# Permafrost Active Layer Dynamics represent a Critical Climate Feedback requiring Space-based Measurements

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1. ***What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming Decade?***

Key Challenge/Question: What are the spatial distributions and temporal dynamics of permafrost soils and what are their feedbacks to/from the regional and global climate?

High latitude ecosystems are among the most vulnerable to the effects of global warming. Permafrost systems, in particular, may be at risk of reduction or loss. Permafrost is soil that is frozen (temperature of $0^{o}C$ or lower) continuously for at least two years. Permafrost is most continuous in the coldest climates such as the North Slope of Alaska, becoming more fragmented in warmer climate zones. The thickness of permafrost changes accordingly, from about 600 m in the north to about 40 m in the Alaskan interior (NRC, 1995). Permafrost is nearly water-impermeable, resulting in non-or slowly draining water within seasonally thawed surface soil layers (Dingman, 1975; Hobbie, 1984). The maximum thickness of the soil that thaws in the summer is called the active layer.

The active layer thickness (ALT) may be increasing in strong correlation with climate warming trends occurring rapidly over northern (≥45°N) latitudes at approximately twice the rate of other global areas. Currently, there are insufficient observations to ascertain the pattern or rates of ALT deepening and permafrost decline at regional or continental scales. There are several adverse effects of permafrost degradation and ALT deepening:

- Loss or reduction of permafrost can have detrimental impacts on urban, rural, transportation,and resource exploration infrastructure in northern communities due to diminished ground stability.
- Permafrost soils contain roughly half of the global reservoir of soil organic carbon, possibly destabilizing as permafrost thaws, thereby increasing atmospheric carbon emissions and intensifying global warming (e.g. Schuur et al. 2015).

- Permafrost degradation and ALT deepening has been shown to impact the dynamics of overlying vegetation in northern regions, altering vegetation structure and productivity, species composition and wildfire (NRC, 1995; Vitt et al., 2000; Camill et al., 2001; Jorgenson et al., 2001; Turetsky et al., 2002b; Christensen et al., 2004; Osterkamp et al., 2000; Jorgenson and Osterkamp, 2005).
- Wetland extent and permafrost are closely linked in the high latitudes (National Research Council (NRC), 1995; Dingman and Koutz, 1974; Van Cleve and Viereck, 1983; Van Cleve et al., 1991; Myers-Smith et al., 2007), and permafrost degradation may result in wetland loss. Conversely, permafrost melting can create additional small water bodies or wetlands that often become anaerobic fostering methanogenic bacteria. These effects can impact flora, fauna, and trace gas balance in the Arctic ($CO_2$ and $CH_4$).

In Alaska, active layer thickness can range from 20 cm to > 2 m (NRC, 1995). Time-series measurements of permafrost soil temperatures at numerous boreholes in Alaska and other northern pan-Arctic land areas have shown significant warming trends within these systems (Romanovsky et al., 2012; Smith et al., 2010). Although this evidence is strong, data are only available at a number of point locations. The large-scale distributions and dynamics are not well known.

2. ***Why are these challenge/questions timely to address now especially with respect to readiness?***

Observations and information on permafrost and active layer dynamics will provide a unique opportunity to assess the climate feedbacks in permafrost systems and are needed to (1) assess their impact on northern communities and infrastructure and (2) inform a succession of land surface hydrology and terrestrial carbon and climate model projections. Even though many groups have investigated and collected data on the spatial distribution and depth of permafrost in Alaska and other northern land areas, these measurements have been of very limited spatial extent; no consistent information is available on the depth of the active layer at larger and continuous regional scales, inter-seasonally or inter-annually. The US Geological Survey (USGS) has conducted extensive borehole temperature measurements acquired in permafrost regions of arctic Alaska between 1950 and 1988 at 87 locations (http://esp.cr.usgs.gov/data/bht/alaska/). Other data sets include 41 University of Alaska borehole measurements, primarily along the trans-Alaska pipeline route (Osterkamp, 1986; Osterkamp and Romanovsky, 1999; Osterkamp, 2008; Romanovsky et al., 2012). The data indicate widespread surface and soil warming trends, ALT deepening and warming of upper permafrost layers. The rate of such possible loss may, at best, be known at the locations of these boreholes, but not on a large spatial scale

There are a number of other ground-based data sets: Nelson (1997, 1998) collected thaw depth and air temperature measurements on the North Slope from 1995-1997 and compared the measurements to analytic model results. Ground penetrating radar (GPR) and LiDAR terrain mapping with ground based GPR and electrical resistivity measurements provide for detailed assessment and process understanding of active layer and permafrost properties but are unsuitable for more extensive regional mapping and monitoring. Others have used combinations of ground-based and (optical) satellite data to produce empirical, semi-empirical, statistical, or process-based maps of permafrost (Jorgenson et al. (2008), Anisimov et al. (2002), Romanovsky and Osterkamp (1997), Zhang et al. (1999), Pastick et al. (2014)). These methods provide for detailed estimation of permafrost properties such as active layer and near surface permafrost conditions, but their accuracy is limited by the duration and range of conditions represented by sparse ground truth measurements used to train or validate the methods.

Satellite microwave remote sensing from long-wavelength active synthetic aperture radar (SAR) sensors may offer a superior approach for direct assessments of active layer and permafrost properties, and regional monitoring of spatial and temporal changes at the scale of landscape heterogeneity in these processes. Use of low-frequency SAR observations may offer the only feasible method for such direct observations. The L-band frequency has been used to estimate soil moisture in the top 0-5 centimeters in the presence of up to 5 $kg/m^2$ of vegetation water content (Dubois and van Zyl, 1995; Oh et al. 1992; Entekhabi et al. 2014; others). P-band and lower frequencies have been used to retrieve soil moisture in the 0 cm to 50 cm depth or more, with as much as 15 $kg/m^2$ of vegetation water content (Moghaddam et al., 2000; Moghaddam et al., 2007; Tabatabaeenejad et al., 2015; others).

While P-band SAR data can retrieve soil moisture content and active layer depth with good accuracy, they do so as long as the depth of the active layer is larger than approximately 10-15 cm (i.e., essentially all permafrost areas of Alaska at peak thaw but a smaller area in Spring and Fall), because the long P-band wavelengths cannot resolve the smaller layer depths. But with simultaneous use of L-band and P-band observations, retrieval in shallower depths becomes more accurate. On the other hand, soil moisture retrieval accuracy is decreased for thicknesses of more than 50 cm, since L-band signals lose their sensitivity to larger depth profiles and thus the deeper frozen layers are more accurately resolved with the P-band data. *Simultaneous SAR observations at P-Band and L-Band, with algorithms that properly balance the contributions of the two frequencies, are therefore required*. There is substantial technology and algorithm heritage for long-wavelength radar sensors, resulting in an advanced readiness level for realizing dual-frequency observations.

The above analysis is consistent with the recommendations of a recent National Academies report prioritizing the need for improved ALT observations from remote sensing, including active layer soil moisture and thermal properties (NRC 2014).

### 3. *Why are space-based observations fundamental to addressing these challenges/questions?*

In response to question 2, above, examples of existing data sets over Alaska are the best data available; even so, their spatial and temporal extents are limited and the various data sets are not spatially and temporally consistent. In the larger circum-boreal and circum-arctic regions outside of Alaska, even fewer data sets are available, leaving an enormous knowledge gap in the dynamics of permafrost soils and active layer, and therefore a critical gap in our ability to understand and predict the social and climate feedbacks of changes in permafrost systems. The boreal and arctic permafrost regions occupy roughly a quarter of the northern hemisphere land surface, and notably, more than 80% of Alaska, more than 50% of Canada, and more than 60% of Eurasia. Space-based remote sensing is the only feasible way to make extensive and frequent observations of these rapidly changing areas.

Satellite microwave remote sensing from long wavelength active radar sensors offer an approach for direct assessment of active layer and permafrost properties, and regional monitoring of spatial and temporal changes at the scale of landscape heterogeneity in these processes, particularly when coupled with LiDAR measurements of surface deformation resulting from ice melt and synergistic use of other efforts mapping surface vegetation and topography as indirect metrics of permafrost extent.

**a) Will existing and planned U.S. and international programs provide the capabilities necessary to make substantial progress on the identified challenge and associated questions? If not, what additional investments are needed?**

The measurements required to achieve the science objectives to characterize spatial and temporal dynamics of permafrost active layer thickness are simultaneous, involving multi-year P-band and L-band polarimetric SAR coupled with other mapping efforts including optical and lidar data. No such capabilities exist from current or planned US or international space-based programs, but a limited number of airborne data sets are available.

Airborne: NASA is supporting the collection of a small number of joint P-band and L-band airborne SAR data in Alaska using the AirMOSS and UAVSAR systems through an Indisciplinary Science (IDS) program. Preliminary retrieval results have shown good promise for mapping the changes in the subsurface, including the depth and moisture content of the active layer and the depth to water table. It may be possible to acquire a more extensive dual-frequency airborne data set over Alaska and western Canada as part of the airborne component of the Arctic Boreal Vulnerability Experiment (ABoVE; Goetz et al., 2011). ABoVE also has substantial ground-based and modeling components, which will be essential in validation of the airborne SAR mapping results, and helping enhance and fine-tune the retrieval algorithms and experiment designs.

Spaceborne: An L-band spaceborne SAR mission is currently operated by JAXA (ALOS/PALSAR-2); an L-band mission is planned for launch in 2020 by NASA/ISRO (NI-SAR); ESA is also planning to launch a P-band SAR in 2020 (BIOMASS). However, each of these satellites has orbits, look geometries, and revisit times that are quite different from the others. Furthermore, it is not clear whether they will cover the northern latitudes that are the specific targets of permafrost studies. Importantly, for ESA's BIOMASS, there is currently no transmit permission over US (including Alaska) or Canada. For non-US satellites, data policies could also be impediments in accessing data reliably. *Therefore, for multiple reasons, the current and planned missions will not provide the data needed for achieving the goal of consistent, sustained, and accurate observations of permafrost soil dynamics*. Any future investments must address the development of simultaneous, or close-tandem, L- and P-band SAR satellites with identical look geometries, with repeat observation cycles that capture the rapid onsets of permafrost active layer freeze and thaw in boreal and arctic zones. Temporal observation frequency must be 2-3 days to resolve the phase transitions in seasonally frozen soils. Because of small-scale spatial variations of permafrost, resolutions of tens of meters are required.

**b) How to link space-based observations with other observations to increase the value of data for addressing key scientific questions and societal needs?**

Jointly acquired airborne L-band and P-band SAR data at a sufficiently representative set of locations in Alaska and Canada are needed to test and fine-tune retrieval algorithms for permafrost soil profile conditions. They will also be needed to understand the spatial and temporal sampling requirements of a prospective spaceborne mission. Additionally, more extensive ground-based data to establish temporal and spatial variabilities of permafrost soil characteristics are needed. This effort is being partly supported by the NASA ABoVE project, described under (a). ABoVE, kicked off in 2015, is planning for an 8-10 year horizon of field and aircraft remote sensing activities, which coincides well with the period of study of the current Decadal Survey.

**c) The anticipated scientific and societal benefits**

Multi-year (5-10 years), spatially consistent (meters to tens of meters), and temporally dense (daily-weekly) observations of permafrost soil and active layer depth are key to understanding arctic and boreal ecosystems, their dynamics, and the feedbacks affecting global climate variability. Information on loss or reduction of permafrost will help us address the impacts of such change on infrastructure in northern communities due to unstable ground, so that proper adaptation strategies can be developed. It will allow investigations and predictions of potential positive feedbacks to climate warming trends due to the release of stored organic soil carbon as a result of thawing. It will also enable the understanding of possible landcover change due to loss or reduction of permafrost.

**d) The science communities that would be involved.**

Observations, characterization, modeling, and predictions of permafrost system dynamics are of great importance to, and will involve, the following communities: terrestrial ecology, carbon cycle science, hydrology, remote sensing, arctic change, earth system modelers, exploration geophysics, land-cover and land-use change.

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