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Widespread permafrost vulnerability and soil active layer increases over the high northern latitudes inferred from satellite remote sensing and process model assessments

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ABSTRACT

Permafrost extent (PE) and active layer thickness (ALT) are important for assessing high northern latitude (HNL) ecological and hydrological processes, and potential land–atmosphere carbon and climate feedbacks. We developed a new approach to infer PE from satellite microwave remote sensing of daily landscape freeze–thaw (FT) status. Our results document, for the first time, the use of satellite microwave FT observations for monitoring permafrost extent and condition. The FT observations define near-surface thermal status used to determine permafrost extent and stability over a 30-year (1980–2009) satellite record. The PE results showed similar performance against independent inventory and process model (CHANGE) estimates, but with larger differences over heterogeneous permafrost subzones. A consistent decline in the ensemble mean of permafrost areas (-0.33 million km^2 decade^{-1}; $p < 0.05$) coincides with regional warming (0.4 °C decade^{-1}; $p < 0.01$), while more than 40% (9.6 million km^2) of permafrost areas are vulnerable to degradation based on the 30-year PE record. ALT estimates determined from satellite (MODIS) and ERA-Interim temperatures, and CHANGE simulations, compared favorably with independent field observations and indicate deepening ALT trends consistent with widespread permafrost degradation under recent climate change.

1. Introduction

Climate change is causing widespread warming in the permafrost zone, defined as permanently frozen ground and occupying approximately one quarter of the Northern Hemisphere land area (Payette, Delwaide, Caccianiga, & Beaucjemin, 2004; Romanovsky, Smith, & Christiansen, 2010; Zhang, Olthof, Fraser, & Wolfe, 2014). Warming of permafrost influences multiple interactive properties affecting land–atmosphere water, energy and trace gas exchange, including active layer thickness (ALT) defined as the maximum depth of seasonal thawing in soil layers overlying permafrost (Hayes et al., 2014; Vaughan et al., 2013). The freeze/thaw (FT) signal observed from satellite microwave remote sensing captures abrupt shifts in landscape dielectric properties between predominantly frozen and non-frozen conditions (Kimball, McDonald, Running, & Frolking, 2004; Kim, Kimball, McDonald, & Glassy, 2011). The relatively coarse (~25-km resolution), but near-daily FT observations from available global satellite environmental data records provide for effective high northern latitude (HNL) regional monitoring of the timing and duration of frozen and non-frozen seasons, which may be interactive with underlying soil and permafrost conditions; however, finer scale properties, including vegetation composition, organic litter layers, subsurface drainage, snow cover, and topography may be dominant factors influencing permafrost distribution and condition at local scales (Duguay, Zhang, Leverington, & Romanovsky, 2005; Zhang et al., 2014; Podest, McDonald, & Kimball, 2014).

Regional permafrost extent (PE) is difficult to determine from direct ground surveys of permafrost features (e.g., digging, core drilling, and temperature measurements in boreholes) due to the extensive PE domain, high costs and inconsistent sampling (Duguay et al., 2005). Consequently, indirect methods for regional PE estimation have been employed using near-surface indicators of underlying permafrost inferred from remote observations of vegetation cover, ground thermal (air and surface temperatures) and hydrological parameters (snow depth and soil moisture) (Minsley et al., 2012; Nguyen, Burn, King, & Smith, 2009; Panda, Prakash, Jorgenson, & Solie, 2012). Land surface modeling is commonly used to estimate PE and related subsurface processes at coarse spatial resolution (Burke, Kankers, Jones, & Wiltshire, 2013; Gruber, 2012; Lawrence, Slater, & Swenson, 2012; Park et al., 2013). Coarse regional patterns of PE can also be observed from sparse climate stations or model reanalysis of interpolated station observations (Zhang et al., 2014). Satellite optical–infrared (IR) remote sensing has been used to infer PE from empirical analyses of various surface indicator observations, including vegetation, land cover, thermokarst ponds and terrain (Morrissey, Strong, & Card, 1986; Panda et al., 2012), and

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image classification techniques (Leverington & Duguay, 1997; Nguyen et al., 2009; Yoshikawa & Hinzman, 2003). However, there are limitations in identifying presence/absence of permafrost due to optical–IR sensor constraints under low light levels and persistent cloud cover conditions characteristic of HNL landscapes. Alternatively, microwave remote sensing is well-suited for identifying permafrost features (Dean & Morrissey, 1988; Granberg, 1994; Yoshikawa & Hinzman, 2003) and degradation (Granberg, 1994; Strozzi, Kaab, & Frauenfelder, 2004), with minimal negative impacts from solar illumination, cloud and atmosphere aerosol contamination. However, to date, little is known regarding the potential for satellite microwave remote sensing to be used for regional PE characterization and monitoring.

The motivation for this study was to develop an effective approach for HNL assessment and monitoring of PE using available satellite microwave remote sensing observations of landscape FT status; here an existing global satellite microwave FT Earth System Data Record (FT-ESDR; Kim, Kimball, Zhang, & McDonald, 2012, Kim, Kimball, Glassy and McDonald, 2014) is used to infer subsurface permafrost conditions and PE. The PE results derived from the FT-ESDR inputs were evaluated against other independent PE estimates from a land surface model (CHANGE; Park et al., 2011) and a static regional inventory based permafrost map (Brown, Ferrians, Heginbottom, & Melnikov, 2014). To our knowledge, this is the first study to estimate PE over the HNL domain using satellite passive microwave remote sensing based FT observations. The FT-ESDR derived PE also defined the domain for estimating ALT and associated changes in the ground thermal regime overlying permafrost using a previously developed empirical method (Zhang et al., 2005) and ancillary surface temperature inputs from both satellite thermal IR remote sensing and global model reanalysis data. These results were evaluated against alternative ALT estimates determined from sparse soil temperature station observations, global model reanalysis, and independent process model simulations. The resulting PE and ALT estimates were determined over a 30-year study period (1980–2009) at 25-km spatial resolution and yearly time step, and used to evaluate regional patterns and recent trends in HNL permafrost and active layer conditions.

2. Data and methods

2.1. Microwave remote sensing based estimation of permafrost extent

We used a global landscape FT-ESDR derived from daily (ascending and descending orbit) 37 GHz, vertically polarized brightness temperature observations from calibrated SMMR (scanning multi-channel microwave radiometer) and SSM/I (special sensor microwave imager) satellite sensor records (Kim, Kimball, Glassy and McDonald, 2014); the FT-ESDR was used to estimate PE over the HNL domain, including all vegetated land area poleward of 45°N. Grid cells characterized by predominantly barren land, permanent ice and snow, and open water bodies are excluded from the FT classification (Kim et al., 2012). The FT-ESDR provides a daily measure of the predominant landscape FT status within each 25-km grid cell posted to an EASE-Grid projection (Brodzik & Knowles, 2002) for the period 1979–2012 (Kim et al., 2012; Kim, Kimball, Glassy and McDonald, 2014). The FT-ESDR is derived from 37 GHz brightness temperatures that are sensitive to land surface FT conditions, but relatively insensitive to potential atmosphere contamination effects (Holmes, De Jeu, Owe, & Dolman, 2009; Kim, Kimball, Didan and Henebry, 2014). The FT-ESDR classifies the predominant frozen or non-frozen condition of the land surface on a daily basis within each grid cell and does not distinguish among individual landscape elements within the sensor field-of-view (FOV), including vegetation, snow cover and soil components. Satellite microwave sensitivity to these landscape elements is frequency dependent, whereby the 37 GHz FT retrievals are expected to be more directly sensitive to land surface conditions, rather than deeper vegetation, snow and soil active layer properties. The estimated FT-ESDR mean annual spatial classification accuracy is approximately 84–91% relative to in situ surface air temperature measurements from the global weather station network (Kim et al., 2012). The seasonal FT-ESDR classification accuracy was generally lower during spring and fall transitional periods, and higher during winter frozen and summer non-frozen periods (Kim et al., 2011); there was also no significant difference in mean FT classification accuracy between the spring (MAM) and fall (SON) periods.

PE has previously been determined manually using the ratio of annual degree days of freezing and thawing, mean annual air temperature, and field observations (Gruber, 2012; Nelson & Outcalt, 1987). The southern limit of permafrost corresponds roughly with the ±1 °C mean annual surface air temperature isotherm (Duguay et al., 2005; Romanovsky et al., 2010). Recent studies showing favorable correspondence between satellite microwave derived surface FT state dynamics and soil active layer thermal properties from in situ monitoring stations, including Global Terrestrial Network of Permafrost (GTN-P) sites, indicate potential utility for satellite-based permafrost monitoring (Naeimi et al., 2012; Du et al., 2014). In this study, regional permafrost extent and condition within the HNL domain was estimated from the satellite microwave remote sensing based FT-ESDR, whereby land surface FT conditions captured by the sensor were assumed to be an effective indicator of underlying soil active layer thermal conditions affecting permafrost. Based on this methodology, grid cells were classified as permafrost where the cumulative number of FT-ESDR defined frozen days exceeded non-frozen days during a water year (September 1 to August 31) and over at least two consecutive years. This approach is consistent with previous studies indicating that when the number of yearly frozen days exceed non-frozen days, the top ground layer experiences longer seasonal freezing, and frost penetration depth increases over time accordingly, leading to permafrost occurrence (Dobinski, 2011; Nelson & Outcalt, 1987; Saito et al., 2013; Zhang et al., 2005). However, deviations from this general premise can occur due to spatial heterogeneity in insulating surface properties, including snow cover, soil organic layer thickness and vegetation cover, especially within southern permafrost boundary regions.

The FT-ESDR PE results were evaluated against a static permafrost map (Brown et al., 2014) derived from International Permafrost Association (IPA) inventory records. A linear trend analysis was applied to quantify CHANGE and FT-ESDR based changes in PE condition from 1980 to 2009, where rate of PE change is used as a proxy for permafrost stability. Tundra and boreal forest biomes within the PE domain were categorized by a global terrestrial biome map (Olson et al., 2001), and mean PE change rate was summarized for these individual biomes.

2.2. Estimate of active layer thickness based on MODIS LST

Active layer thickness (ALT) is predominately controlled by surface FT seasonal regime, soil moisture content, and site topography; the ALT is also influenced by thermal buffering of underlying soil by surface organic layer thickness, snow cover, and vegetation structure (Duguay et al., 2005; Zhang et al., 2014). ALT has been estimated indirectly from in situ surface temperature measurements (Zhang et al., 2005) and ground penetrating radar (Westermann, Wollschlager, & Boike, 2010), active LiDAR remote sensing (Hubbard et al., 2013), and dynamic permafrost models (Burke et al., 2013; Lawrence et al., 2012; Park et al., 2013; Riseborough, Shiklomanov, Etzelmuller, Gruber, & Marchenko, 2008). Zhang et al. (2005) developed an empirical method for estimating ALT using an annual thawing index (ATI) and an edaphic factor (EF) that parameterizes the effect of land cover type on soil thermal state. A similar method was applied to estimate ALT in this study using alternative surface temperature inputs from satellite thermal IR remote sensing and global reanalysis data.

The MODIS Terra and Aqua land surface temperature (LST) product (MOD11C1 and MYD11C1; Wan, 2008) for the 2003–2009 record was used to derive ALT using an ATI defined as the cumulative number of LST defined degree-days above 0 °C for each selected year; MODIS LST