Detecting retrogressive thaw slumps over large permafrost areas: a case study along the Qinghai-Tibet Engineering Corridor

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Permafrost underlays around one-quarter of the exposed land in the northern hemisphere and is undergoing accelerating degradation. One consequence of permafrost degradation is the development of retrogressive thaw slumps (RTSs), which are slope failures due to the melting of ground ice and are reported by many studies in the local regions of the Arctic and the Tibetan Plateau. The locations and distribution of RTSs are poorly investigated due to the challenge of mapping them in the vast permafrost areas. A few studies have applied semantic segmentation algorithms such as DeepLabv3+ to delineate RTSs in local areas on high-resolution imagery and proved the effectiveness of deep learning. However, these algorithms are computationally expensive when applied to a large area. To build an efficient mapping framework that allows us to map RTSs on the entire Tibetan Plateau even with limited computing resources, we adopted a real-time object detection method called YOLOv4 (You only look once, version 4) to locate RTSs from remote sensing imagery.

We chose the Qinghai-Tibet Engineering Corridor (QTEC) as our case study area, where an RTS inventory already exists. We trained a YOLOv4 model using 877 RTSs from the 2019 PlanetScope CubeSat images (~3 m spatial resolution), then applied the trained model to the 2019 and 2020 Planet images covering the entire QTEC. The training process achieved a mean Average Precision of ~88%, indicating that the model was well trained. The model detected 754 and 625 RTSs from the 2019 and 2020 images, respectively; yet it also produced around 10 thousand false positives. Moreover, using two 1080Ti GPUs, it only took the model ~3 hours to scan across the research area, covering 8.5 percent of permafrost in the Tibetan Plateau.

In summary, YOLOv4 can efficiently locate RTSs over vast areas but still needs adjustment to reduce false positives.

Using Radar to Remotely Sensed Active Layer Thickness and Soil Moisture

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Here we describe how we estimate Active Layer Thickness (ALT) and soil moisture using aircraft observations of L-band and P-band Synthetic Aperture Radar (SAR). Permafrost soils heave up when the active layer freezes in winter and subsides when the active layer thaws in summer. We use airborne SAR to measure this seasonal subsidence and soil dielectric constant, from which we calculate ALT and Volumetric Water Content (VWC), and associated uncertainties. We calculated ALT and VWC for aircraft 66 flight lines in 2017 in Alaska and Northwest Canada as part of NASA's Arctic Boreal Vulnerability Experiment (ABoVE). We combine P-band data collected by the Airborne Microwave Observatory of Subcanopy and Subsurface (AirMOSS) instrument and L-band data collected by the Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) instrument. We integrated 350,000 in situ measurements of ALT and VWC from over 100 sites to validate the remotely sensed estimates. Here, we describe our techniques, highlight remotely sensed ALT and VWC for several flight lines, and describe potential applications.

Quantifying Surface-Height Change over a Periglacial Environment with ICESat-2 Laser Altimetry

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In this presentation, we jointly analyze laser altimetry crossovers and repeat tracks from Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) and a time series of surface-height change from the Sentinel-1 interferometric synthetic aperture radar (InSAR) satellite collected over the North Slope of Alaska from 2019-2020. We demonstrate that both instruments can successfully resolve ground surface-height change due to the seasonal freezing and thawing of the active layer. We observe a relationship between ICESat-2-derived surface subsidence/uplift and changes in normalized accumulated degree days, which is consistent with the thermodynamically driven seasonal freezing and thawing of the active layer. Integrating ICESat-2 crossover estimates of surface-height change yields an annual time series of surface-height change that is sensitive to changes in snow-cover during spring and thawing of the active layer throughout spring and summer. ICESat-2-derived surface-height change estimates can be significantly affected by short length-scale topographic gradients and changes in snow-cover and snow depth. We discuss optimal strategies of post-processing ICESat-2 data for permafrost applications, as well as the future potential of complementary ICESat-2 and InSAR investigations of permafrost surface-dynamics.

Investigating the sensitivity of L-band polarization ratio to surface organic soil properties in Arctic tundra area

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Surface soil organic matter (SOM) and soil moisture represent first-order controls on permafrost thaw and vulnerability, yet remain challenging to map or model accurately. Through analyzing the in-situ soil moisture and SMAP brightness temperature data in the Alaska North Slope, we found that the soil moisture dry-down process is closely related to surface organic carbon properties. A more rapid dry-down process during early thaw period was generally observed in areas with high SOM concentration. The dry-down time scale derived from the L-band polarization ratio (PR) shows a significant correlation with SoilGrids surface (0-5cm) SOC concentration ($R=0.54-0.68$, $p<0.01$) at regional scale. To understand the process, we used a coupled permafrost hydrology and microwave emission model to simulate the changes in the soil moisture and L-band PR during the thaw season. Soil parameterization and dielectric models adapted for organic soils were also included to better describe the variations in soil hydraulic, thermal and dielectric properties with SOM. The hydrology model was calibrated and validated using in-situ evapotranspiration, soil moisture and temperature data at the Imnavait Creek site. Models sensitivity runs show larger decreases in the L-band PR values during the early thaw season in soils with higher SOC concentration, consistent with the above analysis. This is mainly because the highly organic soils (SOM>60%) drains water more easily, and a larger amount of water can be discharged or lost (through evapotranspiration) in those soils, comparing with soils with a lower amount of soil carbon (SOM<30%). However, the sensitivity of PR to SOM was reduced with increasing vegetation water content and surface roughness such as during the later thaw season. Our study indicated that L-band may provide critical constraints on predictions of permafrost thaw and vulnerability in Arctic tundra area due to its sensitivity to surface soil moisture and carbon properties.

Permafrost Vulnerability Framework from multiple Essential Climate Variables

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Permafrost is a key indicator of global climate change and hence considered an Essential Climate Variable (ECV). Current studies show a warming trend of permafrost globally, which induces widespread permafrost thaw, leading to near-surface permafrost loss at local to regional-scales, impacting ecosystems, hydrological systems, greenhouse gas emissions, and infrastructure stability. Permafrost is defined as the thermal state of the subsurface but is greatly influenced by changes in the surface energy budget, as it is tightly connected to the atmosphere, biosphere, geosphere, and cryosphere by topography, water, snow and vegetation. However, so far, a combined assessment of these components to better understand, quantify, and project permafrost thaw is still missing.

Therefore, the objective of this ongoing project is to develop a permafrost vulnerability framework which focuses on changes in the surface energy budget and identifies permafrost areas that are particularly vulnerable to thaw by assessing positive and negative feedbacks and interactions in this coupled system. We will derive feedbacks impacting the thermal state of permafrost from spatiotemporal variability assessments of relevant ECVs, including land surface temperature, land cover, snow cover, fire, albedo, soil moisture, and freeze/thaw state. These ECV data sets are derived from remote sensing products. By conducting spatiotemporal variability analyses of the individual ECV parameters, correlation assessments, and decadal trend analyses, a better understanding of the underlying dynamics will be established. Two modelled permafrost ECV products, ground temperature and active layer thickness, serve as spatially continuous observation respondents regarding remotely sensed ECV records. A full range assessment of remotely sensed ECVs will be performed based on permafrost in situ records.

These results will be input for a circumpolar Arctic permafrost vulnerability assessment. The anticipated output will be a more comprehensive and spatially detail-rich understanding of permafrost vulnerabilities, which in turn is useful for quantifying the permafrost-climate feedback.

Mapping ice-rich permafrost using InSAR observations of late-season subsidence

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Ground ice is foundational to the integrity of Arctic ecosystems and infrastructure. However, we lack fine-scale ground ice maps across almost the entire Arctic, chiefly because there is no established method for mapping ice-rich permafrost from space. Here, we assess whether remotely sensed late-season subsidence can be used to identify where the upper permafrost is rich in ground ice. The idea is that, towards the end of an exceptionally warm summer, the thaw front can penetrate materials that were previously perennially frozen, triggering increased subsidence if they are ice rich.

Focusing on northwestern Alaska, we test the idea by comparing the Sentinel-1 InSAR late-season subsidence observations to permafrost cores and an independently derived ground ice classification. We find that the late-season subsidence in an exceptionally warm summer was 4–8 cm (5th–95th percentile) in the ice-rich areas, while it was low in ice-poor areas (-1–2 cm; 5th–95th percentile). The distributions of the late-season subsidence overlapped by 2%, demonstrating high sensitivity and specificity for detecting ice-rich upper permafrost. The strengths of late-season subsidence include the ease of automation and its applicability to areas that lack conspicuous manifestations of ground ice, as often occurs on hillslopes. One limitation is that it is not sensitive to excess ground ice below the thaw front and thus the total ice content.

Late-season subsidence can enhance the automated mapping of permafrost ground ice on large scales. It is complementary to existing (predominantly non-automated) approaches based on largely indirect associations with vegetation and periglacial landforms. Thanks to its suitability for mapping ice-rich permafrost, satellite-observed late-season subsidence can make a vital contribution to anticipating terrain instability in the Arctic and sustainably stewarding its ecosystems.

Advances in Airborne Remote Sensing of Permafrost During ABoVE

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The Arctic is a vast, remote environment largely underlain by permafrost; however, there is minimal infrastructure to support access to critical locations for long-term monitoring and change detection. Remote sensing technologies offer a solution to the problem of access, as well as the potential for contiguous mapping across the pan-Arctic. NASA's Arctic Boreal Vulnerability Experiment (ABoVE) has advanced the use of airborne synthetic aperture radar (SAR), LIDAR, and hyperspectral imaging – alone and in concert – to characterize permafrost state and condition. Detailed studies over selected ground validation sites as well as long-range surveys have been acquired and analyzed. We will discuss the advances in permafrost remote sensing developed during the ABoVE Airborne Campaigns and how these results inform current and future satellite remote sensing missions, including NASA's Earth System Observatory.

Automated quantification of the evolution of retrogressive thaw slumps from multi-temporal high-resolution satellite imagery

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Retrogressive thaw slumps (RTSs) are dynamic landforms resulting from the thawing of ice-rich permafrost and have significant impacts on the local environment. Once an RTS initiates, it can be active for more than a decade and advances toward upslope each summer. However, both the occurrence and evolution of RTSs are poorly quantified in most permafrost areas. To close this gap, we propose a method that integrates deep learning, polygon-based change detection, and medial axis transform, aiming to quantify the RTS development from multi-temporal high-resolution imagery. Firstly, we apply deep learning to multi-temporal imagery to automatically delineate RTS boundaries. Secondly, we input the boundaries into the polygon-based change detection technique and obtain RTS expanding areas, Lastly, we utilize the medial axis transform to measure the retreat distance of each RTS.

We conducted a case study by applying this method to Planet CubeSat imagery covering the Beiluhe region on the Tibetan Plateau taken from 2017 to 2019. The experiments show that automatic delineation based on deep learning can produce similar results to manual delineation, providing the potential of using these results to quantify the changes of RTS boundaries in different years.

Our method reveals that among manually-delineated 342 RTSs in the Beiluhe region, 83% and 76% of them expanded from 2017 to 2018 and 2018 to 2019, respectively.

For the expansion from 2017 to 2018, the average and maximum expanding areas are 0.20 ha and 1.47 ha, while the average and maximum retreat distances are 21.3 m and 91 m, respectively. For 2018 to 2019 the average and maximum expansion areas and retreat distances are 0.22 ha, 2.53 ha, 25.0 m, and 212 m, respectively.

The results show that the method can quantify RTS development automatically on multi-temporal images and can be potentially applied to larger areas.

High-Resolution Permafrost Mapping in the Source Region of the Yangtze River combining a process-based model with InSAR

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Regional warming in the last decades has induced significant changes in the permafrost area in the Tibetan Plateau (TP), which is dominated by discontinuous and sporadic permafrost. However, most models with relatively coarse resolution cannot capture such changes especially at a small scale. To better characterize and understand the spatial and temporal changes in the TP permafrost, high-resolution permafrost mapping is needed. In this study, we aim at developing an approach for high resolution mapping by combining new remote sensing technology InSAR (Interferometric Synthetic Aperture Radar) with high-resolution process-based model simulation. The approach is tested to characterize permafrost in the source region of the Yangtze River located in the Eastern part of the TP. We first simulated the near-surface permafrost distribution at ~1 km resolution using a process-based permafrost model. We further produced an even higher resolution (~40 m) permafrost map, using InSAR-based active layer thickness (ALT) estimates with soil moisture simulated by the model (~1 km). The model simulation results at 1-km resolution show that permafrost and seasonally frozen ground (SFG) account for ~66% and ~34% of the study area during 2003-2018, respectively. Meanwhile, the model-simulated near-surface permafrost areas show a significant decreasing trend ($R2=0.46$, $p<0.005$) with increasing ALT, while the model-simulated SFG areas increase significantly ($R2=0.59$, $p<0.005$) with decreasing maximum frozen depth. Our results also indicate that the InSAR-based method can effectively improve the spatial resolution of ALT estimation (~40 m), and integrating remote sensing such as InSAR with process-based models has a great potential in permafrost mapping. Moreover, the InSAR-based ALT estimates are considered more reasonable when the hydrologic model simulated soil moisture is used instead of using a constant soil saturation in the InSAR retrieval algorithm.

Evaluating a deep-learning approach for mapping retrogressive thaw slumps across the Arctic

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Retrogressive thaw slumps (RTS) are typical landforms indicating processes of rapid thawing and degrading permafrost. Here we present a deep-learning (DL) based semantic segmentation framework to detect RTS, using high-resolution multi-spectral PlanetScope, topographic (ArcticDEM elevation and slope), and medium-resolution multi-temporal Landsat Trend data. We created a highly automated processing pipeline, which is designed to allow reproducible results and to be flexible for multiple input data types. The processing workflow is based on the pytorch deep-learning framework and includes a variety of different segmentation architectures (UNet, UNet++, DeepLabV3), backbones and includes common data transformation techniques such as augmentation or normalization.

We tested (training, validation) our DL based model in six different regions of 100 to 300 km² size across Canada (Banks Island, Tuktoyaktuk Peninsula, Horton Delta, Herschel Island), and Siberia (Kolguev Island, Lena). We performed a regional cross-validation (5 regions training, 1 region validation) to test the spatial robustness and transferability of the algorithm. Furthermore, we tested different architectures, backbones and loss-functions to identify the best performing and most robust parameter sets. For training the models we created a training database of manually digitized and validated RTS polygons.

The resulting model performance varied strongly between different regions with maximum Intersection over Union (IoU) scores between 0.15 and 0.58. The strong regional variation emphasizes the need for sufficiently large training data, which is representative for the massive variety of RTS. However, the creation of good training data proved to be challenging due to the fuzzy definition and delineation of RTS, particularly on the lower part.

We are further continuing to improve the usability and the functionality to add further datasets and classes. The next steps will include the upscaling beyond small test areas towards large spatial clusters of massive RTS presence e.g. Peel Plateau in NW Canada.

The potential of satellite data to identify and quantify permafrost presence and change

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Satellite data can only indirectly reveal changes in permafrost, in sub-ground conditions. The application potential differs with respect to the actual target parameter. International programs and initiatives define usually one or several of the following parameters as essential for monitoring of permafrost on a global scale: ground temperature, permafrost extent and/or active layer thickness. These listings form the basis for e.g. the European Space Agency Climate Change Initiative. Spatially continuous information on these parameters can be only obtained through modelling. Due to the nature of relevant satellite observations, data gaps are common and limit their applicability in this context. In addition, data for calibration is needed which is scarcely existing in a sufficient quality and quantity. Further on, in order to capture actual climate change impacts, satellite records are usually too short.
Thus, satellite data are currently mostly used to capture variations of permafrost proxies (impacts of ground thaw on the landscape) or drivers (observables related to ground temperature). This aids process understanding and regional inventories. Landcover change monitoring is a frequent strategy as it is technically feasible to implement with satellite data. Analyses across landscape gradients opens the way for space for time concepts, but its utility for permafrost research is rarely explored.
This contribution reviews recent achievements based on satellite data on circumpolar scale and along permafrost landscape gradients. Examples are shown for the utility of radar techniques, including surface status observations as proxy for permafrost in comparison to other approaches, specifically considering products available from ESA CCI+ Permafrost (covering 1997-2019). Constraints due to limited availability of in situ observations are discussed in addition.

Using ArcticDEM and shallow boreholes to quantify mass wasting sediment loss of retrogressive thaw slumps in the Eureka Sound Lowlands, Canadian high Arctic

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Retrogressive thaw slumps (RTSs) are mass wasting features that form in degrading ice-rich permafrost, including local erosional processes such as gullying, and regional processes such as increasing summer air temperatures. These features are typically horseshoe shaped with an ablating headwall that feeds fluidized sediment downslope. RTS occurrence and activity is controlled by multiple factors including climate, slope, RTS geometry and ground ice content. Study of RTS typically relies on 2D satellite imagery and the availability of extensive ground ice datasets is limited. We use summer digital elevation models (DEM) between 2009 and 2017 generated by the ArcticDEM project to quantify total volume loss by RTS initialization and retreat in the Eureka Sound Lowlands in west-central Ellesmere Island and southeastern Axel Heiberg Island, Canada. A map of biophysical regions and shallow borehole dataset was used to estimate ground ice content by surface cover to partition sediment and ice amounts lost by RTS activity. ~200 RTSs were identified, including both newly initialized RTS in undisturbed terrain and active RTS that initiated prior to 2009. Overall mean depth of material loss is 1.9 m (standard deviation is 0.79 m) and mean maximum depth was 4.6 m (standard deviation is 2.35 m). Mean total volume loss for individual RTS was 9,000 m^3 (standard deviation is 17,000 m^3). Mean ground ice content for all cores was 49% in the upper 1 m of the ground surface. The incorporation of DEM differencing in RTS studies will compliment previous 2D analysis, furthering our understanding of RTS dynamics and allows for the measurement of volume loss by RTS activity.

High spatial and temporal resolution remote sensing of a collapsing pingo in northern Alaska

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Pingos are ice-cored mounds occurring in permafrost regions that form through processes associated with the injection and subsequent freezing of groundwater. In the continuous permafrost zone of northern Alaska, formation of pingos occurs mainly as a result of freezing of taliks in basins following lake drainage. Here, we document the rapid collapse of a 10 m high pingo that developed in a 2,000 year old drained lake basin in northern Alaska using historic aerial photography, high-resolution satellite imagery, Arctic DEM data, and repeat UAV surveys. A small (45 sq. m) thermokarst depression appeared on the pingo summit in 2010. The depression expanded laterally at a rate of 72 sq. m/yr between 2010 and 2016, with a marked increase in expansion (326 sq. m/yr) between 2016 and 2020. Mean thaw subsidence rates fluctuated between 0.06 and 0.36 m/yr between 2013 and 2018, more than doubling (0.83 m/yr) between 2018 and 2020. Pingo degradation was initially limited by slumping of material that protected the ice core at depth. Drainage of the thermokarst pond in 2017, likely through piping in open frost cracks developed on the flank of the pingo, helped facilitate the rapid pingo collapse that ensued. Sub-lateral drainage of the pond caused evacuation of slumped material from the internal walls of the collapsing pingo, exposing the ice core at depth. A brief site visit to the collapsing pingo in May 2021 revealed a complex pattern of near-surface ice-rich deposits with large bodies of massive ground ice (including intrusive ice, wedge ice, and dilation-crack ice) remaining on the western flank of the pingo and a very thin overburden of organic rich sediments at the surface. The rapid collapse of the pingo was likely triggered by climate-driven increases in active layer that affected the top of the pingo ice core, resulting in more than 60 % of its volume being lost through thermokarst processes in less than ten years. Detailed spatial and temporal observations of the collapsing pingo in northern Alaska provide valuable information for training a deep learning algorithm to more broadly track pingo dynamics using ArcticDEM time series data.