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Spatio-temporal variability of X-band radar backscatter and coherence over the Lena River Delta, Siberia

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ABSTRACT

Satellite-based monitoring strategies for permafrost remain under development and are not yet operational. Remote sensing allows indirect observation of permafrost, a subsurface phenomenon, by mapping surface features or measuring physical parameters that can be used for permafrost modeling. We have explored high temporal resolution time series of TerraSAR-X backscatter intensity and interferometric coherence for the period between August 2012 and September 2013 to assess their potential for detecting major seasonal changes to the land surface in a variety of tundra environments within the Lena River Delta, Siberia. The TerraSAR-X signal is believed to be strongly affected by the vegetation layer, and its viability for the retrieval of soil moisture, for example, is therefore limited. In our study individual events, such as rain and snow showers, that occurred at the time of TerraSAR-X acquisition, or a refrozen crust on the snowpack during the spring melt were detected based on backscatter intensity signatures. The interferometric coherence showed marked variability; the snow cover onset and snow melt periods were identified by significant reduction in coherence. Principal component analysis provided a good spatial overview of the essential information contained in backscatter and coherence time series and revealed latent relationships between both time series and the surface temperature.

The results of these investigations suggest that although X-band SAR has limitations with respect to monitoring seasonal land surface changes in permafrost areas, high-resolution time series of TerraSAR-X backscatter and coherence can provide new insights into environmental conditions.

1. Introduction

Permafrost affects nearly 24% of the land surface in the northern hemisphere, making it one of the largest areal components of the cryosphere. According to Hugelius et al. (2014), permafrost soils in the northern hemisphere contain a total of about 1300 Pg of organic carbon. The release of carbon dioxide and methane from thawing arctic permafrost is currently a major focus of climate change science. Moreover, irreversible landscape transformations resulting from a warming climate (e.g. thaw subsidence, thermo-erosion, and slope failure) disturb the hydrology, fluxes of energy and matter, and moisture balance, affecting both ecosystems and human infrastructure (e.g. Nelson, Anisimov, & Shiklomanov, 2001; Kääb, 2008; Osterkamp et al., 2009; Jorgenson et al., 2013). These far-reaching consequences make the monitoring of the thermal conditions and structural stability of permafrost and the prediction of its future state particularly important.

Sporadic and intermittent in situ observations are often inadequate for monitoring surface changes considering the vastness, remoteness, and poor accessibility of the Arctic region. Satellite remote sensing offers a possible alternative that is able to provide both regular observations and broad spatial coverage. Satellite monitoring systems are well established for other components of the cryosphere (e.g. glaciers, sea ice and snow cover), and provide essential information on the processes and impacts of a changing climate on the Arctic region. In contrast, no such monitoring systems currently exist for permafrost, mainly because permafrost is a sub-surface element and cannot be monitored directly through satellite observations (Westermann, Duguay, Grosse, & Kääb, 2015a).

However, various land surface changes that occur in association with permafrost degradation (such as the formation, expansion, and drainage of lakes, or the occurrence of thaw slumps and ground thaw subsidence) are observable by remote sensing and can therefore provide insight into the actual condition of the underlying permafrost (e.g. Duguay, Zhang, Leverington, & Romanovsky, 2005; Riordan, Verbyla, & McGuire, 2006; Mars & Houseknecht, 2007; Lantuit & Pollard, 2008; Jones et al., 2011; Günther, Overduin, Sandakov, Grosse, & Grigoriev, 2013). In addition, different remote sensing products such as land surface temperature and snow water equivalent can be used as forcing data for permafrost modeling (Langer, Westermann, Heikenfeld, Dorn, & Boike, 2013; Westermann, Østby, Gisnås, Schuler, & Etzelmüller, 2015b). Despite a number of successes in the use of remote sensing for permafrost-related problems, operational satellite-based permafrost

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monitoring systems remain under development and in need of further improvement (Westermann et al., 2015a).

1.1. SAR backscatter intensity for seasonal change detection

Microwave imagery has a distinct advantage over optical imagery in polar areas as it allows data to be acquired independently of cloud cover and solar illumination. Synthetic Aperture Radar (SAR) is an active microwave system that transmits pulses of energy to the target and receives an echo of these pulses through an antenna. The backscatter intensity (subsequently referred to simply as backscatter) of an SAR signal is the portion of transmitted energy that is received by the system. Two properties of the backscattering surface that mainly define the backscatter are the surface roughness and the dielectric constant of the backscattering media. Since the presented study has one focus on radar backscatter, we outline those factors that have the potential to influence backscatter in the context of a typical tundra environment underlain by permafrost. There are static conditions such as the variations in surface roughness associated with different land cover types, and dynamic conditions associated with, for example, soil moistening and drying, soil freezing and thawing, or snow cover onset and melt. Higher surface roughness (relative to the SAR wavelength) typically causes diffuse scattering resulting in higher backscatter, whereas smooth surfaces cause more specular reflection of the signal resulting in lower backscatter. Where surfaces are vegetated it is important to take into account volume scattering within the vegetation which can significantly alter the total backscatter either due to increased backscatter by leaves and branches or due to attenuation of the backscattered signal from the terrain beneath the vegetation layer.

The moisture of soil or vegetation affects the backscatter due to variations in their dielectric properties with water content. Moister soil normally results in higher backscatter than the drier soil. The relationships between radar backscatter and soil moisture have been investigated by, for example, Ulaby, Batlivala, and Dobson (1978); Ulaby, Bradley, and Dobson (1979); Kane, Hinzman, Haofang, and Goering (1996); Lu and Meyer (2002). The backscatter from frozen ground appears similar to that from dry ground because the dielectric constant is much lower for water in a frozen state than for water in a liquid state. Freezing of the ground therefore typically reduces the backscatter and thawing results in a higher backscatter. The influence of ground freezing and thawing on backscatter has been investigated by, for example, Wegmüller (1990) and Rignot and Way (1994). The presence of snow cover affects backscatter in a more complicated manner than freezing and thawing or variations in soil moisture. This is due to complex backscattering within the snowpack and from its surface, as well as from the surface of the ground beneath (if reached by the radar waves). SAR system properties, acquisition parameters, and snowpack conditions all have a strong influence on the observed backscatter. Dry snow typically appears “transparent” to SAR frequencies such as those in X-band and lower, and backscattering occurs mainly from the ground surface beneath the snowpack (e.g. Mätzler & Schanda, 1984). Wetting of the snow can have a major effect on the backscatter as the dielectric contrast at the air-snow interface becomes significant and energy transmission into the snowpack is reduced. The snow surface properties then begin to have a major effect on the backscattered signal, with smooth surfaces (relative to the wavelength of the signal) resulting in low backscatter due to specular reflection of the signal and rough surfaces resulting in higher backscatter.

Volume scattering within the snowpack is influenced by the SAR frequency and acquisition incidence angle, as well as by the properties of the snow such as its density, liquid water content, and grain size. Snow metamorphism, such as changes in crystal size and structure or the formation of ice lenses or layers, can also influence backscatter (e.g. Du, Shi, & Rott, 2010). Backscatter signatures from different snow conditions have been investigated by, for example, Strozzi, Wiesmann, and Mätzler (1997) and Nagler and Rott (2000).

Radar parameters such as frequency, incidence angle, and polarization configuration had a strong influence on the results of the above-mentioned investigations, for which C-band scatterometers and SAR were commonly used. Far fewer investigations into the conditions and processes related to permafrost have been carried out using higher frequency X-band sensors due to the limited availability of such data to date. Among these are investigations by Regmi, Grosse, Jones, Jones, and Anthony (2012) who used TerraSAR-X backscatter for dating drained thermokarst lake basins, by Ullmann et al. (2014) who carried out polarimetric analysis of TerraSAR-X data for different tundra surfaces in the Canadian Arctic, and by Duguay, Bernier, Lévesque, and Tremblay (2015) who tested the use of TerraSAR-X backscatter for monitoring tundra shrub growth.

1.2. SAR interferometric coherence

A second focus of this study is on radar coherence over permafrost landscapes. In contrast to SAR backscatter analysis, SAR interferometry (InSAR) exploits the phase component of the microwave signal. It uses the phase difference between two SAR images covering the same area but acquired at different times to detect surface displacements. InSAR has been shown to be a powerful technique for detecting ground displacement associated with earthquakes and volcanic eruptions (e.g. Massonnet et al., 1993). The method has also recently been tested for monitoring permafrost thaw subsidence and frost heave (e.g. Rykhus & Lu, 2008; Liu, Zhang, & Wahr, 2010; Short et al., 2011; Strozzi, Wegmüller, Werner, & Kos, 2012; Liu et al., 2014; Liu et al., 2015; Beck, Ludwig, Bernier, Strozzi, & Boike, 2015). Other applications of InSAR are for monitoring water level and inundations in the wetlands (e.g. Alsdorf et al., 2000; Hong, Wdowinski, Kim, & Won, 2010; Xie, Shao, Xu, Wan, & Fang, 2013) and for the retrieval of snow water equivalent (Guneriussen, Høgda, Johnsen, & Lauknes, 2001; Rott, Nagler, & Scheiber, 2003; Deeb, Forster, & Kane, 2011).

One of the main limitations of InSAR is the signal loss due to insufficient phase coherence between SAR datasets. This phase coherence (or interferometric correlation) over time indicates the quality of the interferometric phase. There are a number of possible reasons for a loss of phase coherence including thermal noise from the antenna, a large interferometric baseline, topographic effects, misregistration between the SAR images, and atmospheric effects, but it can also be due to land surface changes that occur between SAR acquisitions (Zebker & Villasenor, 1992). The latter are of special interest here because if all other factors causing decorrelation are minimized, the temporal decorrelation due to changes in the land surface can be used as a direct geophysical signal for the detection and interpretation of such changes (e.g. Rignot & Van Zyl, 1993; Wegmüller & Werner, 1997). Interferometric coherence is defined by both amplitude and phase components of the SAR signal and is therefore potentially more sensitive to changes in the land surface than amplitude variations alone. The use of coherence has, however, been less investigated compared to the use of changes in backscatter. Examples of coherence use include the detection of changes in glacier surfaces (Weydahl, 2001a), delineation of the extent of glaciers (Atwood, Meyer, & Arendt, 2010; Frey, Paul, & Strozzi, 2012), Arctic ecozones classification (Hall-Atkinson & Smith, 2001), and mapping wet snow covers (Strozzi, Wegmüller, & Mätzler, 1999).

Similar factors to those influencing backscatter (as discussed in the previous sub-section), may also affect coherence. Some studies have used SAR coherence to supplement backscatter for the detection of temporal changes to the ground conditions (e.g. Rignot & Van Zyl, 1993; Strozzi et al., 1999; Moeremans & Dautrebande, 2000; Barrett, Whelan, & Dwyer, 2012). The results of these investigations have suggested a limited sensitivity of coherence to moisture variations or soil freeze and thaw (i.e. to changes in dielectric properties) compared to variations in backscatter. Far more marked decorrelation can occur due to physical displacement of backscattering elements (for example, due to soil ploughing), a complete change in the nature of backscattering elements (such as from snow-free to snow-covered surfaces, or from bare ground to vegetated ground), or to volumetric decorrelation