Investigation of Permafrost and Soil Moisture Distribution using GPR, NMR, and ERT

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Permafrost thaw affects hydrobiogeochemical cycles and geomorphological evolution in arctic ecosystems. Within the active layer, soil moisture largely controls surface/subsurface energy exchange as the remarkable latent heat of water dampens energy flows into and out of permafrost. Non-invasive geophysical measurement techniques, such as ground penetrating radar (GPR), electrical resistivity tomography (ERT), and nuclear magnetic resonance (NMR) provide opportunities for repeatable, reliable characterization of soil moisture content and soil moisture depth distribution in permafrost ecosystems. GPR, coupled with thaw probe measurements, is useful in assessing depth-averaged soil moisture as the travel time of an incident radar wave within the active layer largely depends on the amount of liquid water between the surface and frost table. ERT yields information about the resistivity of the subsurface which is then inverted to provide clues to relatively wet, dry, or frozen volumes. Borehole NMR—sensitive to the spin magnetic moment of protons within hydrogen atoms of water molecules—yields depth-specific soil moisture information. Uncertainty in the interpretation of geophysical datasets arises due to surface and subsurface heterogeneities and ambiguities stemming from non-uniqueness of inverse solutions. This study aims to investigate the efficacy of multiple geophysical perspectives from ERT, GPR, and NMR in identifying inversion artifacts and interpretation ambiguities from geophysical data. Our test site is a 508 m-long transect spanning the riverine successional landscape next to the Chena River in Fairbanks, AK. We find that borehole-NMR serves to ground-truth frozen vs. unfrozen subsurface in two, 30- and 40 m-deep boreholes along the transect. Similarly, NMR helps with the interpretation of the active layer thickness from a 200 MHz GPR profile. Depth-averaged, borehole NMR sensed soil moisture measurements within the active layer agree with GPR derived, depth-averaged soil moisture—within the uncertainty of the respective techniques. This research highlights the utility of multiple electromagnetic perspectives on high-fidelity soil moisture and permafrost assessment.

High-resolution frost heave map at fire scars in Batagay, NE Siberia, derived by L-band InSAR and validation with field observation

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"Wildfire causes rapid thawing of near-surface permafrost due to the loss of vegetation layer. In addition, the number of fires and burned areas are increasing in the Arctic region due to global warming and will further accelerate the permafrost degradation, especially in ice-rich permafrost regions. However, it remains uncertain how much wildfires could cause permafrost thawing. We study two fire scars formed in 2018 and 2019 in Batagay village, the Sakha Republic, Northeastern Siberia. The two fire scars are located adjacent to the Batagaika mega-slump, located 12km southeast of the village. By monitoring topography change immediately after the fires with a remote sensing technique, we can evaluate the amount of thawed permafrost.

We use Interferometric Synthetic Aperture Radar (InSAR), a remote sensing technique that allows us to detect relative changes in topography between two imaging periods. Yanagiya and Furuya (2020) revealed spatio-temporal variation of post-fire permafrost thawing by InSAR at the 2014 fire scar near Batagay. This study derives the higher-resolution images by ALOS2 L-band SAR satellite over the 2018 and 2019 fire scars, using the 2-meter data of ArcticDEM. We could generate a high-resolution (4m) map of frost heave at the fire scars, which shows spatial variations of heave that have close correspondence to gullies.

The InSAR image indicates spatially uniform heave of up to 10cm over flat areas in the fire scars. In contrast, heave signals are spatially heterogenous at the gullies. Heave occurs especially in the bottom of the gullies, but almost no heave in the flanks. The spatial variation corresponding to the gullies can be caused by spatial differences in the amount of ice lens formation. We are going to validate the heave signal with soil moisture content distribution by field observation in September 2021. Besides, we will further discuss the one-year thawing subsidence maps."

Monthly UAV-based topographic surveys reveal timing and volume budgets of seasonal geomorphic processes within retrogressive thaw slumps

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Ice-rich glaciated permafrost environments across northwestern Canada are amongst the most rapidly changing permafrost landscapes in the world. Retrogressive thaw slumps (RTS) are dynamic mass wasting phenomena occurring when ice-rich permafrost thaws. Satellite technology can now provide weekly-to-monthly observations of RTS, but it is primarily limited to presence/absence detections and surface area estimations. Robust volumetric measurements are required to better understand the geomorphic and geochemical implications of RTS processes. Annual topographic surveys of RTS have recently become more abundant because of Unmanned Aerial Vehicle (UAV) technology and pan-Arctic initiatives (e.g., ArcticDEM), yet these surveys capture the net change observed from a variety of thaw-driven mass wasting processes that vary with respect to importance throughout a seasonal cycle. The timing, mechanics and volume budgets of each geomorphological process within RTS scar zones and debris tongues are poorly understood and nor are its implications to erosion, downstream effects or geohazard risk. This work provides a preliminary overview of efforts to monitor RTS monthly across an age-size-activity spectrum in the Peel Plateau, Canada. Five photogrammetric UAV surveys were conducted over a one-year period for each of three large and highly active RTS which featured primary and secondary (or polycyclic) headwalls of various heights, surface orientations and ground ice volumes. Timing of the surveys occurred between September 2018 and 2019 and aligned with postulated activity periods (September – late season/senescence; June – early summer; July mid-summer; August – late summer). Headwall retreat, areal and volumetric growth rates indicate a wide range of seasonal trajectories. Resultant DEMs illustrate dynamic spatio-temporal zones of mass wasting processes such as ablation/headwall retreat, material accumulation, material transfer and erosion of debris tongues. Together these robust seasonal DEM measurements will reveal insights into permafrost processes and provided a means to better understand the geomorphic implications of rapidly accelerating thaw-driven processes and feedbacks.

Implementation of 3 component seismics on frozen ground

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We wanted to combine a suite of geophysical methods to map the complex, degrading saline permafrost near Ilulissat, Greenland, thawing of which challenges community infrastructure and risks to contaminate their freshwater supply. One of the methods tested was Multichannel Analyses of Surface Waves (MASW) that could resolve the low velocity of the saline layer. For the optimal quality dataset, we used 3-component (3-C) geophones to acquire data containing both Reighley and Love waves. We also conducted a series of tests to identify a mounting method of 3-C geophones in frozen soil that provided (I) level and precise placement of geophones (II) good acoustic coupling of the geophones, and (III) repeatable hammer seismic data.

Four mounting methods were tested on frozen soil samples, in a lab setting. The mounting methods involved pre-drilling holes for the geophone spikes and either using a custom mounting tool, freezing the geophones in the soil, or a combination. Data was collected using a repeatable impact and compared in terms of amplitude and repeatability. Comprehensive testing was also completed on-site in Ilulissat, in a location with natural spatial variability in the ground surface conditions due to variations in vegetation, peat cover, and snow/ice conditions.

The coupling between frozen ground and the geophones was generally good. The four mounting methods showed similar amplitudes. In terms of repeatability, we found that using stacking of 10 measurements gave remarkably consistent data. The biggest challenge was mounting the geophones precisely and level in the uneven and spatially variable surface conditions. We found that removing the snow and ice, pre-drilling holes in the frozen ground for the three spikes on the geophone, and adding water to freeze the geophone in place was the best method to consistently mount the geophones level and provide good coupling.

Using Landsat imagery to identify landscape change over the last 40 years from seismic exploration within the Arctic National Wildlife Refuge, Alaska.

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The oil and gas industry on the North Slope of Alaska has long pursued drilling permits within the Arctic National Wildlife Refuge (ANWR). In 2017, the Tax Cuts and Jobs Act included a provision that mandated leasing of the 1002 region of ANWR. While recent political changes have called into question whether exploration and extraction will be permitted, land managers need to understand the causes of permafrost degradation and potential mitigation strategies to minimize environmental impacts. To date, the largest industrial footprint within the Arctic Refuge has been seismic exploration using acoustic signals, created by explosives or vibrating vehicles (Vibroseis method), to sense subsurface geology. To create seismic signals, heavy machinery and crews of over 100 people must travel across sensitive tundra for months at a time. Vehicular travel from seismic exploration activities has resulted in long-lasting changes to the surface vegetation, hydrology, and permafrost conditions. By studying old seismic exploration lines from winter campaigns in 1984 -1985 with Landsat imagery, we identify regions within ANWR that exhibit anomalous change over the past ~40 years. Combining imagery from the Thematic Mapper (TM), Enhanced Thematic Mapper (ETM+), and the Operational Land Imager (OLI) instruments (Landsat 5,7, and 8) we identify trends in common vegetation (NDVI, EVI), moisture (NDWI, MNDWI, AWEI), and Tasseled Cap Transformation indices. Using in-situ observations from Jorgenson et al 2010, we attribute spectral changes to observed landscape transformations to inform a future random forest model for permafrost degradation risk across the 1002 region of ANWR.

Geophysical Validation of Airborne SAR-Observed Permafrost Active Layer Estimates, Alaska USA

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Permafrost active layer thickness (ALT) measurements are valuable to observe the effects of climate change and to improve understanding of hydrologic processes and biogeochemical cycles. Synthetic aperture radar (SAR) measurements from aircraft-based sensors have recently emerged as a tool for observing land surface subsidence from seasonal thaw, soil volumetric water content, and ALT. The objective of this study is to quantify the correspondence between airborne ALT estimates and ground based data. Here we present validation of ALT estimates derived from airborne SAR in three regions of Alaska, USA using ground penetrating radar (GPR) data. The airborne ALT estimates agreed with the field measurements within uncertainty at 79% of locations. Average uncertainty of the GPR ALT dataset was 0.14 m while the average uncertainty of the airborne ALT was 0.19 m. In the region near Utqiaġvik, the airborne ALT estimates appeared slightly greater than field measurements while around the Yukon-Kuskokwim Delta, the airborne ALT observations were slightly less than field observations. In the foothills to the north of the Brooks Range, there was negligible bias between the field data and airborne-derived estimates. These findings indicate that airborne SAR-derived ALT estimates produce results similar to ground based probing and GPR, suggesting that aircraft-mounted SAR is a useful tool for monitoring permafrost ALT.

Permafrost warming and thaw in the discontinuous zone tracked using electrical resistivity tomography, Alaska Highway corridor, Canada

Antoni Lewkowicz

Permafrost change due to climate warming or surface disturbance may be difficult to detect using borehole temperature measurements as they approach 0°C because the requirement to satisfy latent heat slows the rate of change. Electrical resistivity tomography (ERT) can be a useful addition to borehole monitoring as the technique provides a two-dimensional image of a site and measures the electrical properties of the ground that mainly reflect differences in unfrozen moisture contents. Here we report on the use of repeat ERT to detect change over a decade at a transect of ten forested sites in the sporadic discontinuous and isolated patches permafrost zones in southern Yukon and northern British Columbia. The sites exhibited permafrost during Roger Brown's survey in 1964 and it was present along parts of the ERT profiles at each site in 2010, but had partially or completely degraded at several of them by 2018. Degradation was caused by higher water levels due to drainage change at two sites, but at others, loss appeared to be climatically-induced. Since there was no significant climatic change during this period, these marginal permafrost sites were already in disequilibrium when monitoring began. Sites where permafrost has persisted are mostly those with visibly elevated sections and greater thicknesses of frozen ground. Although their general trend was towards warming with increasing unfrozen moisture and lower resistivities, several of these sites cooled between 2017-2018. Repeated ERT is an effective technique to evaluate the thaw of thin permafrost and proved to be more sensitive than temperatures measured in boreholes in tracking progressive change.

Standardized processing of geoelectrical data for permafrost applications: Initial findings from a new IPA action group

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Geoelectrical surveys are commonly used in permafrost studies to map the electrical resistivity of the subsurface and make inferences about the presence and distribution of permafrost. Repeated surveys are especially valuable in determining how permafrost conditions are changing over time. However, no framework for widespread sharing of geoelectrical datasets currently exists. Our recently formed International Permafrost Association (IPA) action group is working to create an International Database of Geoelectrical Surveys on Permafrost (IDGSP). This database will promote data sharing, integrate historical and recent surveys, enable targeted repetition of measurements, and facilitate interpretations of changing permafrost environments over large spatial and temporal scales.

To justifiably make comparisons between resistivity surveys, the data need to be processed in a consistent way. Geoelectrical data processing involves filtering out "bad" data points and inverting measured data to produce a map of subsurface resistivity. Data filtering is often done by manually deleting obvious outliers and/or by applying filters with site-specific thresholds. The inversion of geoelectrical data involves inputs related to the data error model, model and data misfit calculations, and regularization, but data processing is usually done using proprietary software with limited flexibility and transparency. An important goal of our IPA action group is to create a standardized, clear, and accessible data processing workflow that produces good results in a diverse range of environments. Here, we present our progress on determining optimal data processing parameters for permafrost studies. We demonstrate our data processing workflow on a range of field datasets and examine the sensitivity of the results. By establishing clear guidelines for data processing, we aim to produce consistent, reliable outputs that can be used to interpret long-term permafrost changes at a global scale.

In-Situ Monitoring of Permafrost's Geophysical and Geomechanical Characteristics Using Distributed Acoustic Sensing (DAS)

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Warming air temperatures are driving the warming of permafrost across the Arctic and sub- Arctic. This in turn degrades the geomechanical properties of soils, disrupts both the natural environment and built systems, and results in long-lasting societal impacts. Understanding the in-situ geophysical and geomechanical processes and forecasting the characteristics of degrading permafrost in the Arctic are crucial for building and maintaining resilient infrastructures in the changing Arctic. We will present an ongoing research project of using distributed acoustic sensing (DAS) technique to monitor permafrost's in-situ geophysical and geomechanical properties at relevant spatial and temporal scales. We will deploy a 2.0- kilometer-long fiber-optic DAS array in Utqiaġvik, Alaska in August 2021 for long-term, in- situ permafrost monitoring. The fiber-optic cable will be buried at approximately 20 cm below ground surface and above the permafrost table; the cable embedment is conducted using careful hand excavation and backfilling of the excavated and relatively undisturbed ground material. The DAS interrogator is housed in a Department of Energy facility in Utqiaġvik. Seismic strain rate data induced by ambient noises will be collected along the cable route in minute scale for multi-year duration, with spatial data collection resolution of 2 meters. This presentation will focus on the fiber-optic cable installation (including newly-developed installation techniques for permafrost sites), instrumentation deployment, and workflow of using DAS to determine permafrost's geophysical and geomechanical characteristics.

Quantification of lake change through time and extrapolation of in situ greenhouse gas flux analysis using remote sensing

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The current rate and magnitude of temperature rise in the Arctic is disproportionately high compared to global averages and this, along with other natural and anthropogenic disturbances, has caused widespread permafrost degradation and soil subsidence. The ice-rich permafrost region of Central Yakutia (Eastern Siberia, Russia) is particularly sensitive to these disturbances, which have precipitated a period of dynamic change in the area. As a result, thermokarst (thaw) lakes have become more prolific in Central Yakutia within the last few decades. These lakes are hotspots of greenhouse gas emissions (CO2 and CH4), but with substantial spatial and temporal heterogeneity across the Arctic and subarctic. Lake type (recent thermokarst lakes, hydrologically connected early-Holocene lakes, and endorheic (hydrologically unconnected) early-Holocene lakes) and season play an important role in determining the amount of greenhouse gas flux to the atmosphere. This study extrapolates greenhouse gas flux analysis, which was calculated from in situ data collected during the fall 2018, spring 2019 and summer 2019 field campaigns, to cover a more substantial landscape area and determine the relative contribution of greenhouse gases from each lake type to the atmosphere. Additionally, a long-term remote sensing analysis of lake formation and development was conducted for an approximately 50 x 50 km2 area in Central Yakutia. The analysis spans a time series from the 1946 ¬– present and incorporates historical areal imagery, CORONA, HEXAGON, and GeoEYE satellite imagery. These results suggest that climate change and other disturbances are having a strong impact on the landscape cover and hydrology of Central Yakutia. This will likely affect regional and global carbon cycles, with implications for positive feedback scenarios in a continued climate warming situation.

Geophysical Monitoring Shows that Spatial Heterogeneity in Thermohydrological Dynamics Reshapes Transitional Permafrost Systems

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Climate change is causing rapid changes of Arctic ecosystems. Yet, data needed to unravel complex subsurface processes are very rare. Using geophysical and in situ sensing deployed at a long-term study site on the Seward Peninsula, AK, we closed an observational gap associated with thermo-hydrological dynamics in discontinuous permafrost systems. Monitoring for more than 2 years, our data highlight the impact of vegetation, topography and snow thickness distribution on subsurface thermo-hydrological properties and processes. Large snow accumulation near tall shrubs insulates the ground and allows for rapid and downward heat flow during snowmelt and rain events. Thinner snowpack above the graminoid leads to surficial freezing and prevents water from infiltrating into the subsurface. Analyzing short-term disturbances such as snowmelt or heavy rainfall, we found that lateral flow could be a driving factor in talik formation. Linking our field data with laboratory derived property-relationships, we show that deep permafrost temperatures increased by about 0.2°C over 2 years, while also showing spatial variability in the magnitude of changes.

By highlighting the link between above and below ground properties and processes in the Arctic, our results are useful for improving predictions of Arctic feedback to climate change. They also show that Arctic warm permafrost systems are changing rapidly. For instance, our data suggests that permafrost at our study site could disappear within the next decade. This process could be accelerated by thaw-induced changes in subsurface permeability, but also changes in snowpack distribution and rainfall patterns.

Developing a user-friendly forward modelling and inversion tool to inform electrical resistivity tomography studies of permafrost

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Electrical resistivity tomography (ERT) is a non-invasive geophysical method that is commonly used in permafrost studies. ERT produces 2D or 3D images of subsurface resistivity, which can then be used to infer the distribution of frozen ground, including the presence, depth, and continuity of permafrost. The success of an ERT survey depends on how the survey is designed, how the data are processed, how the resulting resistivity image is interpreted, and how uncertainty is quantified. However, best practices for permafrost studies are not clearly established, and vary depending on the site and the study objectives. Here, we present a software tool that allows the user to input a subsurface resistivity model, i.e. expected frozen ground conditions, and simulate (forward model) the data that would be observed. The user is free to modify the survey design parameters, including the number of electrodes, electrode spacing, and array type. The data can then be processed (inverted) to produce an estimate of subsurface resistivity. If the target is poorly resolved, the user can test an alternative survey design. This iterative testing enables the user to plan an ERT survey that is most likely to be successful prior to expending the time and effort on field data collection. The user can also test models with features of various shapes, sizes, locations, and resistivities to better understand how model resolution changes depending on the subsurface resistivity. Using case studies, we demonstrate that this simple forward modelling and inversion tool can be used to guide ERT survey design, explore resolution limits, and develop appraisal expertise for the interpretation of field data.

Spatial variability of vegetation and surface cover within drained lake basins, North Slope Alaska

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Drained lake basins (DLBs) are common landforms in lowland permafrost regions in the Arctic and widely cover 50% to 75% of the landscape. However, detailed assessments of DLBs including distribution, abundance and spatial variability across scales are limited.

Depending on the age of a given DLB, surface characteristics such as surface roughness, vegetation, moisture and abundance of ponds may vary between basins. Spatial heterogeneity within a single basin also depends on time passed since the drainage event occurred. In situ observations of these surface characteristics of DLBs are crucial for a better understanding of these features but can only describe a small percentage of existing DLBs on the Alaskan North Slope.

In this study we use both multispectral (Landsat-8) and Synthetic Aperture Radar (SAR) data as well as information from the ArcticDEM to assess the inter and intra-DLB spatial heterogeneity of surface characteristics. To focus our analysis on areas likely to be DLBs, we utilize a newly published DLB data product covering the North Slope, Alaska. The DLB data product is based on a novel and scalable remote sensing-based approach to identifying DLBs in lowland permafrost regions, using the North Slope of Alaska as a case study. We validated the data product against several previously published sub-regional scale datasets and manually classified points. The study area covered >71,000 km2, including a >39,000 km2 area not previously covered in existing DLB datasets. The data set provides a pixel-by-pixel statistical assessment of likelihood of DLB occurrence in sub-regions with different permafrost and periglacial landscape conditions.

Geophysical and Remote Sensing Investigations of Changing Permafrost Landscapes

Building on existing research describing DLBs according to their vegetation cover and other surface characteristics, we group DLBs into 4 distinct clusters which correspond to previously published DLB age classification schemes (young, medium, old and ancient DLBs). Clusters differ in both vegetation characteristics and relative age of the different basins. To complement and verify our remote sensing based approach, we collected a wide array of field data across multiple sites on the North Slope, including vegetation surveys among other parameters. First results show distinct differences in surface characteristics such as greenness, wetness and brightness as well as surface roughness between DLB clusters derived from remote sensing data.

Recent widespread thaw degradation of Interior Alaska permafrost quantified from repeat surveys, remote sensing, and geophysics

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Much of the permafrost in Central Alaska represents syngenetic ice-rich, high carbon content “yedoma” which is spread sporadically across a 500,000 km2 region expanding from the Canadian border west to the Seward Peninsula. Numerous recent studies highlight recent warming and permafrost degradation in the area. A series of 400 to 500 m long transects representing a variety of boreal and taiga ecotypes were established near Fairbanks, Alaska in 2013. Repeat active layer depth measurements, electrical resistivity tomography (ERT), permafrost temperatures, deep (5-15 m) boreholes, and repeat airborne Light Distance and Ranging (LiDAR) have been used to measure top-down thaw, map discontinuous permafrost bodies, and track thermokarst feature development. Tussock tundra and spruce forest ecotypes yield the lowest mean annual near-surface permafrost temperatures. Mixed forest ecotypes are warmest, exhibit the highest degree of recent warming, and have the highest prevalence of thaw degradation. Thermokarst features, residual thaw layers, and taliks have been identified at all sites with boreholes and geophysical measurements. Deep boreholes confirm ERT measurements that identify thawed regions and in some areas, the thickness of tabular permafrost bodies. Long-term records from yedoma sites spread across Interior Alaska show widespread near-surface permafrost thaw since 2010. A projection of top-down thaw since 2013, by ecotype, across the Central Alaska yedoma domain yields a first-order estimate of 0.44 Pg of thawed soil organic carbon. The ultimate fate of this carbon is unknown, however, it is roughly equal to Australia’s yearly CO2 emissions.

Estimating sub-surface snow density using the surface reflection method

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The surface reflection method is a popular method of determining layer dielectrics in road pavements. McCallum (2014) applied this technique to snow to estimate surface snow density. Here, this method is extended to estimate sub-surface snow density and layer thicknesses. An air-coupled 800 MHz Ground Penetrating Radar (GPR) antenna was used to image alpine snow, and comparison was made with an ideal reflector, a metal plate. Quantitative analysis of the GPR trace and application of the surface reflection technique allowed sub-surface snow density and surface layer thickness to be resolved. Although discrimination of second layer thickness was poor, this technique introduces a simple method by which surface and sub-surface snow layer density and thickness could be rapidly estimated over large spatial areas.

Airborne Surveys of Rapidly Changing Permafrost Landscapes in Western Alaska

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"Permafrost landscapes in western Alaska are undergoing rapid changes due to increasing air temperatures and precipitation, decreasing sea-ice cover, and intensifying disturbances. Recent findings include field and satellite observations of warming ground temperatures, rapid lake growth and drainage, substantial ice-wedge degradation, beaver range expansion, and accelerating coastal erosion.

Western Alaska extends across broad environmental gradients of permafrost extent, vegetation zones, and topography. Climate change directly affects a large number of communities as well as land resources in National Parks and Fish and Wildlife Refuges. Multiple settlements are highly prone to infrastructure damage and loss and some are actively planning relocation. Therefore, it is a prime study region for better understanding the fate of permafrost landscapes in a warming world and the consequences of climate change. At the same time, permafrost research in this region may provide an immediate impact to help improving livelihoods in affected communities.

We here report on observations and first results from our Perma-X airborne campaign based out of Kotzebue in summer 2021. We used the AWI Polar-6, a Basler BT-67 / Douglas DC-3C airplane equipped for polar research to conduct surveys across multiple target sites of interest at 1000-1500m altitude above terrain. Onboard-sensors included a high-resolution Modular Aerial Camera System (MACS) by the German Space Agency featuring two RGB cameras in stereo-mode and one NIR camera, as well as a Riegl Q680i full-waveform laser scanner.

Geophysical and Remote Sensing Investigations of Changing Permafrost Landscapes

We focused on sites with historical datasets available (i.e., LiDAR, aerial imagery) or that experienced disturbances in the past or recently. This included sites with vulnerable settlements, coastal erosion, thaw slumping, lake expansion and drainage, ice wedge degradation and thaw subsidence, fire scars of different age, pingos, methane seeps, and beaver-affected sites.

In our presentation, we highlight first findings and observations from this hotspot region of permafrost change and invite the community to discuss the best use of the data for maximized benefit."

Quantifying the Surface Deformation of Pingos on the Alaskan North Slope using Interferometric Synthetic Aperture Radar (InSAR)

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Pingos are large ice mounds with cores composed of intrusive ice. These ice structures can form in either regions of discontinuous permafrost, commonly as hydraulic pingos, or in locations of continuous permafrost, commonly as hydrostatic pingos. The formation mechanisms of pingos can shed light on the subsurface hydrologic regime in areas underlain by permafrost, and pingos can in turn modify their local hydrology, ecology, and freeze/thaw regime. Despite the importance of pingos in periglaciated regions, knowledge of how they change over time, and the implications of their temporal evolution, are limited due to a paucity of geophysical studies of pingos. In this presentation, we processed Interferometric Synthetic Aperture Radar (InSAR) data from the C-band Sentinel-1satellite over the North Slope of Alaska. InSAR is a spaceborne radar remote sensing technique that can quantify changes in the Earth's surface at high spatial resolution, making it an efficient tool to monitor surface deformation in periglaciated regions. Using an InSAR dataset spanning January 2016 to December 2020, we generated several time series of hydrostatic pingos and the surrounding tundra in our study site. With these time series, we were able to quantify seasonal and interannual ground subsidence patterns of pingos and the surrounding tundra; these signals can be used to quantify seasonal freezing and thawing of active layer as well as long term deformation signals associated with the aggradation and degradation of ice, respectively. Finally, we will discuss the implications of our results for the vulnerability and resiliency of pingos within the context of a warming Arctic environment.

Diminishing cryoturbation and shrubs on the march in the Siberian Arctic: detecting sorted circles and vegetation change using convolutional neural networks

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The expansion of shrubs in Pan-Arctic ecosystems—shrubification—is among the most conspicuous and pervasive vegetation changes being observed in permafrost landscapes and is expected to continue in the future. Across the Low Arctic, permafrost and active-layer disturbances frequently are “hotspots” of rapid shrub increase, and patches of tall shrub vegetation can serve as bioindicators of past disturbances. In this work, we apply convolutional neural networks (CNN) to map changes in tall shrub cover in very-high resolution (VHR; < 1 m) commercial satellite image pairs acquired circa 2005 and 2020 in Low Arctic ecotones of northwestern Siberia. The study landscapes include extensive areas of patterned ground (sorted circles) with a known history of shrub increase dating to the mid-1960s. The VHR satellite constellation has grown and acquired data with ever-increasing frequency and detail, enabling comparative analysis of images from sensors with similar spatial and spectral resolutions across time periods long enough to detect changes in shrub abundance and periglacial geomorphology. In addition, the development of high resolution, wall-to-wall spatial data products for landscape properties including topography, soils, disturbance, permafrost characteristics, and bedrock geology permit analysis of landscape covariates of shrub expansion. We seek to answer the following research questions:

1.Are CNNs effective at discriminating tall shrubs and changes in their cover in VHR imagery over decadal timescales?

2.What are the spatial properties of sorted circles in the study landscapes, and how has the extent of active features changed in recent decades?

3.What is the relative importance of landscape covariates, such as topography, periglacial geomorphology, snow properties, and disturbance regime, in influencing observed patterns of change (or stability) in shrub cover?

Three-dimensional investigation of a broad-based closed-system pingo on the Tuktoyaktuk Peninsula, Northwest Canada

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The formation and internal structures of closed-system pingos have been studied in the Mackenzie Delta region for several decades and especially John Ross Mackay has gained a lot of important knowledge about these landforms. Nevertheless, the current state of knowledge is mainly based on one-dimensional or at most two-dimensional measurements and observations. Within the scope of our project, three-dimensional geophysical measurements should therefore contribute to a detailed investigation of the three-dimensional internal structures of a broad-based closed-system pingo and thus enable further conclusions on the formation and development of such landforms. The use of ground-penetrating radar enabled an area-wide detection of the permafrost table and the localisation of ice wedges in the area of the pingo. The active layer thickness seems to be clearly related to relief position, vegetation and the proximity to surface water bodies. To investigate the linkages to surface properties detailed drone-based mapping of vegetation classes and height was performed, but also high-resolution digital elevation models were produced using a structure-from-motion approach. In addition, quasi-three-dimensional electrical resistivity tomography enabled a detailed localisation of the massive ice core of the pingo and the delineation of frozen and unfrozen areas below the pingo and its surroundings. Particularly striking is a clear asymmetry of the massive ice core compared to the shape of the pingo itself and its decentralised position below the western flank of the pingo. Below the eastern flank, only less icy permafrost and in some areas possibly at least partially unfrozen substrate could be detected. These structures clearly deviate from the structures expected based on theory and show for the importance of further research concerning the formation and internal structures of closed-system pingos.

Leveraging new satellite technologies to better understand permafrost-surface water feedbacks in the Arctic

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Through rising air temperatures, varying precipitation patterns and enhanced moisture transport from low latitudes, surface water in the Arctic is undergoing substantial change. In particular, understanding the complex feedbacks between surface water and permafrost presence/distribution is vital towards better constraining current and future changes in surface water and related impacts on carbon emissions and ecosystems. Despite the importance of Arctic water bodies, however, their seasonal and interannual dynamics remain largely unquantified, particularly at regional to global scales and for small (< 0.1 km2) water bodies, which make up the vast majority of water bodies in the Arctic. Here we present work seeking to better understand Arctic surface water variability and its relationship to permafrost thaw through leveraging two new satellite technologies. First, using the high spatial and temporal resolution of Planet CubeSats, we can now observe surface water dynamics at 3-5 m at near-daily time scales. Our initial analysis found that Arctic surface water was more dynamic than previously thought, particularly outside of wetland environments. By intersecting these maps of surface water variability with permafrost presence, we can assess to what degree permafrost presence affects these patterns, or whether secondary factors such as topography, land cover and surficial geology exert a greater control on surface hydrology dynamics. Second, NASA's recently launched ICESat-2 laser altimeter now provides high resolution observations of surface water levels, allowing observation not just of area variability but also of water level and storage. As permafrost acts as an impenetrable barrier between surface water and groundwater, this ICESat-2 data allows us to test multiple hypotheses related to permafrost/surface water feedbacks, such as whether contemporaneous lake levels in continuous permafrost are more spatially variable than in low permafrost presence terrain. Overall, while this work remains in progress, these two datasets already show substantial promise for enabling unprecedented insight into Arctic surface hydrology, including creating potentially powerful tools for remotely identifying permafrost presence and thaw.