the Arctic cryosphere, satellite-based monitoring schemes do not exist. Nevertheless, numerous ecosystem processes of the Arctic are directly or indirectly related to the thermal state of permafrost and the freeze–thaw dynamics of the upper most soil (active) layer (Van Everdingen, 1998). This is especially true for the energy, water, and carbon cycles which are strongly determined by sub-surface processes that often operate on spatial scales below the grid spacing of atmospheric models (Wania et al., 2009a,b). If satellite-based permafrost monitoring can provide an improved spatial resolution, this would strongly improve the impact assessment of climate change in the Arctic (ACIA, 2004; AMAP, 2011). In addition, an operational scheme could be beneficial for risk analysis for infrastructure such as roads, pipelines, and buildings which are directly affected by the thermal stability of permafrost (Larsen et al., 2008).

One of the biggest challenges is that permafrost is a subsurface thermal phenomenon which cannot be directly observed by remote sensing techniques. Thus, current approaches of permafrost monitoring make use of surface indicators such as vegetation cover (Stow et al., 2004), geomorphological units, or combinations of different surface features (Panda et al., 2010) in order to infer information about the permafrost conditions. However, these methods can only provide a qualitative measure of the thermal state of permafrost and changes are only detected when there is an impact on the surface. The application of land surface temperature (LST) records measured by satellites such as MODIS in order to retrieve freeze–thaw degree days is proposed by Hachem et al. (2009). In principle, such LST time series can be used to force a transient permafrost model that is able to reproduce the full thermal dynamics of the ground as proposed by Marchenko et al. (2009). Further studies suggest that the quality as well as the spatial and temporal resolution of MODIS LST products would be sufficient for permafrost modeling in non-mountainous terrain (Langer et al., 2010; Westermann et al., 2011b). However, model approaches are always subject to numerous assumptions, limitations, and uncertainties resulting from e.g. neglected processes and uncertainties in the forcing data or parameter settings (Boike et al., 2012b). Especially the soil and snow properties such as water/ice content, thermal conductivity, heat capacity, and density are usually unknown which introduce large

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uncertainties in heat flow calculations (e.g. Goodrich, 1982; Gouttevin et al., 2012; Rinke et al., 2008).

This study provides a proof-of-concept for a satellite-based permafrost monitoring and assesses its performance for a typical low land tundra site in NE Siberia. We (i) perform a thorough validation for the employed satellite data at the study site, (ii) present a thermal permafrost model forced by satellite data that delivers soil temperature and thaw depth, and (iii) evaluate the performance of the scheme and provide a sensitivity analysis for uncertain model parameters and inaccurate forcing data.

2. Validation site

The study site is located in Northern Siberia on Samoylov Island (72.4°N; 126.5°E) in the Lena-River Delta (Fig. 1). The local climate is described as arctic-continental with a mean annual air temperature (MAAT) of about −13 °C and a large annual air temperature amplitude ranging from about −45 °C in winter to 20 °C in summer (Boike et al., 2012a). The total annual precipitation is about 200 mm of which about 25% falls as snow during winter (Boike et al., 2008; Langer et al., 2011a). The polar night lasts from the mid of November to end of January and polar day lasts from the beginning of May until the beginning of August. Samoylov Island features a typical tundra landscape underlain by continuous permafrost. The permafrost reaches depths of about 200 m (Grigoriev, 1960) and features relatively cold temperatures of about −9 °C at the depth of zero annual amplitude (20 m) (Boike et al., 2012b). However, temperature observations indicate strong changes in the thermal state of permafrost which shows a steady warming of about 1 °C between 2006 and 2011 at a depth of about 10 m (Boike et al., 2012a).

Samoylov Island belongs to an alluvial river terrace (Schwamborn et al., 2002) elevated about 20 m above the normal river water level. The lower western part of the island constitutes a modern floodplain which is frequently flooded during ice break-up of the Lena River during spring. The validation site of this study is located on the elevated river terrace mainly characterized by moss and sedge vegetated tundra (Fig. 1). In addition, several lakes and ponds occur which make up about 25% of the surface area of Samoylov Island (Muster et al., 2012). The land surface of the island features the typical microrelief of polygonal patterned ground caused by frost cracking and subsequent ice-wedge formation (Lachenbruch, 1962). The polygonal structures usually consist of depressed centers which are surrounded by elevated rims. The polygonal structures often occur in different stages of degradation with partly to completely collapsed rims. The soil in the polygonal centers usually consists of water saturated sandy peat with the water table standing close to or above the surface (Langer et al., 2011a). The elevated rims are usually covered with a dry moss layer underlain by wet sandy peat soils featuring massive ice wedges. The volumetric water/ice content of the peat soils typically ranges from 60 to 80%. The volumetric mineral content is reported to range from 20 to 40% while the volumetric organic content is on the order of 5 to 10% (Kutzbach et al., 2004; Zubrzycki et al., 2012). This cryogenic soil complex reaches depth of 10 to 15 m and is underlain by sandy to silty river deposits. The Lena River deposits are reported to reach depths of at least 1 km in the delta region (Grigoriev et al., 1996).

3. Methods

3.1. Model description

This study makes use of a 1D soil heat transfer model capable of representing the freeze–thaw cycle and a dynamic snow cover formation and ablation. The model is based on solving the heat transfer

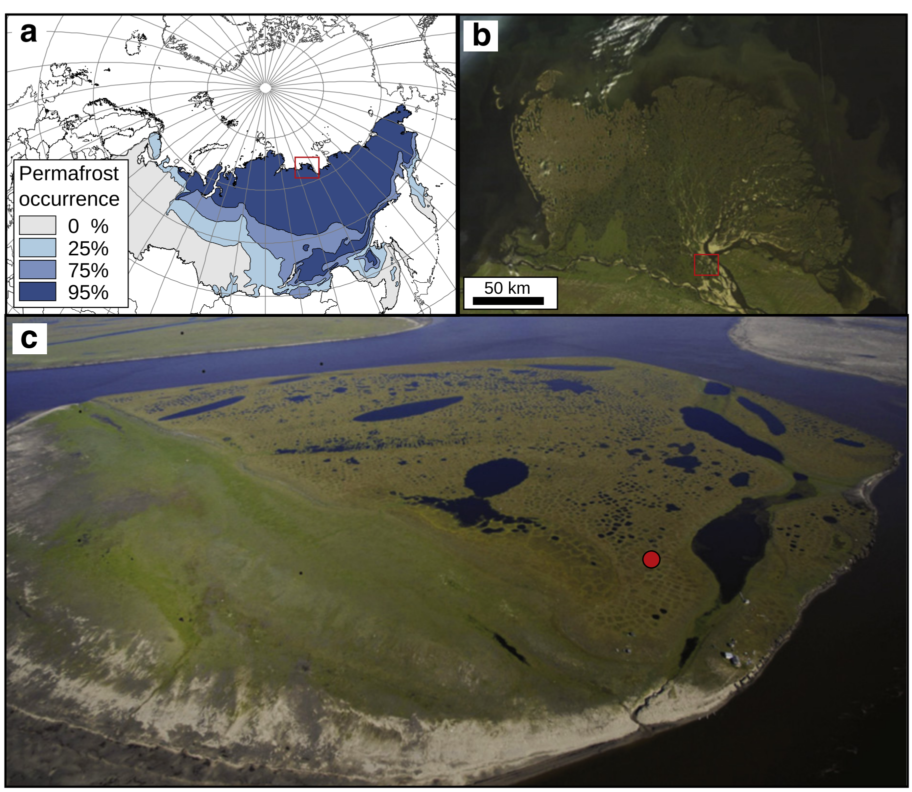

Fig. 1. Location of the validation site on Samoylov Island. (a) Extent of permafrost in Russia with the location of the Lena River Delta marked with a red box (after Kotlyakov & Khromova, 2002). (b) MODIS (Terra) satellite image of the Lena River Delta obtained in August 2012 (NASA, 2012). (c) Aerial photograph of Samoylov Island featuring a surface area of about 4.5 km^2. The location of the measurement site is marked with a red dot.