Abstracts: 2021 Regional Conference on Permafrost and 19th International Conference on Cold Regions Engineering

Edited by
Thomas A. Douglas
Kevin Schaefer
Anna Liljedahl

2021 Regional Conference on Permafrost
19th International Conference on Cold Regions Engineering
October 24-29, 2021 - Online Virtual Conference

Cover photograph provided by Thomas A. Douglas.
High-centered polygons in Horseshoe Lake near Fairbanks, Alaska.

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2022

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Preface

The US Permafrost Association and the American Society of Civil Engineers (ASCE) jointly organized and convened, with support from the International Permafrost Association (IPA), the 2021 Regional Conference on Permafrost (RCOP) and the 19th International Conference on Cold Regions Engineering (ICCRE) on October 24-29, 2021. Due to the COVID-19 pandemic, the IPA canceled the 12th International Conference on Permafrost (ICOP), scheduled for China in 2020 and approved an RCOP in the United States. Because of Covid-19, the US organizers chose an all-virtual meeting platform. Thomas A. Douglas, USA CRREL Fairbanks, chaired the virtual conference with co-chairs Kevin Schaefer of the National Snow and Ice Data Center at the University of Colorado Boulder and Anna Liljedahl of the Woodwell Climate Research Center. Peppi Croft oversaw USPA web support and finances.

The Permafrost Young Researchers Network (PYRN) held its annual meeting the day prior to the conference opening ceremonies. This included presentations and breakout meetings on proposal writing, science communication, and work-life balance. Alaska Senator Lisa Murkowski opened the conference with a video presentation followed by Larry Hinzman of the White House Office of Science and Technology Policy. Other plenary presentations included the Eb Rice lecture "Tears of a Rapper: The Science and History behind the Art of Frozen Debris Lobe Rap Videos" by Margaret Darrow of the University of Alaska Fairbanks and "Perspectives on Climate Change: On-the-Ground Impacts of Climate Change in Arctic Communities" by Darcy Peter of the Woodwell Climate Research Center. Jerry Brown received the IPA Lifetime Achievement award, presented by IPA President Chris Burn. Fritz Nelson provided a tribute to Jerry's career accomplishments. The ceremonies included a tribute to Art Lachenbruch (1925-2021) and acknowledgement of other recently deceased members of our permafrost community. The USPA presented four awards for best oral and poster presentations.

Of the 416 registered participants from 20 countries, 237 came from the United States and 98 from Canada. The four-day virtual technical program consisted of six keynote sessions, 21 technical sessions, and 22 poster sessions for a total of 280 presentations. The ASCE's Cold Regions Engineering Division, under the leadership of Jon Zufelt (HDR, Anchorage) published a special conference volume of 34 peer-reviewed papers.* This volume contains 255 abstracts.

USPA thanks the conference sponsors for their generous support: Arctic Foundations Inc., Geo-Watershed Scientific, PND Engineers, Golder and Associates, BGC, Campbell Scientific, Woodwell Climate Research Center, CRW Engineering Group, beadedstream, Cryogeeks, The National Snow and Ice Data Center, and Stantec. We also acknowledge Thomas Alton as the production editor of this proceedings volume, Jerry Brown for assisting in the editing, and Ben Jones and the Institute of Northern Engineering, University of Alaska Fairbanks, for editorial office support and as an in-kind sponsor of this volume. The US Permafrost Association provided funds to produce this volume of abstracts.

Thomas A. Douglas (National Snow and Ice Data Center, University of Colorado Boulder)
Kevin Schaefer (University of Colorado Boulder)
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Peppi Croft

*Zufelt, J. (2021). *Permafrost 2021: Merging Permafrost Science and Cold Regions Engineering.* In: Proceedings of the 2021 RCOP and the 19th ICCRE, Online, 24-29 October 2021. American Society of Civil Engineers (ASCE), 381 pp. (https://ascelibrary.org/doi/epdf/10.1061/9780784483589).

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

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Dan Glaser *US Army Cold Regions Research and Engineering Laboratory*
Jon Maakestad *US Army Cold Regions Research and Engineering Laboratory*
Dragos Vas *US Army Cold Regions Research and Engineering Laboratory*
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Stephanie Saari *US Army Cold Regions Research and Engineering Laboratory*
Anna Wagner *US Army Cold Regions Research and Engineering Laboratory*

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, Alaska. 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.

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High-Resolution Frost Heave Map at Fire Scars in Batagay, Northeastern Siberia, Derived by L-band InSAR and Validation with Field Observation

Kazuki Yanagiya *Hokkaido University*
Masato Furuya *Hokkaido University*
Go Iwahana *University of Alaska Fairbanks*
Petr Danilov *North-Eastern Federal University in Yakutsk*

Wildfire causes rapid thawing of near-surface permafrost due to the loss of vegetation layer. In addition, the number of fires and burned areas is 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. In addition, 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

Jurjen van der Sluijs *Northwest Territories Centre for Geomatics, Government of Northwest Territories, Yellowknife*
Steve Kokelj *Northwest Territories Geological Survey, Government of Northwest Territories, Yellowknife*
Jon Tunnicliffe *University of Auckland*
Ashley Rudy *Northwest Territories Geological Survey, Government of Northwest Territories, Yellowknife*

Ice-rich glaciated permafrost environments across northwestern Canada are among 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 as 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

Thomas Højland Lorentzen *Technical University of Denmark, Department of Civil Engineering*
Sonia Tomaskovicova *Technical University of Denmark, Department of Civil Engineering*
Thomas Ingeman-Nielsen *DTU Byg*

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 contamination of the freshwater supply. One of the methods tested was Multichannel Analyses of Surface Waves (MASW), which 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 using either a custom mounting tool, freezing the geophones in the soil, or a combination. Data were 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

Julian Dann *University of Alaska Fairbanks*
Bob Bolton *University of Alaska Fairbanks*
Paul Leonard *U.S. Fish and Wildlife Service, Arctic National Wildlife Refuge*
Simon Zwieback *Geophysical Institute, University of Alaska Fairbanks*

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 ANWR 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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Richard Chen *Jet Propulsion Laboratory*
Roger Michaelides *Colorado School of Mines*
Taylor Sullivan *University of Wyoming*
Leah Clayton *Yale University*
Lingcao Huang *University of Colorado*
Yuhuan Zhao *University of Southern California*
Elizabeth Wig *Stanford University*
Mahta Moghaddam *University of Southern California*
Howard Zebker *Stanford University*
Kevin Schaefer *University of Colorado Boulder*

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, 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 *University of Ottawa*

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 it 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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Rebecca Gugerli *University of Fribourg*
Christian Hauck *University of Fribourg*
Christin Hilbich *University of Fribourg*
Andreas Hördt *TU Braunschweig*
Andreas Kemna *University of Bonn*
Christof Kneisel *University of Wuerzburg*
Antoni Lewkowicz *University of Ottawa*
Jonas Limbrock *University of Bonn*
Coline Mollaret *University of Fribourg*
Cécile Pellet *Department of Geosciences, University of Fribourg*
Riccardo Scandroglio *Chair of Landslide Research, Technical University of Munich, Germany*
Sebastian Uhlemann *Lawrence Berkeley National Laboratory*

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.

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

Ming Xiao *Department of Civil and Environmental Engineering, Penn State*

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 a 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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Frédéric Bouchard *Université Paris Saclay, Centre d'études nordiques (CEN), Université Laval, Canada*
Antoine Séjourné *Université Paris* Saclay
Adèle Joyeux *Laboratoire de Géologie de Lyon*

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 sub-Arctic. 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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Baptiste Dafflon *Lawrence Berkeley National Laboratory*
John Peterson *Lawrence Berkeley National Laboratory*
Craig Ulrich *Lawrence Berkeley National Laboratory*
Ian Shirley *Lawrence Berkeley National Laboratory*
Sofia Michail *ETH Zurich*
Susan Hubbard *Lawrence Berkeley National Laboratory*

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, Alaska, 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 suggest 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

Teddi Herring *University of Ottawa*
Antoni Lewkowicz *University of Ottawa*

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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Benjamin Jones *University of Alaska Fairbanks*
Kenneth Hinkel *Department of Geological and Mining Engineering and Sciences, Michigan Technological University*
Louise Farquharson *University of Alaska Fairbanks*
Benjamin V. Gaglioti *Institute of Northern Engineering, University of Alaska Fairbanks*
Andy Parsekian *University of Wyoming*
Mikhail Kanevshiy *University of Alaska Fairbanks*
Noriaki Ohara *Department of Civil & Architectural Engineering University of Wyoming*
Rodrigo C. Rangel *Department of Geology and Geophysics, University of Wyoming*
Guido Grosse *Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research*
Ingmar Nitze *Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research*

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 subregions with different permafrost and periglacial landscape conditions.

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, but it is roughly equal to Australia's yearly CO2 emissions.

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Estimating Sub-Surface Snow Density Using the Surface Reflection Method *

Adrian McCallum *University of the Sunshine Coast, Australia*

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.

***For full text, see *Permafrost 2021: Merging Permafrost Science and Cold Regions Engineering*, American Society of Civil Engineers. https://ascelibrary.org/doi/epdf/10.1061/9780784483589**

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 improve 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.

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 maximum benefit.

* * *

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

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Roger Michaelides *Colorado School of Mines*
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Pingos are large ice mounds with cores composed of intrusive ice. These ice structures can form either in 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.

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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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Ksenia Ermokhina *A.N. Severtsov Institute of Ecology and Evolution, Russian Academy of Sciences*
Howard Epstein *University of Virginia*

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

Julius Kunz *University of Wuerzburg*
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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 localization 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 localization 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 decentralized 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

Sarah Cooley *University of Oregon*

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.

Analysis Of Road Salt Use and Its Impact on Groundwater Within the Context of Changing Winter Weather Conditions

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Jonathan Rubin *University of Maine*

The study focuses on the contamination risk of groundwater wells due to winter road salt, sodium chloride, with particular attention to changes in long-term weather conditions. Despite great advantages for traffic safety, road salt infiltrates soil, and eventually joins surface and groundwater, leading to their salinization. We use data on contamination concentrations in the wells tested by the Maine Department of Transportation to estimate well contamination risk in Maine.

Since there exist no practical technologies for removing salt from contaminated water sources, reducing salt application, where appropriate, is the only solution. Winter severity Indices (WSI) are tools used to assess and compare the severity of winters and road salt use. In this study we also relate a wide range of WSIs with statewide road salt usage and compare their ability to explain the trend in road salt in Maine. We compute WSIs at 12 locations and apply Principal Component Analysis to achieve dimensionality reduction and address multicollinearity. Our linear regression-based results show that various combinations of WSI indices show statistically significant relationships with salt usage. At the same time, the spatial patterns associated with the principal components highlight the regional differences in winter severity across Maine's climate zones. Ongoing work seeks to relate salt use to climatic variability and changes in usage patterns; at the same time, a new suite of indices to include non-snow or precipitation situations is being developed, so as to understand the salt applications in frost-induced icing situations and their changing prevalence over the past two decades.

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On the Use of Electrical Resistivity Tomography Measurements and Induced Polarization-Surveying in Arctic Landfill Assessments

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Variations in ground temperature affect the physical properties of permafrost, such as the amount of unfrozen water and the ice content. In the context of Arctic landfills, it is important to understand to which extent permafrost acts as a geological barrier, and how this barrier characteristics will be impacted by climate change. This applies to both existing landfills for waste from local communities and mining activities, as well as for the planning of future landfills.

Here we present three examples where combined Electrical Resistivity Tomography (ERT) measurements and Induced Polarization-surveying (IP) were used to detect the interface between sediments and bedrock within permafrost ground, and to investigate potential environmental hazards related to run-off paths from existing and planned landfills. Study sites were an active landfill near the town of Longyearbyen, and two potentially new landfills near Longyearbyen and Barentsburg (the latter one for surplus masses resulting from coal mining). As permafrost traditionally had been considered as a natural flow barrier for such landfills, understanding its degradation owing to climate change is key in the planning of future sites.

Eight profiles were carried out in September 2018, when expected active layer thicknesses were at their maxima. Two-dimensional inversion was performed with the commercial software RES2DINV for the resistivity data and Ahrusinv for the chargeability data. The results of our case studies show the benefit of simultaneous ERT- and IP-measurements, to both map active layer depths and determine sediment depths in permafrost areas. They also

gave valuable insights in understanding potential environmental hazards related to run-off from the landfills as a consequence of water entering the landfill in the summer period. ERT/IP surveys are flexible and relatively easy to deploy. The technique is non-destructive and is, therefore, also suitable for planning and maintenance activities in vulnerable arctic tundra environments.

* * *

Teamwork in the Trenches: An Interdisciplinary Effort To Address Utility-Related Tundra Rehabilitation

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In Arctic Alaska, fiber optic cables were installed in 2015 to 2017 along a 240-mile stretch of the Dalton Highway. The cables were installed mostly in winter with some installation having been completed in summer using various trenching techniques. The region is characterized by continuous permafrost and ecosystems with widely varying ground ice volume from boreal forest to the coastal plain. Shortly after installation, mechanical and thermal erosion was observed to have caused ground subsidence within and adjacent to the trenches. A team of science and engineering expertise that includes geocryology, permafrost hydrology, tundra revegetation, restoration ecology, water resources engineering, and remote sensing was assembled to address the permafrost degradation using multiple rehabilitation techniques of the tundra surface. Individual rehabilitation plans for each problem site were informed by thermal balance equations, evaluations of watershed hydrology, experience in rehabilitating and revegetating tundra, and repeat photogrammetry by unmanned aerial vehicle (UAV). The sites were evaluated using historic and current aerial photography and visiting sites during high-water spring freshet and during mid-summer. Rehabilitation techniques include backfilling subsided areas and placing transplanted tundra sod over the backfill, placing water bars in strategic locations, live-staking willows, and placing transplanted tundra sod by hand in highly sensitive areas. The rehabilitation work begun in 2020 continues in 2021, and it will likely continue for several more years.

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Arctic Expeditionary Infrastructure Research*

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The warming of high-latitude regions is spurring development across the Arctic. The need for tested and developed Arctic infrastructure, particularly the more expedient type, is required. Operating requirements for high-latitude conditions are vastly divergent compared to temperate locations, with parameters to sustain human habitation at -60°F (-80°F survivable), withstand 100 mph wind speed and support 25 lb/ft2 snow load. Although great advances have been made in providing efficient and comfortable Arctic infrastructure since the onset of the Cold War, significant work remains to further increase efficiencies and adapt to changing climate parameters. To address infrastructure technology gaps, we recently launched an Arctic Infrastructure Research Group (AIRG). Current members of AIRG include ERDC researchers and other US Federal agency stakeholders. The purpose of the AIRG is to provide a forum and platform to coalesce and pursue needs, ideas, and technical projects. Current ERDC efforts on additive construction provide innovative solutions for Arctic infrastructure capabilities. Leveraging prior joint service Small Business Innovative Research efforts in rigid-wall insulation kits, ERDC will build an Arctic version of Mobile Insulation System for Energy Reduction (MISER), with Permafrost protection. Also, a parallel effort is initiated

to fully characterize the effects of extreme environments on certain expeditionary structures at the Farmers Loop Permafrost Experiment Station (FLPES). Our goal is to create a research-centric facility at FLPES to test new technologies and innovative materials while testing the requirements of Arctic hardened infrastructure for the benefit of all Arctic stakeholders.

***For full text, see *Permafrost 2021: Merging Permafrost Science and Cold Regions Engineering*, American Society of Civil Engineers. https://ascelibrary.org/doi/epdf/10.1061/9780784483589**

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A Brief Review of Frigid-Winter and Ice Effects on Earth Embankments: Three Case Studies

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This paper briefly reviews the present state of knowledge regarding winter and ice effects on embankments in cold regions. It draws on the writer's experience in cold-regions hydraulics and presents three case-study examples of ice effects, discusses the physical processes associated with ice effects, indicates the likely consequences for riprap and other means of embankment protection, and describes early hydraulics laboratory experiments conducted to improve understanding of ice effects on levees.

Frigid winter and ice effects may pose problems for diverse earthen embankments (e.g., dams, levees, roads, and port causeways). Thermal effects may weaken earthfill used to form embankments. Water currents (especially during ice-cover breakup) may drive ice floes and rubble against and onto embankments. Also, wind drag may impart large momentum to floating ice sheets, causing them to severely impact embankments. Moreover, continuous ice impact can lead to ice override of embankments, imperiling near-by facilities. Current- or wind-driven ice places unforeseen loads on embankments and the various erosion-protection methods intended to shield embankments from erosion. For example, riprap rock protecting a dam's or levee's upstream face may be dislodged. Ice impact and override weaken embankments, exposing them to subsequent erosion and possible failure by water flow. There is scant information on ice-sheet override and ice loads, and little guidance on how to protect embankments or on how to maintain soil strength year-round.

Early evidence shows that ice impact accumulation may lead to erosion of the embankment's downslope, while ice accumulation against an embankment's upstream slope may impose additional forces whose type and magnitude vary greatly. The three case studies illustrate several mechanisms of winter and ice interaction with earth embankments.

* * *

Synopsis: Permafrost Engineering in a Warming Climate – Current State and Future Strategy*

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Post-World War II and Cold War activities initiated North American studies on permanently and seasonally frozen soils. The 1970s was a pinnacle period where the knowledge and technology advances culminated in the successful design of a warm oil pipeline constructed to traverse the disturbance-sensitive permafrost terrains of Alaska. Since that time, a few technological advances have been made, mostly in the area of maintaining permafrost in the frozen state. Now the profession is confronted with the next stage of evolution in frozen ground engineering as the last few decades have seen a steady rise in permafrost temperature, with some areas experiencing significant foundation weakening and active thermokarst terrain. Overall, the changing environment is generating uncertainty with regards to safe engineering and planning, resulting in overly conservative designs which greatly increase development

costs while affecting government, private sector, and industry planning. Therefore, a high priority is the next generation of technology and methodology for design, construction, and maintaining of frozen ground infrastructure in a warming climate. The ASCE Cold Regions Engineering Department (CRED), Frozen Ground, Structures and Foundations, and the Transportation and Infrastructure committees agreed that a review of the current state of the profession and an outline of a future strategy was needed to facilitate advances for the common good of everyone in cold regions. The International Permafrost Association (IPA) sanctioned an Action Group to perform a current look at the permafrost engineering discipline, determine knowledge gaps, and suggest a path forward. This paper will present a synopsis of the more important findings of this Action Group and provide a forum for further discussion. Some of the more important findings are the need for programmatic work in developing 'living' permafrost temperature forecast tools, and technical advances in methods to design for increasing thaw sensitivity, designing and planning with threats from altered hydrology (thermo-erosion) and slope instabilities, and techniques to mitigate thaw-affected vertical and horizontal infrastructure, to name a few. Most importantly, the engineering profession, with the help of universities, must promote the backfill of the retiring frozen ground engineering workforce.

***For full text, see *Permafrost 2021: Merging Permafrost Science and Cold Regions Engineering*, American Society of Civil Engineers. https://ascelibrary.org/doi/epdf/10.1061/9780784483589**

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New Economical Ice Coring Method for Accreted Ice on Vertical Piles

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Ice coring auger machines can cost thousands of dollars and are generally made for vertical extraction from sea ice or glaciers. This research required compression testing of ice accreted on vertical piles at the Port of Alaska in Anchorage, Alaska, USA. This meant extraction was horizontal and needed to be completed during the short low tide window. This presentation will cover the development of a method to economically harvest and process ice into cylindrical cores.

The best method to obtain ice from the field location was found to be to cut roughly 24-inch cubes with a chain saw and extract them with a crane. The cubes were then transported and cored in a laboratory walk-in freezer. Cores were drilled with a hand drill using a core-bit that was custom fabricated from a 3-inch diameter, 8-inch-long steel tube welded to two concentric holesaws. It was found that the holesaw blades cut quickly and produced smooth ice surfaces if a mechanism was provided to evacuate the cut ice chips. To facilitate this, two adjoining ¾-inch-diameter evacuation holes were drilled prior to coring. These evacuation holes had to be located and directed precisely so that they connected with the outside diameter of the forthcoming core cut over its entire length but did not infringe on and damage the ice core. To do this, a metal cutting template was laid flat on the ice surface and used to locate the three holes. The template also included a steel rod welded perpendicular to the plate which guided the hand drill so that all three holes were aligned and parallel through the block. With this new method, an ice block can be converted into up to a dozen test-ready compression cylinders within a few hours.

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Employing Polyols for Increasing Ice Melting Capacity and Decreasing Freezing Point of Salt Brine Deicer

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Salt brine deicers are commonly employed in North America for snow removal operations during the winter season. While NaCl-based brines (23.3% wt. NaCl) are effective in mild winter, their effectiveness reduces significantly when temperatures drop below -21°C regardless of any increase in the NaCl concentration. Moreover, NaCl-based brine has been observed to become ineffective in ice melting when temperatures drop below -10°C. This study aims to improve the effectiveness of NaCl-based salt brine deicer by employing three types of polyols, namely sorbitol, mannitol, and maltitol. To this end, each of these polyols is separately added to 23.3% NaCl salt brine in concentrations ranging from 7.14% to 27.77%, and their influence on ice melting capacity and freezing point depression is investigated using extensive experimentation. Moreover, their effect on the skid resistance of pavements and dissolved oxygen levels is also studied. The results obtained from freezing point depression tests and ice melting capacity tests revealed the addition of 7.14% to 27.77% polyols in the salt brine deicing solutions significantly improve the ice melting capacity of salt brine and considerably depressed the freezing point of NaCl brine. The highest ice melting capacity is observed in the case of mannitol whereas the freezing point of salt brine is observed to reach -38.1°C after the addition of 27.77% polyol in the salt brine. The results obtained from the skid resistance tests showed that polyol-based deicers result in slightly lower skid resistance in the PCC pavement when compared to NaCl salt brine. Moreover, the dissolved oxygen levels did not increase considerably after the addition of polyols in the NaCl salt brine deicers. Overall, the polyol-based deicing solutions are observed to significantly improve the ice melting capacity and reduce the freezing point of salt brine with minimal impact on the skid resistance of PCC pavement and dissolved oxygen level in river water when compared to salt brine deicers. The results obtained from this study will lead to improving the effectiveness of salt brine deicers in snow removal operations, particularly at very low temperatures.

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Application of Empirical Correlations for Predicting Thaw Settlement: A Case Study of Nunavik, Canada

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Permafrost is widespread in the Arctic and sub-Arctic regions. Covering 40% of Canada, permafrost provides support for infrastructure built in these regions. Climate warming has altered the ground thermal regime in permafrost regions, initiating permafrost thaw and degradation, and thus threatening the safety and stability of the built environment and impacting future development in these regions. Quantifying the ground settlement induced by permafrost loss is essential for designing infrastructure to avoid compromised serviceability and safety conditions. Current practice uses empirical correlations relating permafrost and sediment index properties to estimate thaw strain and settlement. This study reviews the available thaw settlement correlations and illustrates their applicability using data from Nunavik. The applicability of the most widely used correlations is assessed by comparing the values obtained from these methods with thaw consolidation test results conducted by the Centre d'Études Nordiques (CEN) on approximately 100 permafrost samples from Nunavik, Quebec. Despite the extensive data available, some of the proposed empirical methods required inputs that were not recorded, thus this restricted application of some correlations. Comparison of thaw strain estimated from the correlations with measured values from the dataset, shows a large dispersion between the results. This can be partially attributed to the proposed correlations being established based on a wide scatter of data points, covering all sediment and permafrost types. Deviation of measured values from the estimations is particularly large for ice-rich permafrost samples, with the applied correlations underestimating the thaw stain for the majority of samples, particularly in ice-rich samples. Since the thaw settlement properties of soil are highly dominated by the compositions and fabric of the soil, developing a unique relation between index properties and thaw settlement properties for different soil types and ice conditions would improve the correlation coefficient and our confidence in permafrost thaw settlement predictions.

Deformation Caused by Frost Heave on a Rock Slope of Mudstone*

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Hokkaido, the northernmost island in Japan, suffers from frequent frost damage due to its cold climate. It has also been reported that civil engineering structures such as tunnels, roads, and slope protection works can be deformed by the frost heaving of rock. Therefore, it is important to understand the frost susceptibility of bedrock in Hokkaido, Japan. Especially, the occurrence of a freezing phenomenon on a rock slope may lead to a major disaster such as a bedrock collapse; therefore, it has been attracting a lot of attention. With this background, we have been investigating the deformation of rock slopes. In this study, we measured the freezing depth, the amount of frost heaving, and the weathering depth of the mudstone slope where the damage occurred. In addition, a frost heaving test and a slaking test were conducted on rocks collected in the field. The results of the laboratory tests found that the rocks collected in the field were easy to slake and had high frost susceptibility. From the field measurements, it was found that the rock slope frost heaves significantly in winter and that the surface layer of the slope thaws in spring and becomes extremely weak. Furthermore, the weathering depth of the rock slope was found to be in good agreement with the freezing depth. On the other hand, the weathering depth of the rock slope did not change during the summer, and no slaking was observed due to repeated dry and wet. In summary, it is clear that the weakening of rock slopes in cold regions is largely influenced by freezing and thawing cycles.

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A Second Foundation Review of AHTNA Corporation Glennallen Facility, Alaska, USA*

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Charles Riddle *Retired, R & M Consultants, Inc.*

This paper is an attempt to identify and provide a brief summary of some industry efforts that I was involved with or aware of during the late 1960s through the mid-1980s. All of the test sites were focused on evaluating terrain conditions and assessing potential pipeline impacts that would be involved while dealing with frozen ground conditions. The efforts included various organizations and participation by government agencies that occurred during the Alyeska Pipeline Service Company (APSC) Artic Gas Pipeline and the Alaska Northwest Natural Gas Transmission System early project activities. There were at least 11 test sites having locations in various parts of Alaska. These included Barrow, Prudhoe Bay, Prospect Creek, Hess Creek, the Fairbanks area, and Glennallen. They addressed concerns relating to thermal modeling of a hot oil 48-inch pipe buried in frozen ground, thaw settlement/ frost heave effects, trench excavation methods, and testing vertical support solutions for the designated above-ground pipeline segments. Access to published information on these test sites is varied, and the concern is that some of this history of early pipeline studies, related design input, and the possible influence on eventual construction (at least for APSC) be recorded.

***For full text, see *Permafrost 2021: Merging Permafrost Science and Cold Regions Engineering*, American Society of Civil Engineers. https://ascelibrary.org/doi/epdf/10.1061/9780784483589**

Laboratory Testing of Thermosyphon Fin Designs

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Air temperatures in the Arctic and sub-Arctic are increasing at an alarming rate, which can lead to failure in existing infrastructure where permafrost is present. Designing future and existing infrastructure to be resilient to a changing climate is critical to avoid collapsing infrastructure due to thawing permafrost. Thermosyphons, passive ground freezing heat transfer devices, can be used to freeze and stabilize the ground when constructing infrastructure (both vertical and linear). Thermosyphon freezing rates depend on a variety of factors (e.g., air temperature, wind velocity, fin area, and thermosyphon material). The condensation of the pressurized fluid that transfer heat from the bottom to the top of the thermosyphon takes place at the fins (the condenser). In the past, there has been limited testing on different fin designs. To address this shortfall, we tested and evaluated four different fin designs (twisted fins, stainless steel twisted fins, helical fins, and no fins) within a controlled environment at the Frost Effects Research Facility (FERF) at the Cold Regions Research and Engineering Laboratory (CRREL). The twisted fins are currently used by the manufacturer and therefore are referred to as the control. Freezing rates of the four thermosyphons are comparable. The helical fin design had a slightly lower rate of cooling close to the thermosyphon. At a distance of 25 cm from the helical fin thermosyphon, freezing occurred 12 days later than the control and 21 days later at 50 cm from the thermosyphon. The freezing front for the no fin thermosyphon reached 25 cm 1 day earlier than the control and reached 50 cm only 2 days later compared to the control thermosyphon. The freezing front for the stainless steel thermosyphon reached 25 cm 4 days later than the control but was 2 days earlier at the 50 cm distance. Varying soil moisture and sensor placement could have impacted these rates, but these results suggest that a simplified design of the thermosyphon with no fins could be used in place of a more expensive design where expedient freezing rates are not crucial for construction.

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Rethinking Water and Sanitation in Challenging Environments: Lessons Learned from Installing Portable, Adaptable, Mid-Tech Household Systems*

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Traditional permanent water and sanitation infrastructure faces major technical and economic challenges in cold regions communities because of the threats of freeze-thaw cycles, permafrost instability, and a changing climate. As a result, thousands of households suffer health and wellbeing consequences because they live without basic access to clean water, safely managed sanitation, and appropriate hygiene. In response, the Alaska Native Tribal Health Consortium has spent five years developing, piloting and deploying portable, adaptable, mid-tech household water and sanitation systems in unpiped communities in rural Alaska. These Portable Alternative Sanitation Systems (PASS) work with natural freeze-thaw cycles to manage wastewater, can be adapted to various modes of operation based on end-user preferences, require little training and technical expertise to operate and maintain, and can be easily moved to new locations if households have to relocate. End users have demonstrated that PASS units can be successful at providing incremental improvements in water and sanitation services to households, if they are appropriately designed, installed, and supported. We discuss lessons learned from deploying these innovative mid-tech systems in houses, such as the need to develop basic technical standards and socially appropriate trainings to ensure success of the technology. These lessons can be used to support the development of new types of adaptive and resilient infrastructure with low environmental impacts for cold climate communities to ensure the wellbeing and livelihoods of the people who live there.

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Microbe-Substrate Interactions Following Simulated Microbial Inoculation to Thawed Yedoma Permafrost in Anaerobic Environments

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The relative roles of ancient versus modern microbial communities in yedoma permafrost carbon decomposition and subsequent greenhouse gas (GHG) production are poorly understood. We anaerobically incubated sediments collected from a 12-m yedoma profile in Interior Alaska to examine: (1) interaction between thawed substrate and microbial community composition (16S RNA) and function (metagenomics); (2) how mixing modern CH4-producing communities with microbial communities present in frozen permafrost affects community composition and function following thaw; and (3) subsequent effects on CO2 versus CH4 production. Inoculation with modern CH4-producing communities from surface sediment collected from an adjacent thermokarst lake (Methanobacteriales, Methanomicrobiales, and Methanosarcinales) altered both microbial community development and organic matter utilization. For most depths, the inoculation increased CH4 (7.6 - 390x) and CO2 (1.0 - 2.7x) production and decreased CO2:CH4 ratios (36 – 99 % decrease) compared to controls. Combined data from our metagenomic functional pathway and Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR-MS) analyses show this increase in anaerobic GHG production following inoculation is the result of enhanced intermediate organic matter (OM) degradation (carbohydrateactive enzyme classes) breaking down more recalcitrant OM classes (carbohydrate-like compounds and lignin-like compounds) compared to the controls. Yedoma sediments with the highest initial substrate potentials (high relative abundance of aliphatic- and peptide-like compounds) that had not thawed since their formation experienced the strongest effects from inoculation, supporting previous suggestions that GHG production in thawed yedoma is microbially limited. Changes in microbial community composition (R2 = 0.90 and 0.51 for CO2 and CH4, respectively) and organic matter characterization (R2 = 0.68 and 0.33) provided better fits for estimating anaerobic GHG production potentials than initial microbial community composition (R2 = 0.32 and 0.41) and organic matter characterization (R2 = 0.49 and 0.29). This suggests predicting the evolution of microbial communities following thaw in conjunction with substrate potential will yield more accurate estimates of GHG production potentials compared to characterizing initial communities alone.

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Investigating Microbial Dormancy Within the Permafrost Microbiome

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Arctic ecosystems are experiencing warming at twice the rate of the global average, and this is causing rapid permafrost thaw. During thaw, previously unavailable soil carbon and nutrients serve as inputs for microbial decomposition which can release greenhouse gases into the atmosphere and further accelerate climate change. Microbial

communities in permafrost soils contain a diverse array of active, dead, and dormant microbes that experience widespread environmental and ecological change during thaw. An important metabolic strategy employed by dormant bacteria to survive stressful environments is to form endospores. Bacterial endospores represent a pool of latent metabolic capacity whereby they are metabolically inactive under frozen conditions and could be metabolically active under thawed conditions. Favorable abiotic conditions (i.e., elevated temperature, pH, and available labile soil carbon) following thaw could possibly resuscitate large proportions of the endospore-forming community. However, which members of the permafrost microbiome are dormant and which will be resuscitated upon thaw is unknown. We conducted a 1-month permafrost incubation experiment to assess changes to bacterial dormancy over the course of permafrost thaw. Our samples include permafrost replicates collected from above the CRREL Permafrost Tunnel and Farmer's Loop sites near Fairbanks, Alaska, and Utqiaġvik, Alaska. Throughout the incubation, we monitored the relative abundance and identity of endospore-formers present in permafrost immediately before and after thaw via isolation of endospores and subsequent 16S rRNA gene sequencing. This work provides insight into the effect of thaw on permafrost microbial diversity, which will advance understanding of microbial decomposition and the release of greenhouse gases in thawing permafrost landscapes.

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Permafrost Microbial Communities are Structured by Latitudinal and Soil Chemical Gradients

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The pan-Arctic biogeography of permafrost microbial communities (PMCs) and their functional potential is an important area of research, because PMCs may reveal information about permafrost history, biogeochemistry, and response to thaw. Permafrost soils vary by climate zone (both historic and current), history of vegetation and disturbance, parent material, and age, all likely affecting PMCs. We asked whether PMCs clustered into unique functional groups that are reflective of the biogeochemistry of the associated soils. We analyzed metagenomes from 133 samples from across North America, Europe, and Asia. The phylogenetic composition of communities did not cluster into components based upon environmental factors such as carbon content or pH, or permafrost characteristic such as permafrost age or depth, though a unimodal relationship between microbial diversity and soil pH was observed. In contrast, the functional composition of PMCs, based on largest variation in functional gene distribution, clustered into six types differentiated by latitude, pH, and soil depth. PMC clusters each had a dominant functional profile that included exclusively or in unique combination the following attributes: 1) fermentation and methanogenesis, 2) toxin/antitoxin defense mechanisms, 3) osmoprotectants, 4) nitrate and nitrite reduction, 5) the use of 'alternate' substrates (e.g., waxes, fatty acids, acetate, alkanes) that are metabolized exclusively through acetyl-CoA rather than pyruvate, and 6) iron uptake and utilization. At the panarctic scale, significant variation in the functional potential of PMCs was observed that could be explained by environmental data. However, marker genes were not predicted by environmental data, despite significant variation among sites. These patterns may help to explain variation in microbial processes observed across permafrost soils such as methane and nitrous oxide production, iron reduction, and amino acid cycling, and these data could help to identify locations with high potential for climate feedbacks following thaw.

Changes in Permafrost Microbial Community Composition after Thaw

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Arctic and sub-Arctic permafrost is thawing at an unprecedented rate, significantly altering the ecosystem. Microbial blooms triggered by permafrost thaw accelerate global warming, change permafrost structure, and impact the vegetation. Where and when these blooms will occur is poorly understood. Our study examined the microbial communities in permafrost over a controlled thaw regime. Samples consisted of five different permafrost soils collected in interior and northern Alaska. Both abiotic and biotic factors were examined to investigate drivers of the microbiome and associated processes. We seek to determine which bacteria represent the core microbiome of Alaskan permafrost soils and how these groups change through thaw.

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Investigating the Preservation Process of DNA in the Cold and Arid Paleoshores of the Antarctic Untersee Oasis

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The perennially frozen Lake Untersee and its paleoshores make up the Untersee Oasis, located in Eastern Antarctica, where the mean annual temperature is -10˚C (Andersen, T., Journal of Applied Meteorology and Climatology, 2015). The lake itself contains actively growing, modern microbial mats, and the cold, arid paleoshores of Lake Untersee are home to dry paleomats, which are remnants of microbial mats that lived within the lake hundreds to thousands of years ago. The combination of the modern and desiccated paleomats provide a unique sample set for the study of biosignature preservation in cold, dry conditions. Recent studies of biomarker preservation have been focused on lipids and other fatty acids which are well preserved in these cold and dry conditions (Wilhelm, M. B., Organic geochemistry, 2017). However, in this study, we focus on the preservation of DNA, a much more information-rich molecule. I have analyzed and sequenced DNA extracted from both paleomats found in the shores and modern mats within the lake. Using metagenomics, I study the changes in community structure and composition through time. I study the chemical changes that DNA undergoes through the early stages of diagenesis during which most degradation occurs. Previous studies found the chemical changes to include strand break and deamination damage to bases such as cytosine, adenine, and guanine (Shapiro, B., Science, 2014). Here, I assess the DNA quality in the mats by studying the changes in strand length through time. I use Uracil N-Glycosylase treatments to study deamination in the samples.

Microbial Response to a Long-Term Anoxic Batch Scenario of Permafrost-Affected Soil

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Permafrost-affected soils are widespread in the Arctic and store about half the global soil organic carbon. This large carbon pool becomes vulnerable to microbial decomposition through permafrost warming and deepening of the seasonal thaw layer (active layer). Here we combined greenhouse gas (GHG) production rate measurements with a metagenome-based assessment of the microbial taxonomic and metabolic potential before and after five years of incubation under anoxic conditions at a constant temperature of 4°C in the active layer, permafrost transition layer, and intact permafrost. Warming led to a rapid initial release of CO2 and, to a lesser extent, CH4 in all layers. After the initial pulse, especially in CO2 production, GHG production rates declined, and conditions became more methanogenic. Functional gene-based analyses indicated a decrease in carbon- and nitrogen-cycling genes, and a community shift to the degradation of less labile organic matter. This study reveals a decrease in the relative abundance of major metabolic pathway genes and an increase in carbohydrateactive enzyme classes in long-term batch scenarios of thawed permafrost soils and suggests that when labile carbon is steadily depleted, the less labile carbon fractions are increasingly utilized maintaining low but constant microbial GHG production.

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Life in the Freeze: Microbial Community Growth and Greenhouse Gas Production Across a Holocene to Pleistocene Permafrost Chronosequence Revealed by Stable Isotope Probing

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Permafrost is an extreme habitat which hosts a community of microorganisms that may survive and reproduce for millennia despite acute limitations in water and substrate availability. Many studies focus on DNA-based methods for determining microbial community composition, however these do not distinguish active and in-active cells or preserved DNA. In order to better understand microbial growth and transformation of permafrost C to greenhouse gas, we combined DNA-stable isotope probing (SIP) with process measurements data to reveal activities of microbial communities across a permafrost chronosequence from Holocene (5 ka) to Pleistocene (19 ka, 33 ka). Soils were collected, stored, and incubated at in situ temperatures (-3 °C) with either 18O-water, to target all active microbes, or 13Cglucose, to target actively growing microorganisms which may derive C from glucose. During the incubation period, we collected headspace gas measurements at 3-week intervals and destructively harvested samples for molecular analyses at 6, 12, and 18 months. We found evidence that microbial populations are actively growing and respiring across the entire Holocene to Pleistocene age permafrost gradient. The 5 ka soils yielded the most glucose-derived CO2, though this represented less than 0.05 % of the total 13C added. The 19 ka and 33 ka samples also produced 13CO2, with rates decreasing with increases in permafrost age. The 19 ka samples produced an order of magnitude more CH4 than either the 5 ka or 33 ka permafrost. Actively growing bacteria and archaea were found in all of the samples, although the relative abundance of the microbial population decreased with increasing soil age. DNA-SIP facilitated characterization of the metabolic pathways in growing organisms that likely drove differences in flux of CO2 and CH4. Results indicate the microorganisms are actively growing in intact permafrost and changes in C availability due to slight shifts in temperature may lead to substantial shifts in community composition and the potential release of GHG.

Mercury, Methylmercury, and Microbial Communities in a Degrading Palsa of the Hudson Bay Lowlands, Far North Ontario*

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The Hudson Bay Lowlands (HBL) is the second largest northern peatland in the world, hosting North America's lowest latitude continuous permafrost. The mobilization of inorganic mercury from thawing permafrost may contribute mercury for methylation and subsequent uptake for biota and human exposure. Based on published circumpolar estimates, 81-150 mg/m2 of mercury may be stored in the top 100 cm of HBL peats; these values are among the highest in permafrost zones of the Northern Hemisphere, although this has not been directly quantified. Moreover, estimates of the inorganic or total mercury pool does not provide any insights into the amounts of methylmercury found there, which is the form of mercury that bioaccumulates, biomagnifies. This paper assesses shifts in microbial community diversity and composition, inorganic mercury, and methylmercury concentrations in surface peat in degrading palsa fields of the HBL in northern Ontario to test the hypothesis that the transition from palsas to thermokarst fens via permafrost degradation creates biogeochemical conditions that enhance methylmercury production. We measured rates of permafrost degradation and collected cores of permafrost, active layer, and thermokarst from a palsa in a degrading palsa field. One set of core subsamples were freeze-dried, and solid peat was analyzed for total and methylmercury using certified ultra-trace methods. Microbial community composition was examined in another set of core subsamples via DNA extractions and high-throughput sequencing of the 16s rRNA gene. In the study region, we found that palsas lost ~0.83% of their area per year as they collapsed into adjacent thermokarst fens. As a result of shifting biophysical conditions, microbial diversity was significantly higher (<0.001) in samples from thermokarst than intact palsas. Through relating surficial permafrost features to microbial community and mercury data, we make important links between the potential release of inorganic mercury stores in permafrost, and methylmercury production in thermokarst as palsas degrade.

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Seasonal Variation in Microbial Community Depth Profiles: Implications for Understanding Nutrient Movements

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Climate warming is resulting in permafrost thaw and the deepening of the seasonally thawed soil active layer. These changes are likely to be accompanied by changes to soil biogeochemistry and nutrient cycling, mediated by shifts in the permafrost microbiome, with implications including the potential for feedback to climate change. To date, however, research has largely focused on changes to the permafrost microbiome from spring snowmelt through summer, when cold regions are most accessible. In this study, we explore active layer, transition zone and permafrost bacterial and fungal communities from summer through fall, using 16S rRNA gene and ITS amplicon sequencing of samples collected from Imnavait Creek, Alaska, in June, August, and October 2019. Our preliminary sampling suggests changes in the depth profile of the microbial communities between these time points, potentially reflecting processes such as movement of pore water, or microbial dispersal. Our findings suggest that summer sampling alone may not generate a complete picture of the linkages between microbial communities and nutrient movements through groundwater, highlighting the importance of capturing seasonal variation by sampling throughout the year.

Climate Change Effects on Microbial Activity in Arctic Permafrost and Considerations for Modeling This System in Transition

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Permafrost is thawing at unprecedented rates, significantly altering the landscape through changing subsurface conditions, soil properties, and vegetation characteristics. Permafrost microbes activate as permafrost soils warm and thaw. The contribution of temperature or starting inoculum on the microbial trajectory and potential function after thaw remains a research gap. We hypothesize that the initial soil microbial composition rather than the temperature dictates the end-state microbial community along a short transect of permafrost. We sampled permafrost from five discrete locations representing different ages of deposition in the Cold Regions Research and Engineering Laboratory Permafrost Tunnel in Alaska. In a laboratory incubation study, we gradually warmed the permafrost samples from -3˚C to 6˚C and continuously measured heterotrophic respiration. DNA was extracted and metagenomes were analyzed. Under frozen conditions, microbial respiration rates from different PT locations were similar to one another, ranging from 2 to 12 mg C-CO2 kg-1 d-1. Respiration increased during thaw for three of the permafrost locations but remained stable for two of the permafrost locations. There was an average of 21.9 million reads per sample. Analysis of the shotgun metagenomes revealed that the trajectory of dominant taxa and their potential function during thaw in a given permafrost location was more influenced by starting inoculum than by incubation temperature. Location was found to be a significant ($p = 0.001$) factor in differentiating taxonomy and potential functional profiles. Furthermore, the five most abundant classes in the permafrost samples include Alphaproteobacteria, Actinobacteria, Clostridia, Betaproteobacteria, and Bacilli. The differential response of microbiome from different locations has important implications for modeling soil biochemical processes across a dynamic landscape. What remains unknown are the effects of long-term thaw and in turn microbial composition on soil function.

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Mycorrhizal Species Characterization of Tundra Plant Roots

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North American Arctic plant communities are shifting from graminoid-dominated to shrub-dominated in a process known as shrubification, a change that is associated with shifts in belowground microbial ecology such as mycorrhizal colonization and rhizosphere community composition, and biogeochemical functions such as soil carbon sequestration and decomposition. The variation of mycorrhizal species colonization across different tundra plant types remains a knowledge gap. Likewise, it is unclear the extent to which mycorrhizal colonization can affect the community composition of root associated bacteria and fungi. Since rhizosphere microorganisms can have substantial impacts on carbon fluxes between soil organic matter and the atmosphere, we wanted to examine if mycorrhizal fungi influence the rhizosphere community composition of various plants throughout the tundra. It has been shown that different tundra plant species will harbor different compositions of mycorrhizal fungi and rhizosphere communities; however, less is known about mycorrhizal and rhizosphere variation within a plant species. Since most tundra plants are generalists and can harbor many different species of mycorrhizal symbiotes, it was expected that within plant species variation of mycorrhizal composition would be high. To that end, we hypothesized that the mycorrhizal fungi composition would be an explanatory variable of rhizosphere community composition. Our sampling was conducted August of 2021 near Toolik Lake Field Station, Alaska. Roots and rhizosphere soil of various tundra plants were collected and sequenced using amplicon sequencing with general bacterial, fungal, and mycorrhizaespecific primers to determine the rhizosphere and mycorrhizal species composition. The primary purpose of this study was to look at variation within and between the mycorrhizal and rhizosphere community compositions across different tundra plant species. We hope this work will serve as foundational information for other researchers involved in tundra biogeochemistry and mycorrhizal fungi.

Assembly of Microbial Communities in Thawing Permafrost

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Andy Leu *University of Queensland*
Ben Woodcroft *University of Queensland*
Gene Tyson *University of Queensland*
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Background: Arctic permafrost soils store one-third of the world's soil carbon, and amplified Arctic warming is thawing permafrost. Microorganisms in thawing permafrost can access previously unavailable soil organic matter and release greenhouse gases through decomposition. The rate and type of gases released depends on thaw-induced changes in microbial community structure and functional capacity. However, predicting these changes and subsequent carbon release is challenging since the community shifts – collectively known as assembly – are the result of a combination of eco-evolutionary and environmental processes, some of which can be directly predicted from species identity ("deterministic" forces) and others which are random with respect to species ("stochastic" forces). Due to compounding perturbations and the potential for hysteresis during assembly, predicting multi-year effects of thaw on communities is particularly challenging without first understanding the deterministic and stochastic forces in play. Yet this mechanistic understanding of community assembly is vital to design more accurate predictive models of permafrost carbon dynamics.

Objective: To better understand how the ecological processes structuring these microbial communities and their functions over time, we used shotgun metagenomics to investigate the changes in active layer soil microbial communities over six years (2011-2017) along a permafrost thaw gradient in Stordalen Mire, near Abisko, Sweden. We then used ecological models to identify and quantify assembly processes.

Results: We found that soil communities transitioned from homogenizing to heterogeneous selection as permafrost thawed, and that habitat-specific selection increased across years. This suggests a switch from abiotic pressure to competition during thaw which increased from 2011 to 2017. We also identified genes and organisms most associated with selective forces and therefore most likely to be affected in thawing permafrost. These results give us a better idea of the ecological forces structuring post-thaw microbial communities, and they will help us better predict carbon dynamics in thawing permafrost ecosystems.

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The Transition from Stochastic to Deterministic Bacterial Community Assembly During Permafrost Thaw Succession

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Climate warming has resulted in permafrost thaw across the Northern high latitudes over the past several decades. Thaw-induced environmental changes lead to shifts in microbial communities and their associated functions, however the ecological processes that shape the final composition of microbial communities are not well understood. Understanding how the processes that structure the identity and abundance (i.e., assembly) of pre- and post-thaw microbial communities may inform our ability to predict the functional outcomes of permafrost thaw. Deterministic processes are driven by abiotic and biotic selection pressures, and stochastic processes are associated with more uncertainty. The objective of this study was to determine the relative contribution of stochastic and deterministic assembly processes in active layer and permafrost soils before and after thaw. Specifically, we aimed to characterize the effect of time since thaw on assembly processes and evaluate the impact of increased temperature on assembly dynamics. We characterized microbial community assembly during permafrost thaw using in-situ observation and a laboratory incubation encompassing active layer, transition zone, and permafrost soils from the Storflaket Mire in Abisko, Sweden, where permafrost thaw has occurred over the past decade. We found microbial community assembly was driven by stochastic processes immediately after thaw. As post-thaw succession progressed, deterministic processes became increasingly important in structuring microbial communities. Furthermore, laboratory-induced thaw was reflective of assembly dynamics in-situ immediately after thaw; however, short-term lab studies might not capture the long-term effects of permafrost thaw on microbial community dynamics. Our results suggest predictions of microbial community dynamics in the weeks to years after thaw confounded by the high amount of stochasticity structuring the communities.

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Altered Microbial Structure and Function after Thermokarst Formation

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Permafrost thaw could induce substantial carbon (C) emissions to the atmosphere and thus trigger a positive feedback to climate warming. As the engine of biogeochemical cycling, soil microorganisms exert a critical role in mediating the direction and strength of permafrost C-climate feedback. However, our understanding about the impacts of thermokarst (abrupt permafrost thaw) on microbial structure and function remains limited. Here we employed metagenomic sequencing to analyze changes in topsoil (0-15 cm) microbial communities and functional genes along a permafrost thaw sequence (1, 10, and 16 years since permafrost collapse) on the Tibetan Plateau. By combining laboratory incubation and a twopool model, we then explored changes in labile and stable soil C decomposition along the thaw sequence. Our results showed that topsoil microbial α-diversity decreased, while the community structure and functional gene abundance did not exhibit any significant change at the early stage of collapse (1 year since collapse) relative to non-collapsed control. However, as the time since the collapse increased, both the topsoil microbial community structure and functional genes differed from the control. Abundances of functional genes involved in labile C degradation decreased while those for stable C degradation increased at the late stage of collapse (16 years since collapse), largely driven by changes in substrate properties along the thaw sequence. Accordingly, faster stable C decomposition occurred at the late stage of collapse compared to the control, which was associated with the increase in relative abundance of functional genes for stable C degradation. These results suggest that upland thermokarst alters microbial structure and function, particularly enhances stable C decomposition by modulating microbial functional genes, which could reinforce a warmer climate over the decadal timescale.

Impact of Large Herbivores on Permafrost Soil Carbon Storage

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In our study we examined the effects of large herbivorous animals on soil carbon storage in a permafrost landscape in northeastern Siberia. To assess the impact of those animals on the soil carbon storage, we examined soil profiles and permafrost cores from areas with different grazing intensities within landscape units, more specifically a drained thermokarst basin and the surrounding uplands. To do so, we chose our study sites in the Pleistocene Park near Chersky, as this area provides known animal densities and fenced areas, which allowed us to compare intensively grazed, extensively grazed, and non-grazed sites on a small spatial scale.

We found significantly higher carbon (TOC) values at those sites with intensive animal grazing, compared to non-grazed sites, especially within the active layer. Also, vegetation was shifted on intensively grazed sites from shrubby tundra vegetation to grasslands. In addition, active layer depth was smaller on grazed sites.

We conclude that the animals improve carbon storage and permafrost stability by changing the vegetation and removing or trampling down snow in winter, both of which led to colder ground conditions and hence reduced organic matter decomposition. This could be a hint to possible strategies to locally prevent permafrost thaw by rewilding or an intensification of animal husbandry in tundra areas.

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The Great Unknown: Thermokarst Lakes and Response to Permafrost Carbon Feedback Cycle

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Permafrost, which is also called perennially frozen ground, is soil, sediment, or rock that remains at or below 0°C for at least two consecutive years. Permafrost occupies approximately 24 percent of the exposed land surface of the Northern Hemisphere. The Arctic is dramatically warming. Over the past 50 years its temperature has risen at a rate more than twice the global average. This also creates a great risk for permafrost zones, which have a significant carbon store, estimated to be about 1.500 gigatons of carbon. That is twice the amount currently present in the atmosphere. Abrupt thawing of permafrost in the Arctic thus will double the previous predictions of potential carbon emissions. It is rapidly changing the landscape as well as the ecology of the circumpolar North. An obvious consequence of permafrost degradation is thermokarst lakes, also known as thaw lakes of ice-rich permafrost. These are net greenhouse gas sources as century-old carbon deposits become bioavailable and are mineralized to $CO2$ and $CH4$. However, response to feedback loops in the Arctic still remains uncertain. In a thermokarst system, for instance, a ground ice melt causes the land surface to subside, which changes the hydrodynamics of the landscape in return. Due to further climate change, water balance, or topography affects water bodies of all sizes and may cause diverse trends of waterbodies shrinking and growing, which means releasing long-term carbon stocks into the atmosphere, thereby initiating a positive climate feedback. There are also potential risks to local communities and their livelihood, including the loss of Arctic wildlife habitat. This study focuses on a literature review of thermokarst lakes in the permafrost lowlands, particularly the Seward Peninsula, Alaska, to investigate the relationship between waterbody differentiation and changes in the Arctic ecosystems.

The Transition to a Permafrost-Free Arctic - Revelations from Deep Soil Cores

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Field and laboratory studies aimed at forecasting greenhouse gas emissions from thawing permafrost soils commonly contrast emissions from the seasonally thawed active layer to those from underlying permafrost. However, previous work in the continuous permafrost zone has highlighted the existence of an ice-rich transition zone that can exceed 30% of the active layer thickness and thermally isolates the underlying substrate. Substrate in the transition zone undergoes state changes from seasonally thawed to perennially frozen to over multiple years and may be identified by the presence of ataxitic (suspended) ice.

Here we show that measurements of the isotopic composition of bulk soil organic matter (Δ14C, δ13C, δ15N) in deep soil cores can be used to identify the long-term position of the active layer, transition zone, and permafrost. In graminoid tundra, the depth of the transition zone almost doubles the depth of intermittently frozen or thawed substrate.

Our data also demonstrate that the transition zone is not just enriched in ice, but also carbon and nitrogen (and likely microbes) and that transition zone emission of CO2 and N2O exceed those from both the active layer and permafrost. Thus, rapid thaw and drainage of the transition zone in the next decades may generate a pulse of greenhouse gas emissions that may not be sustained with deeper thaw. However, an analysis of the International Soil Radiocarbon Database shows that the majority of radiocarbon measurements have focused on 0 to 1.2 m depth.

Taken together, our analyses identify an urgent need and opportunity for the permafrost community to reconsider the 2-layer permafrost model and to study of deeper soil and sediment cores to constrain the greenhouse gas feedback to permafrost thaw and the role of permafrost in a warming world.

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Slope Failure at the Base of Permafrost Increasing Frequency and Magnitude of Thaw-Driven Mass-Wasting Across Discontinuous Permafrost Terrain in the Central Mackenzie Valley Foothills, Northwest Territories

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Widespread hillslope mass-wasting in the extensive discontinuous permafrost zone of the (fluviallyincised) central Mackenzie Mountain foothills has significantly increased in frequency and size in the past 15 years. The increase in thaw-driven mass-wasting is largely a function of increasing air and ground temperatures, precipitation, and legacy thermal disturbance from forest fire activity. In contrast to retrogressive thaw slumps, which initiate and develop from the progressive top-down and lateral thaw of permafrost, we identify an increasing frequency and magnitude of deep-seated translational permafrost landslides with failure planes at depths up to tens of meters below the active layer. We identify a suite of thaw-driven processes that involve basal permafrost sliding, thaw-driven fluidized flow, and continued scarp enlargement by retrogressive failure. Thaw-driven detachment of materials at depth produce the capacity to rapidly transport large amounts of frozen sediment downslope in a blocky manner, often resulting in individual disturbances covering tens of hectares across varied permafrost terrain. Characteristic of these features is the presence of conical mounds up to 10m high on their debris tongues, termed molards, that are produced from the thawing of translocated ice-rich permafrost blocks. We employ high-resolution satellite and UAV imagery, along with repeat digital elevation models, geological observations, and electrical resistivity tomography surveys to infer that 'bottom-up' thaw from the base of the permafrost table is driving the initiation of these features. We present these observations and put forward a conceptual framework outlining the setting and basal permafrost failure mechanisms of these features. Further understanding of the setting and variability of permafrost mass-wasting and landscape trajectories has implications at all scales, not least of which involves assessing permafrost carbon release through hillslope thermokarst.

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Vertical Distribution of Excess Ice in Icy Sediments and Its Statistical Estimation from Geotechnical Data (Tuktoyaktuk Coastlands and Anderson Plain, Northwest Territories)

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Excess ground ice can be found distributed within icy sediments and in the form of massive ice. It is an important variable to quantify, as it strongly influences the landscape's response to permafrost thaw and the release of carbon stored in frozen soils. Thawing of excess ice in the western Canadian Arctic has led to thaw subsidence and abrupt thaw events, such as retrogressive thaw slumps and the formation of thermokarst lakes. These processes play an important role in generating carbon emissions to the atmosphere, as they expose previously frozen carbon to microbial decomposition and fluvial export and alter local to regional topography and hydrology. A large amount of geotechnical data is available in the Tuktoyaktuk Coastlands. However, field assessments typically only involve the estimation of visible ice. To add more value to these datasets, a cryostratigraphic dataset collected along the Inuvik-Tuktoyaktuk Highway (n = 566 boreholes) is used to develop and parameterize a beta regression model to predict excess ice content of icy sediments based on depth, visible ice content, materials, and Quaternary deposits. The predictions are compared to recorded massive ice intervals and show that excess ice within icy sediments can contribute up to 65% of the excess ice and thaw strain within the first 10 meters from the surface in this area. Abrupt thaw events in ice-rich soils are known to be influential to the carbon cycle but are not well represented in permafrost models. This new modeling approach to estimate the distribution and characteristics of excess ground ice found as massive ice and within icy sediments may help incorporate better representations of abrupt or gradual thaw processes in coupled models and help account for the additional carbon released in the atmosphere.

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Soil and Plant Community Characteristics Across Successional Stages of Ice-Wedge Degradation and Re-Stabilization in the Tundra of Northern Alaska

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Recent warming has resulted in ice-wedge thaw in polygonal landscapes of northern Alaska, leading to changing topography and hydrology. Soil warming and altered hydrology influence the availability and transport of nitrogen, with consequential impacts on vegetation. Nitrogen cycling can vary substantially across successional stages

of ice-wedge degradation and re-stabilization. Resultant changes in plant communities and biomass can lead to feedbacks of further degradation or stabilization. This study aims to understand how soils and vegetation interact across ice-wedge successional stages at two sites in Arctic Alaskan tundra (Jago River and Prudhoe Bay). Jago is an acidic Arctic tundra site with some topographic heterogeneity and distinct vegetation types across the different successional stages of icewedge degradation and re-stabilization. Prudhoe Bay is an alkaline, urban site with less topographic heterogeneity and less distinct vegetation types across stages. We measured soil moisture, total soil C and N, net N mineralization, and soil NO3- and NH4+ at the drier ice-wedge successional sites. We harvested plant biomass from all of the successional stages, and Eriophorum angustifolium was used as a benchmark species to compare across stages. Jago soils had greater soil %N by mass compared to Prudhoe Bay, but due to differences in bulk density, Prudhoe Bay soils had greater total C and N. At Jago, inorganic N availability (resin probes) was greater at sites with some degree of degradation, but the opposite was true for Prudhoe Bay. There is a clear shift in plant functional groups toward dominance by hydrophilic sedges and mosses with increasing degradation at both locations, and greater overall vegetation biomass at Jago. At Jago, the N content of E. angustifolium is elevated in degrading sites, but this is less distinct at Prudhoe Bay. These data suggest that ice-wedge degradation may affect soil characteristics by increasing N availability and transport in sites that have experienced degradation, and therefore may play a key role in vegetation response to climate warming in dynamic, heterogeneous Arctic ecosystems. Our data suggest, however, that these trends may be heavily dependent on specific local conditions.

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Submarine Permafrost as a Long-Term Late Quaternary Carbon Sink

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Organic carbon (OC) stored in Arctic continental shelf sediment is a climate-sensitive but poorly quantified component of the global carbon cycle. The current interglacial period means that most shelf permafrost, along with its OC, is currently warmer than -2 °C, and therefore susceptible to small additional warming in the near future. Estimating how much OC is potentially stored in subsea permafrost is thus key to a quantitative understanding of potential impacts of permafrost thaw on carbon mobilization in a warming Arctic.

We developed a process-based model of permafrost distribution and organic matter (OM) sedimentation and decomposition to estimate the contribution of submarine permafrost to Arctic shelf organic carbon stocks. Driven by Earth System Model forcing, our model calculates 1D heat flow below the earth surface, ice caps and seabed and uses a reactivity continuum model of OM decomposition. We restrict our modeling to sediment that was buried within the last four glacial cycles (450 kyr) and therefore neglect OC stocks deeper than about 100 m, including any gas hydrates.

Restricting OM decomposition to the liquid habitat for microbial activity in the sediment, we estimated that permafrost below the Arctic Shelf stores at least as much OC as the terrestrial counterpart at preindustrial time, and probably in the range of twice to three times as much OC. We compared the effect of varying the OC sedimentation rates and OC reactivity. Higher reactivity in marine sediments combined with lower ice contents to increase the rate of OM decomposition, relative to sediment deposited in terrestrial settings. As a result, permafrost in our model preserved a greater proportion of marine OM from decomposition while having little effect (< 5%) on the amount of recalcitrant terrestrial OC. These differences in sedimentation rate and reactivity influence the distribution of OC preservation on the Arctic shelf.

Our modeling shows that subsea permafrost is a relevant OC stock and that more research is needed to understand microbial OM decomposition in cold but not necessarily frozen sediments. Given that deeper deposits and gas hydrates are not included, we provide conservative estimates of Arctic shelf OC stocks and suggest that the shelves have acted as long-term carbon sinks over multiple glacial-interglacial cycles.

Ice Wedges as a Winter Paleotemperature Proxy: Limitations and Local Noise in Their δ18O Record

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Recently, ice wedge research has shifted towards its use as paleoclimate proxies, using the D-18O signature recorded in the wedge ice to reconstruct past Arctic winter climates. The purpose of this research is to investigate the validity of the ice wedge stable isotope signature as a valid proxy for winter climate. Ice wedges in Eureka, Nunavut, were analyzed for DOC 14C and D-18O. Radiocarbon ages extracted from eight ice wedges show peripheral cracking in one-quarter of the sampled wedges. Comparison of sampled ice wedges ages to the MacKay (1974) Gaussian distribution suggests that ice wedges of medium widths (1-2 m) are more reliable for paleoclimate dating because of a higher probability of cracking. Cracking irregularity and peripheral cracking suggest that ice wedge D-18O should rely on veinlets' direct dating to establish a proper chronology. Symmetry analysis of the ice wedge D-18O showed a statistically different average δ18O at depth within three of the four sampled ice wedges. Additionally, the δ18O signature within the sampled ice wedges shows an increasing trend from the center to the wedge's edge. This change can be attributed to increased moisture and mixing near the intersection between ice wedge and icy permafrost. Consequently, against ice cap Agassiz δ18O, the ice wedge isotopes show a high degree of variability throughout the Quaternary and are attributed to the random timing of meltwater fractionation infiltrating the ice wedge crack. Finally, it is proposed that a smoothing spline be used with multiple ice wedge δ18O records to create a robust and reliable chronology.

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Quantifying Erosional Dynamics in Ice-Wedge Networks with Computer Vision and Graph Theory

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In the face of a warming Arctic, ice-rich permafrost landscapes are undergoing rapid changes. Ice-wedge polygonal networks in Arctic lowlands are especially vulnerable and melting ice wedges can induce widespread subsidence and trough formation. The transition from low-centered to high-centered polygons can have important implications on surface hydrology, as the connectivity of the newly forming trough networks determines the rate of drainage for these lowland landscapes. However, quantifying such dynamics can be challenging, as even small-scale changes can have far-reaching implications for the larger scale hydrology of a region. In this talk, we introduce an automated workflow that enables quantification of trough network dynamics in thaw-affected landscapes. We use methods from traditional computer vision to extract (a) the spatial pattern of the trough network and (b) the morphological parameters of trough width and depth from high-resolution digital terrain models. Finally, we (c) incorporate this information into graphs -- a mathematical concept used to represent complex networks -- and use graph analysis methods to determine progressing subsidence and trough formation. Based on a study area in the Anaktuvuk River fire scar on the North Slope, Alaska, USA, we present the potentials and benefits of such graph algorithms for quantifying the erosional development of this thaw-affected landscape. In our study region, we observed an increase (+127%) in the number of discernible troughs as well as their connectivity (number of disconnected networks decreased by 89%) over the observed period of ten years. The average width of troughs has increased (+14.5%), while the depth has decreased (-12.5%). With this approach, for the first time, a large-scale analysis of such detailed ground-ice and hydrological surface dynamics is made possible.

Initial Investigations of Degrading Peat Plateaus in the Central Mackenzie Valley, Northwest Territories

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Peat plateaus dissected by dendritic fluvial and fen networks are common landforms in the central Mackenzie Valley, Northwest Territories. These networks tend to be associated with sloping site conditions (up to ~ 3m per km) and are largely developed on moraine and glaciolacustrine sediments. These sites are often covered by tussocks, reindeer lichens (Cladonia sp.), and varying cover of open black spruce (Picea mariana). Field investigation of 3 sites in 2021 showed that peat thicknesses were ~ 2m with structureless pore ice, that was overlaying several meters of ice-rich diamict or glaciolacustrine sediments. Electrical resistivity tomography profiles indicate that permafrost is typically thin in these areas (5-12 m), and through-going taliks forming the channel network are common and increase in frequency downslope. The taliks appear to extend under the margins of the peat plateaus adjacent to the taliks and are commonly captured to form the dendritic network. There seems to be little evidence for surface disturbances. Local depressions on the surface appear to extend into the underlying ice-rich sediments and are very recent based on flooded black spruce (Picea mariana) and reindeer lichens (Cladonia sp.) within ponds. We hypothesize that these are slowly expanding thaw networks, likely driven by basal permafrost thaw near taliks.

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Holocene Carbon Dynamics from a Permafrost Peatland in the Sporadic Permafrost Zone, Kenai Peninsula, Alaska

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Permafrost and landscape history, in addition to ground ice content, are increasingly identified as important components in predicting permafrost thaw trajectories. Together with cryostratigraphy, plant remains can provide useful information about past permafrost aggradation and thaw. We analyzed plant macrofossil assemblages, cryostratigraphy, and radiometric dating to reconstruct vegetation and permafrost history using peat cores from two permafrost peat plateaus and two adjacent collapse-scar bogs from a peatland complex in the sporadic permafrost zone on the Kenai Peninsula, Alaska. Organic matter content and bulk density are used to evaluate corresponding carbon dynamics. Preliminary results from the permafrost plateau suggest that permafrost aggraded syngenetically with peat accumulation during the early Holocene, but a possible unconformity characterized by mineral-rich sediment interrupted peat accumulation between ~9 to ~3.5 thousand years ago (ka). Evidence from cryostratigraphy and exceptional peat preservation below the mineral unconformity suggests that deep permafrost (>3 m) did not degrade during the Holocene. The resumption of peat accumulation characterized by abundant rich fen macrofossils (e.g., Carex spp., Calliergon, Drepanocladus spp., Paludella squarrosa) above the mineral horizon suggests near-surface conditions were permafrost free and that permafrost re-aggraded in the late Holocene (3 m depth). The permafrost plateau is losing surface peat due to oxidation, likely as drainage increased to the adjacent collapse-scar bog. This loss suggests that for permafrost peatlands significantly impacted by recent thaw, remaining peat plateaus can rapidly lose carbon from the active layer before permafrost thaw occurs. These results also suggest that post-thaw peat carbon loss may be confined to the upper 1-2 m.

Circumpolar Observations of Thermokarst Pool Expansion from High-Resolution Satellite Imagery

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One of the most conspicuous signals of climate change in high-latitude tundra is the expansion of thermokarst pools above melting ice wedges. Beyond expressing permafrost degradation, this process exerts strong feedbacks on subsequent thaw rates through a series of positive and negative feedbacks which play out over timespans of decades. Preliminary regional-scale modeling studies indicate that, when these feedbacks are accounted for, the mass of permafrost-affected carbon susceptible to thaw by 2100 may be as much as twelve times greater than otherwise expected. However, at the global scale, the magnitude of this effect is poorly constrained due to a lack of historical observations. In this study, we assessed circumpolar thermokarst pool expansion from 2008 to present at twenty-seven survey areas dispersed throughout the Arctic. Our workflow, based on convolutional neural networks paired with subsequent image processing operations, segmented thermokarst pools from submeter-resolution panchromatic imagery from the WorldView satellites. The results revealed that recent circumpolar pool expansion has been uneven but widespread, including in very cold settings. Among other findings, the observations indicate that topography plays a significant role in determining ice wedge vulnerability to climate change, as pool expansion was often concentrated in convex regions within upland landscapes. These data comprise a unique glimpse at recent thermokarst pool expansion around the Arctic and provide valuable context for evaluating the impact this process will have on rates of global permafrost thaw.

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Shifts in Plant-Soil Interactions Following Ice-Rich Permafrost Thaw: Implications for Carbon Storage

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Permafrost soils hold globally significant quantities of carbon that are experiencing enhanced decomposition due to surface warming, forming one of the most important biogeochemical feedbacks to future climates; however, the magnitude of this feedback remains poorly constrained. Current model predications indicate enhanced primary productivity within the vegetative community may initially offset microbially mediated carbon losses from permafrost ecosystems, but confidence in these projections is limited by the availability of empirical data. To address this knowledge gap, we evaluated the impacts of ice-rich permafrost thaw on plant-soil interactions in study systems spanning central Alaska, USA, and southern Northwest Territories, Canada. To discern the role of thaw on limiting resources, we characterized shifts in porewater chemistry (C and N species) and associated C emissions for two years in incubated permafrost soils. This work was complemented by an in situ simulated permafrost thaw resource pulse experiment, which quantified changes in belowground biogeochemistry, carbon emissions, and plant community composition and productivity. Our longterm incubation study demonstrated abrupt changes in porewater

C and N quantity and quality following experimental thaw, with dissolved organic carbon and dissolved nitrogen concentrations 160% and 70% above mean values, respectively. Despite this, simulated in situ resource pulses did not affect ecosystem respiration and net ecosystem exchange of CO_2, although CH_4 production rates increased by 11-fold. Early signs of such thaw events were indicated by the vegetative community as an increase in graminoid and sphagna abundance and a decrease in ericoids. Taken together, this research provides first-order mechanistic knowledge needed to further constrain the permafrost-carbon feedback and parameterize Earth System Models quantifying the warming potential of global permafrost decay.

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Impacts of Shrubification on Ground Temperatures and Carbon Cycling in a Subarctic Fen near Churchill, Manitoba*

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One of the fastest progressing environmental changes reported from permafrost areas is the proliferation of shrub species (shrubification) in tundra ecosystems. Changes in vegetation structure affect ground thermal regime and biogeochemical cycling, but the nature of these relations is still poorly understood. This paper examines the impact of shrubification on ground temperatures and greenhouse gas production potential in a fen environment of the Hudson Bay Lowlands, near Churchill, Manitoba. Churchill is located near the latitudinal forest-tundra transition, in the continuous permafrost zone. The study site was dominated by Carex aquatilis, but in some areas Betula Glandulosa has recently proliferated. We assessed shrubification rates in the Churchill area by evaluating NDVI (Mann-Kendall) trends using Landsat 5 to 8 to assess change from 1984 to present. We installed temperature sensors just below the ground surface in sedges and shrubs to assess differences in thermal regime. We collected active layer samples from shrub and sedge sites to perform incubations in anaerobic (4 weeks) and aerobic (4 days) conditions. Gas samples were analyzed for CO_2 and CH_4 through gas chromatography. Preliminary results show differences in shrubification rates between terrain units. At our study site in the fen (intermediate shrubification rates), mean ground surface temperature was more than 3°C warmer under Betula. There, summer temperatures were greater and more variable than under Carex due to drier ground and limited shading effects. Winter temperatures were also less variable and greater than in sedges, consistent with insulation provided by snow accumulation in shrubs. While the sedge fen could sustain permafrost, with mean ground surface temperatures below 0°C, it seems unlikely that permafrost would be sustainable where shrubs encroached, with mean ground surface temperatures several degrees above 0°C. Incubations indicated a lower methane production potential in areas where shrubs had encroached compared to the sedge fen.

***For full text, see *Permafrost 2021: Merging Permafrost Science and Cold Regions Engineering*, American Society of Civil Engineers. https://ascelibrary.org/doi/epdf/10.1061/9780784483589**

Ground Ice Survey Designed for Data Holders and Data Users to Improve Understanding of Ground Ice Content in Permafrost Across the Arctic

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Permafrost contains ice in the form of pore ice, ice lenses, and ice wedges, the latter occupying up to 80% of the soil volume. About two-thirds of the total permafrost zone is categorized as low ice content and one-third with medium to high ice content. Permafrost areas containing high ice content are highly susceptible to abrupt thaw with serious disturbances and consequences to ecosystems and human infrastructure. In order to identify the most vulnerable areas for accelerated permafrost degradation and abrupt thaw, improved accuracy and detailed maps of ground ice distribution are necessary. With feedback from internationally recognized permafrost researchers and the Interagency Arctic Research Policy Committee (IARPC), we developed a ground ice survey https://tinyurl.com/yxqwhejs that polls data holders and data users about the availability of ground ice data and the need for better ground ice maps. The survey will identify who has data, where they are, and at what scale in time and space. In detail, the survey identifies the region of data collection, ecosystem type, soil type, spatial extent, type and purpose of data collection, as well as ancillary data collected. The goal of this initial survey is to improve ground ice maps that will be useful to the various needs of scientists, engineers, and other stakeholders. We invite scientists, engineers, modelers, and other data holders to fill in the survey with data availability and their specific needs for improved ground ice maps.

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The Thermokarst Detection Algorithm: A Case Study at Eight Mile Lake, Alaska

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To date, thermokarst detection from remote sensing techniques has been limited to areas with repeat elevation imagery or by spectral methods which cannot be applied beyond a single image, making it difficult to assess the extent of abrupt thaw across the circumpolar region, despite the important role this process has in our ability to predict future carbon fluxes. To try to overcome this obstacle, we developed the thermokarst detection algorithm, which is capable of detecting thermokarst features from a single elevation image. We applied it in an 81 km2 area surrounding Eight Mile Lake, Alaska, near Denali National Park. The algorithm identifies areas where the local elevation is lower than the median elevation in a surrounding circular neighborhood of variable size, allowing the detection of variously sized features. The algorithm had an overall accuracy of 71.5% and identified thermokarst features in 7% of the study area with sizes ranging from 1 m2 (the resolution of our imagery) to over 100,000 m2 and an average of 25 m2. The majority of features by count were small thermokarst pits; however, the largest impact by area was caused by more extensive water tracks. Using the thermokarst classification and eddy covariance, we were able to determine that abrupt thaw resulted in higher carbon release at the site. Carbon dioxide release was higher following abrupt thaw as it promoted ecosystem respiration more than photosynthesis on an annual timescale, although there was a larger impact on photosynthesis during the summer. Methane release was also higher following abrupt thaw, as it was promoted nearly year-round. Because the thermokarst detection algorithm does not rely on site-specific relationships or time-dependent imagery, it has the potential to be broadly applicable at sites across the permafrost zone. Although our study relied on high-resolution elevation data, we believe it would be feasible to use lower resolution data to identify the majority of thermokarst features (by area), particularly in locations where larger features such as retrogressive thaw slumps and active layer detachment slides are the prevalent form of thermokarst. Given the importance of abrupt thaw in driving carbon fluxes, and the increasing availability of remotely sensed elevation data, we believe that this method will have great utility in studying thermokarst and carbon fluxes across the circumpolar region.

Relict Basal Ice from the Laurentide Ice Sheet Near Lac De Gras, Slave Geological Province, Northwest Territories, Canada

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A 2015 drilling campaign of the Slave Province Surficial Materials and Permafrost Study near Lac de Gras has recovered permafrost core interpreted to contain preserved basal ice of the Laurentide Ice Sheet. Previous samples of basal ice from ice sheets originate from coring beneath modern ice divides, modern margins of Arctic icecaps that have preserved basal ice-sheet ice, or from studies near the margins of former ice sheets. The present study may be the first evidence of basal ice a few hundred kilometers from ice divides. In this intermediate zone, rates of erosion beneath an ice sheet increase and the thermal regime at the base varies. Our finding is relevant because it highlights the mosaic character of a landscape that contains terrain types with non-negligible ground-ice content, poised for climate-driven thaw and landscape change. The occurrence and mosaic character of preserved ice can be reconciled with glaciological theory and observations from mineral prospecting using the theory on the genesis of dispersal plumes in till developed by Hooke et al. (2013). The existence of preserved basal ice opens novel basic-research opportunities alongside exploration, mining and infrastructure development in the area.

Related publications:

Subedi, R., Kokelj, S. V., and Gruber, S. 2020: Ground ice, organic carbon and soluble cations in tundra permafrost soils and sediments near a Laurentide ice divide in the Slave Geological Province, Northwest Territories, Canada, The Cryosphere, 14, 4341–4364, https://doi.org/10.5194/tc-14-4341-2020.

Hooke, R. L. B., Cummings, D. I., Lesemann, J. E., and Sharpe, D. R. 2013: Genesis of dispersal plumes in till, Can. Jo. Earth Sci., 50, 847–855, https://doi.org/10.1139/cjes-2013-0018.

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Distribution, Morphometry, and Ice Content of Ice-Wedge Polygons, Central Yukon, Canada

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Investigations of the regional distribution of ice-wedge polygons and wedge-ice volume allow for the assessment of the vulnerability of permafrost landscapes to thaw-induced disturbances and related ecological feedbacks. Ice-wedge polygons have been described in multiple studies in flat terrain and low-gradient hillslopes, but few studies have examined ice-wedge polygons in mountainous terrain. This study investigates the distribution, morphometry, and wedge-ice content of ice-wedge polygons in Tombstone Territorial Park, a mountainous permafrost region in central Yukon. Results show that ice-wedge polygons occupy 2.6% of the park and preferentially develop in woody sedge peat, glaciofluvial, and alluvial deposits along the lower reaches of the Blackstone and East Blackstone rivers on hillslopes ≤1. The morphometry of five of six polygonal sites studied showed statistically similar polygon sizes and trough angles, while showing different development stages based on vegetation type, surface wetness, and spatial pattern. The estimation of wedge-ice volumes in the ice-wedge polygons is 8–22% and is comparable to that of other Arctic regions. However, the estimated wedge-ice volume represents a minimum value because older generations of ice wedges are truncated 3–4 m below the surface with no evidence of surface polygons, and the polygonal network can be obscured by slope processes, vegetation, and icewedge inactivity. This study provides insights into the application of morphometric and soil parameters for the assessment of ice-wedge polygon distribution and development stages.

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.

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Using Radar to Remotely Sense 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.

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

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Marnie Bryant *Scripps Institution of Oceanography, UC San Diego*
Matthew Siegfried *Colorado School of Mines*
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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.

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Investigating the Sensitivity of L-Band Polarization Ratio to Surface Organic Soil Properties in the Arctic Tundra Area

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Richard Chen *Jet Propulsion Laboratory*
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Charles Miller *Jet Propulsion Laboratory*

Surface soil organic matter (SOM) and soil moisture represent first-order controls on permafrost thaw and vulnerability, yet they 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 the 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, p60%) 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.

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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.

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Advances in Airborne Remote Sensing of Permafrost During ABoVE

Charles Miller *Jet Propulsion Laboratory*

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.

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Automated Quantification of The Evolution of Retrogressive Thaw Slumps from Multi-Temporal High-Resolution Satellite Imagery

Lingcao Huang *University of Colorado*
Lin Liu *The Chinese University of Hong Kong*
Kevin Schaefer *University of Colorado Boulder*

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

Hui Jiang *Sichuan University*

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.

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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 a 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.

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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.

Investigating the Relationship Between Permafrost, Climate Change, and the Built Environment in Arctic Coastal and Riverine Environments

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Environmental processes can have dramatic effects on community infrastructure in Arctic environments. In many communities, the impacts of these processes are intensifying with climate change. The thawing of permafrost, in particular, poses a serious threat to the built environment in the Arctic. Permafrost when thawed creates unstable soil conditions, which are more susceptible to larger magnitudes of settlement as well as erosion in coastal and riverine environments. Currently, there exist several knowledge gaps on the relationship between permafrost thaw and the built environment. Additionally, the interactions between permafrost thaw and other climate-change-driven processes that impact civil infrastructure such as coastal flooding and riverine erosion are not well understood. In this study, we present a synthesis of a detailed literature review and workshop on currently available data and observations on the interaction between permafrost thaw and the built environment in Arctic communities and provide an outlook towards future trends in the context of climate change. Initial observations suggest that erosion, flooding, and permafrost thaw damage infrastructure in over 40% of all communities in Alaska. Furthermore, we discuss existing knowledge gaps and pathways to fill these gaps through innovative and sustainable data collection strategies.

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Permafrost Characterization Using Ground Penetrating Radar (GPR) in Support of Land Use Planning, Inukjuak, Nunavik

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With climate warming affecting the high latitudes, there is a growing need for knowledge concerning the spatial and vertical distribution of soil properties at the scale of communities in order to assess terrain sensitivity to permafrost thawing, estimate bearing capacity for infrastructure, and ensure proper design foundations for buildings. Given a strong demographic growth in Inukjuak, there is an important need for the development of housing projects and municipal infrastructure. It is therefore essential to proceed to high resolution permafrost characterization (about 100 m2 resolution) to support urban land use planning and to select foundation designs for buildings in accordance with local permafrost conditions.

The main objective of this project was to compile a map of geomorphological and permafrost features that are key to support decision making in land use planning and construction. Those features are the depth to bedrock, the distribution of surface geological units and strata, and the extents of zones of thaw sensitive ice-rich permafrost zones in the community area. The final map provides necessary information for selecting the best choices of foundation designs such as pads, piles to bedrock, adjustable studs and thermosiphons throughout the urban area with a concerted vision for urban planning.

GPR was used as a key research tool in the mapping project. A total of 21 km of GPR profiles surveyed in the summers of 2015 and 2017 were interpreted with the help of other sources of information such as analysis of aerial photographs, surficial geology maps, excavations, drill holes and field observations. Some sectors of the Inukjuak area are underlain by thaw sensitive permafrost, mostly because of the presence of ice-rich silty glacio-marine sediments under low-lying ground between bedrock outcrops. The largest part of the community, however, is either on thick marine sand with low ice content or has bedrock at shallow depths (i.e., between 3,5 and 6,5 m below the surface).

The compilation of permafrost data and the map of depth to bedrock shall help decision making by the community and the supporting regional government and will be a tool to plan an adaptation strategy to climate change.

Multi-Disciplinary Hazard Mapping Framework for Critical Infrastructure on Permafrost, Ilulissat, West-Greenland

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In the face of climate change, degrading permafrost and inappropriate construction practices often threaten the integrity of the built environment. As a result, Arctic communities become increasingly vulnerable and exposed to hazards. The implementation of adaptation strategies integrating future climate scenarios is fundamental to guide urban planning and expansion onto permafrost areas. In order to provide reliable decision support tools to local governments, hazard and risk assessments resulting from collaborative science and multi-disciplinary approaches have the potential to address stakeholders' needs, while taking account of local resources, data availability, and societal and environmental settings.

Like other Arctic settlements, Ilulissat, West Greenland, experiences many construction challenges and infrastructure stability issues, notably due to the presence of ice-rich and saline permafrost. For this reason, the area was chosen to develop and implement a community-scale risk assessment framework. Based on the methodology deployed in the Canadian Arctic (Allard et al., 2012) and supplemented by permafrost modelling, the core of the approach consists in characterizing surficial geology, topography, and ground ice distribution from field measurements and remote-sensing products.

Here we present preliminary results from a multi-disciplinary study combining INSAR (interferometric synthetic aperture radar) measurements, field data, and local knowledge. Processing Sentinel 1 images covering thawing seasons from 2015 to 2019, we derived average seasonal deformation and long-term permafrost degradation rate maps at the community scale. Results were validated by cross-referencing available geotechnical information from borehole networks and maps of existing infrastructure conditions and damages produced in collaboration with stakeholders. Sensitive high-risk permafrost areas, affected by amplified ground movements and/or long-term subsidence, could be identified. Easily accessible interactive web maps and stories were finally developed for outreach purposes and with the aim to support urban development, help prioritizing maintenance operations, and raise awareness regarding local permafrost conditions.

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Using Geo-Data to Adapt to a Changing Arctic

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Rapid environmental changes present challenges for infrastructure, land management, and natural resource development in the Arctic. Geo-data is critical to understanding, predicting, and addressing the impacts of anthropogenic and climate-driven changes on these assets. This presentation will address current Geo-data needs in the Arctic and present methodologies for collecting this information. Improvements in Geo-data accuracy and increased autonomy will be discussed in a context of three challenges common to the Arctic and cold regions: 1) coastal hazards, 2) geologic hazards related to permafrost degradation, and 3) data sharing and management across disciplines and sectors. This presentation will benefit Geo-data users and anyone with the responsibility of making infrastructure, land, and resource planning and managing decisions.

Geomorphological Mapping in Permafrost Terrain to Inform the Routing and Planning of the Kivalliq Hydro-Fibre Link, Manitoba to Nunavut, Canada

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The proposed 1,200-km-long corridor for the Kivalliq Hydro-Fibre Link (KHFL), between Gillam, Manitoba, and Baker Lake, Nunavut, extends from sporadic discontinuous to continuous permafrost, traverses the forest-tundra transition, and crosses diverse Quaternary deposits commonly within the marine limit. The aerial cables for the KHFL are proposed to be suspended from towers founded on piles every 300 to 500 m. Initial conceptual routing of the KHFL was based on regional land use planning and previous studies of a proposed all-season road. A systematic and phased approach for establishing a preferred alignment for the KHFL, from a terrain and permafrost perspective, was initiated through a collaboration between geomorphologists and permafrost scientists.

A 1,200-m-wide corridor within which terrain conditions appear most favorable for the KHFL was delineated following review of regional surficial geology mapping, models of potential ground ice distribution, and scarce geotechnical data for previous infrastructure projects (e.g., PolarGas pipeline proposed in the 1970s, Gillam to Churchill hydro line energized in 1987). Geomorphological mapping has focused on identification of frost-susceptible soils and indicators of ground ice, based on field reconnaissance and interpretation of stereo imagery. More detailed mapping will be completed within a narrowed corridor based on recent LiDAR/imagery and geophysical surveys and shallow permafrost drilling.

Preliminary mapping indicates strong associations between surficial geology and ground ice. Gravelly beach ridges and till veneers exhibit few surface indicators of ground ice. Small thermokarst depressions commonly punctuate thicker till units. Wave action during marine regression modified till surfaces, with at least local effects on permafrost possible. Large ice-wedge polygons typify sandy beaches and eskers. Numerous thermokarst ponds have recently formed and coalesced in fine-grained glaciolacustrine and marine deposits. Transmission towers will optimally take advantage of localized beach deposits and wave-washed tills, where bedrock and well-drained materials are unavailable along the finalized alignment.

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Mesoscopic-Model Simulation of Freeze and Thaw with Groundwater Flow for Terrain Change in Permafrost Regions

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Recently, in permafrost regions, it has become known that terrain change including consecutive subsidence may be caused by abnormally high air temperature or wildfire. Such a phenomenon affects the safety, stability, and reliability of existing infrastructures. This study aims to simulate terrain change in permafrost regions due to environmental disturbance such as abnormally high air temperature or wildfire with a numerical analysis originally developed by the authors. Based on the simulation, the authors attempt to explain the phenomenon and to propose countermeasures for mitigation and prevention of terrain change.

This quasi 3-dimensional simulation combines a vertical heat transfer model of soil column for freeze and thaw analysis of permafrost with a 2-dimensional finite difference model for groundwater flow which covers several hundred square kilometers of the region as a mesoscopic model. By introducing environmental conditions such as air temperature and precipitation, it becomes possible to follow the freeze and thaw process in the region with groundwater flow, and to evaluate the surface subsidence and frost heave. Then the effects of abnormally high air temperature or wildfire on the terrain change can be evaluated.

The authors conducted simulations to assess the effect of wildfire in Siberia on the terrain change. By comparing the simulation results with the evaluation by InSAR, the authors verified the validity of the simulation. For example, the consecutive subsidence calculated by the simulation shows a good coincidence with the monitoring results by InSAR. The simulation results imply that the frost heave in winter and the subsidence in summer are seriously affected by the groundwater flow based on the characteristics of terrain as well as the insulation effects near the surface. Those findings are helpful to predict the upcoming terrain change due to abnormally high air temperature or wildfire, and to maintain healthy infrastructures in permafrost regions.

Permafrost Monitoring Network in the Northern Da and Xiao Xing'anling Mountains, Northeast China

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In addition to the latitudinal zonation, the development and distribution of permafrost in the northern Da and Xiao Xing'anling Mountains, Northeast China, are affected by many local factors. The Xing'an permafrost is sensitive to climate change and surface disturbances, but there were only short-term observations and a paucity of ground temperature data. Hence, since 2009, an observational network has been gradually established at multi-locations in the northern Da and Xiao Xing'anling Mountains, Northeast China, including at least 43 ground temperature boreholes, 2 automatic meteorological stations (sets), 2 snow pillows (2 sets), and 10 sets of observation systems for ground temperatures and soil moisture content of the active layer. Some data have been obtained on the thermal regimes of active layer and permafrost (most to a depth of 20 m, one to 50 m, and two to 80 m). According to data of the last ten years (2009-2020), mean annual ground temperatures (MAGT) at 20 m in depth ranges from -2.83°C (Nanwenghe) to

-0.50 °C (Genhe), and the depth of the permafrost table varies from 0.8 m (Nanwenghe) to 9.0 m (Hola Basin). The Da Xing'anling Mountains have been experiencing significant climate warming in the past 60 years, and the changing trends of hydrothermal dynamics of nearsurface permafrost and active layer in Xing'an permafrost regions vary greatly over time and space. Moreover, the MAGT in some regions of the ecosystem-protected Xing'an permafrost showed a cooling trend. This has demonstrated very complicated hydrothermal mechanisms of permafrost dynamics and history in Northeast China. These results can provide important information for regional development and engineering design and permafrost maintenance in Northeast China.

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Permafrost Warming in the Swiss Alps: Current State and Long-Term Trends

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The Swiss Permafrost Monitoring Network PERMOS documents the state and changes of permafrost in the Swiss Alps since the year 2000. Over the past two decades, its observation strategy was repeatedly evaluated and adapted based on evolving scientific methods and findings. Today the monitoring strategy focuses on three observation elements: (1) ground temperatures near the surface and at depth, (2) changes in ground ice content, and (3) permafrost creep velocities. These three elements complement each other to capture not only the various effects of changing climate on permafrost conditions, but also the specific responses of different topo-climatic and (sub-)surface settings. Results obtained during the warmest two decades ever measured in Switzerland show a consistent picture for all observation elements: permafrost is warming, containing less ice but more water, and is creeping faster. Ground temperatures show a clear warming trend near the surface and at larger depth throughout the entire Swiss Alps, especially between 2009 and 2016. The most pronounced warming trends are measured at cold permafrost sites like the rock glacier Murtèl, where an increase of +0.5°C has been observed at 20 m depth over the past 30 years, and +1°C increase at 10 m depth over the same period. In ice-bearing permafrost close to 0°C, temperature changes are minimal due to the latent heat effects. The latter, however, result in significant changes in electrical resistivity such as at Schilthorn, where repeated ERT measurements show an overall decreasing trend of resistivity since 1999, pointing to a substantial decrease in ice-water ratio in the subsurface, which cannot be captured by temperature measurements. Significantly, increasing creep rates of alpine rock glaciers further corroborate the warming trend, since the creep rates were shown to follow an exponential relationship with ground temperatures. In this contribution, we present the current state and long-term changes of permafrost in the Swiss Alps. More specifically, we quantify and analyze the observed warming rates and resistivity decrease using 20-year time series of continuous monitoring in mountain permafrost collected in the framework of the PERMOS network.

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A Thermokarst Monitoring Network for Alaska

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Once permafrost starts to thaw, all components of the affected ecosystems change, and there are strong positive and negative feedbacks that control how degradation progresses. Thermokarst features occur across a wide range of terrain and ground-ice conditions, develop into a wide range of sizes (m2 to km2), and have numerous degradation and stabilization stages that can span a wide range of ages. Grappling with this heterogeneity of terrain, dynamism, size, and ages requires a multi-component and multi-scale approach. Accordingly, we have been developing a monitoring network for Alaska that integrates regional, landscape and local scale monitoring strategies. For regional assessment of the nature, extent, and trends of thermokarst features, we are using two approaches. First, we acquired high-resolution stereo airphotos at 10-km spacing along longitudinal transects across Alaska in 2006 and determined the absence or presence of thermokarst and its type in the center of each of the 655 airphotos. Determinations at the systematically distributed points were done through photointerpretation of vegetation, geomorphology, topography, and pattern recognition based on experience gained from field surveys. This network is intended to be updated every ~10 yrs with high-resolution satellite imagery but without georectification. Second, we established 50 random remote sensing monitoring grids (2 x 2 km, with 100 points at 200 m spacing) across northern and central Alaska to quantify historical rates of change back to the 1940s using the same photo-interpretation technique as previously described. These repeat monitoring grids use a time-series of georectified imagery to track changes at 5000 points to provide more robust analyses of state transitions. For landscape-level monitoring of change, we established 33 study areas widely distributed across Alaska with active thermokarst where we have been mapping thermokarst features within 2–5 km2 areas at 1:2,000 scale using airphotos and satellite imagery from ~1950, ~1980, and ~2010 to document intermediate-term changes. For local-scale monitoring and evaluation of thermokarst processes, a comprehensive set of ecological components has been sampled along 200–300 m transects at the 27 study areas, representing different landscapes, including topography (surveying, ground-based LiDAR, airborne LiDAR, or photogrammetry), hydrology and snow (water-table surveys, water-level recorders, time-lapse photography), soils and ground ice (coring and sampling for ground-ice and soil organic carbon content), paleoecology (peat and stratigraphic interpretation, radiocarbon dating), thaw depths and permafrost table (probing and geophysical surveys), soil and water thermal regimes (dataloggers), and vegetation (occular estimates or point sampling by species). At the most intensive study areas, sampling for the entire suite of components has been stratified into 4–6 degradation/stabilization stages with each stage replicated at three plots. These monitoring transects initially were established on state and federal lands as part of NSF-funded studies of permafrost degradation, with the first study areas established in 1994. We have been partnering with agency personnel to continue long-term monitoring at the study areas. The field surveys and remote sensing are designed to be repeated every 5 and 10 years, respectively.

Global Long-Term Active Layer Thickness Trends

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Active layer thickness (ALT) is defined by the World Meterological Organization's Climate Observing System (GCOS) as an "essential climate variable" for the characterization of cold region processes with impacts for the global climate system. Within the GCOS Global Terrestrial Network for Permafrost (GTNP) is the Circumpolar Active Layer Monitoring (CALM) program. The CALM program constitutes 293 currently registered monitoring sites distributed throughout permafrost regions in the Arctic, midlatitude alpine regions (265 sites total in the CALM-North network), and Antarctic (28 sites in the CALMSouth network). Established in the early 1990s, the publicly available CALM database (https://www2.gwu.edu/~calm/) offers long-term, standardized ALT records from a variety of regionally representative periglacial landscapes. A synthesis of regional trends from around the globe will be presented and discussed in this presentation. This analysis is based only on sites that have reported data within the last four years and with a minimum decade of continuous records. Around the globe ALT is generally thickening, but at variable rates and statistical significance. The most drastic increasing trends, in excess of 10 cm per year, are observed at sites on bedrock in the European Alps. The majority of sites on unconsolidated sediments in the Arctic exhibited trends ranging from 0.2 from the Alaskan North Slope to 3.5 cm per year from the Russian European North and Northwest Siberia. Minor to statistically insignificant trends were observed in the Antarctic. Pervasive increasing trends in ALT have profound implications for natural and anthropogenic processes necessitating the continuation and expansion of monitoring for this essential climate variable.

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Developing a Regional Permafrost Monitoring System in Yamalo-Nenets Autonomous Okrug, Russia

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The Yamalo-Nenets autonomous district with its developed energy sector lies on the southern limit of permafrost. According to recent assessments made independently by researchers from Finland, the USA, and Russia, the zone with continuous permafrost will move 300-500 km northward by 2050, leaving mass destruction. In order to develop a timely adaptation plan, the district administration initiated a series of actions aimed at collecting knowledge on the current state and recent dynamics of permafrost both in natural settings and under infrastructure.

More than 80 boreholes were drilled and equipped with thermistor strings connected to the modern GSM transmitting dataloggers in cold ventilated cellars of residential buildings of Salekhard and Novy Urengoy. Features of soils are analyzed in the lab and put into a GIS database so that the bearing capacity of sediments could be estimated for different types of basements. A unique early-warning system based on bearing capacity modeling is under development. Issues with leaking communications and artificial icing formation encourage us to propose regional construction and exploitation guidelines supplementing the federal standards.

To discover the trends in permafrost dynamics, we derived historical measurements of temperature of permafrost in geological settings common for a town but in nearby undisturbed landscapes. The new temperature boreholes were drilled on the historical sites to get the long-term change in temperature. Permafrost temperature change during up to 50 years became available. In all 13 boreholes, we found a warming tendency. The record high shift was over 4

degrees Celsius from -6.7 degrees C. On the southern limit of permafrost in several locations, the depth of annual amplitudes decreased, with the temperature getting closer to 0 to -0.1 from about -1 to -0.2 degrees C.

Along with doubtless practical application, monitoring permafrost on the southern limit provides an interesting insight on the fundamentals of permafrost degradation processes.

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Permafrost Measurements Best Practice: GCW's Contribution to Standardization of Global Observations

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The Global Cryosphere Watch (GCW), in the context of the framework of the World Meteorological Organization (WMO), published the Measurement of Cryospheric Variables, Volume II of the Guide to Instruments and Methods of Observation in 2018, in which best practice for observations of snow parameters was included. As a follow-up effort, measurement best practices for the other cryosphere components are under development, including permafrost and seasonally frozen ground.

The measurement best practice for permafrost aims to define reference methods for the configuration and ongoing operation of stations for in-situ observations in high mountains and polar regions. It will address gaps in the existing permafrost monitoring systems, define methods for improving traceability and comparability, recommend instrumental characteristics, and provide measurement uncertainty evaluation. A further objective is to support capacity building of countries in terms of developing a permafrost observation network.

A task team within the framework of GCW was established to lead the development and publication of a complete guide to the measurements of permafrost variables. The documents in preparation will be coordinated with the ongoing revision of Products and Requirements of the Global Climate Observing System (GCOS) Permafrost Essential Climate Variable (ECV), including existing variables measured by the GTN-P (Global Terrestrial Network for Permafrost). Further, the needs of developing Essential Arctic Variables (EAV) and Shared Arctic Variables (SAV) identified at the Arctic Observing Summit (AOS) are considered. The work will be based on existing methodologies, promoting and recommending methods to improve data reliability and traceability, also for the implementation of new stations.

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Climate-Related Operational Permafrost Monitoring in Svalbard and Norway

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The web portal for cryospheric information of the Norwegian Meteorological Institute (MET Norway), https://cryo.met.no, provides access to the latest operational data and products and the current state of sea ice, snow, and permafrost in Norway, the Arctic, and the Antarctic. The subjects of this contribution are the operational permafrost monitoring at MET Norway and the new permafrost monitoring products on cryo.met.no. Systematic long-term monitoring of permafrost in Svalbard and Norway essentially began 23 years ago under the European Union-funded Permafrost and Climate in Europe (PACE) project, with the installation of ground temperature measurements in deep boreholes. More than 35 additional instrumented boreholes have been established in Norway and Svalbard since then. In recent years five new permafrost boreholes have been established at remote locations on Svalbard. Here we present methods for visualizing real-time permafrost temperature data from operational monitoring sites in Svalbard and Norway. The latest permafrost temperatures are compared to the climatology generated from the station's data record, providing median, confidence intervals, extremes, and trends. At these locations, there are also operational weather stations with extended measurement programs. The collocated monitoring provides daily updated data to study and monitor the current state, trends, and the effects of, e.g., extreme climate events on permafrost temperatures. The operational monitoring provides information more rapidly than at any time in the past and may contribute to early detection of, e.g., record-high active layer thickness, pronounced permafrost temperature increases, and early-warning systems for natural hazards associated with permafrost warming and degradation. Currently, data and metadata are reported to the international Global Terrestrial Network for Permafrost manually. Work is in progress to develop operational permafrost data services through the WMO Global Telecommunication System to support, e.g., the WMO Global Cryosphere Watch datastream.

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Standardized Monitoring of Permafrost Thaw: A User-Friendly, Multi-Parameter Protocol

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There is an urgent need for data collection to better understand permafrost thaw and its interaction with vegetation, hydrology, soil, and snow. Greater spatial coverage and improved coordination and consistency of measurements are particularly needed. To enable this, the Permafrost Thaw Action Group of T-MOSAiC has developed a data collection protocol and a user-friendly app (myThaw) aimed at non-experts to facilitate collection and synthesis of data from across the Arctic.

Recognizing the fundamental role of interactions between the different components of the permafrost system, we addressed the need to measure the interconnected parameters of snow, vegetation, hydrology, and permafrost in a single protocol so that measurements will be co-located in space and time, allowing relationships between variables to be disentangled. In particular, the protocol locates all measurements on 10-30m transects that are revisited throughout the year. The measured variables include snow depth, vegetation height, soil texture and type, water level, and permafrost thaw depth.

This protocol uses simple measurements so more difficult-to-measure parameters are not collected, but the lack of specialist equipment and skills should enable a much greater participation in data collection and thus an improved coverage of the permafrost region, which is a central goal of this action group.

Along with the protocol and the myThaw app, we present here the first results from the data collection, which has been live now for several months, and details of how to get involved.

Performance of Bridges in Cold Regions with Sliding Seismic Isolation Bearings*

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Effects of extreme temperature on highway bridges in cold regions seismically isolated with sliding type bearings is investigated. The critical factor in consideration is the change in the performance of isolation bearings with significant variation in temperature between seasons. The sliding bearing behavior is characterized by the friction coefficient of the sliding surfaces. The friction coefficient during a seismic motion varies with the sliding velocity and temperature at the sliding surface. Tests associated with past applications have indicated a marked increase in the value of friction coefficient resulting in higher stiffness of bearings at very cold temperatures. The effects of change in bearing stiffness on seismic performance of the bridge in general and the substructure in particular are demonstrated here. This study aims to capture the change in bearing response and subsequently the overall structural response considering a temperature variation between -400C and +400C. Response parameters considered for this study are the base shear in the piers, the acceleration of the bridge deck, maximum and residual displacement of the isolation bearings, as well as the energy dissipation capacity. It is observed that the higher bearing stiffness at extreme cold temperature leads to additional forces on the substructure, which reduces the margin of safety and hence should be considered carefully in design.

***For full text, see *Permafrost 2021: Merging Permafrost Science and Cold Regions Engineering*, American Society of Civil Engineers. https://ascelibrary.org/doi/epdf/10.1061/9780784483589**

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Developing Pavement Performance Prediction Models Using Rutting Criteria for a Cold Region Environment*

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Maintenance and rehabilitation of roadway pavements in Alaska's southcentral and south coast regions are triggered by rutting based on the FHWA threshold of 0.5 in. (12.7 mm) used by the Alaska Department of Transportation and Public Facilities (DOT&PF). This leads to short pavement life due to a relatively high rut rate caused by studded tire use during winter. Research into the overall rut in these regions shows insignificant rutting from truck traffic. Average pavement resurfacing life in these regions, when considering the effects of rutting, is seven to nine years for freeways and higher for other road classes. This represents about half of the expected design life for principal arterials. Establishing a prediction model that considers the overall rutting will allow agencies to incorporate these models in their Pavement Management System (PMS). Using rutting and age as the dependent and independent variables, respectively, two models were developed, one for interstate pavements and another for other principal arterial pavements.

***For full text, see *Permafrost 2021: Merging Permafrost Science and Cold Regions Engineering*, American Society of Civil Engineers. https://ascelibrary.org/doi/epdf/10.1061/9780784483589**

Modelling Consequences of Permafrost Degradation for Arctic Infrastructure: A Case Study of the Dalton Highway

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The fate of infrastructure in the Arctic and in high-altitude regions is heavily dependent on the stability of the frozen ground it is built on. Climate change and consequent degradation of permafrost will negatively affect various infrastructure types and can cause ultimate failure. Comprehensive pan-Arctic assessments are urgently needed to better quantify environmental, economic, and societal risks and to help adaptation planning. The use of physical models can be a powerful tool for risk evaluation, but modelling challenges remain with respect to resolving construction details at infrastructure scales together with decadal-scale climate change impacts. Here we used the dynamic permafrost land-surface model CryoGrid3 (including a soil subsidence module) to capture both the effects from the interaction of small-scale infrastructure with permafrost and large-scale climate change effects evolving in the 21st century under an extensive climate warming scenario. We discuss how infrastructure can affect ground temperatures and how climate change increases the risk of future infrastructure failure. As an exemplary case of permafrost-affected infrastructure failure, we modelled a gravel road on continuous permafrost at Prudhoe Bay, Alaska. We investigate the timing of infrastructure failure from soil subsidence in dependence of assumed embankment thickness and depth of excess ice in the ground.

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Numerical Modeling of a New Covered Arch Bridge and Its Future Impact on the Surrounding Ground Thermal Regime in Continuous Permafrost

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The Gunghi Creek site, located at 131.2 kilometers at the north end of Inuvik-Tuktoyaktuk Highway (ITH) in the Northwest Territories, Canada, recently had corrugated steel pipe (CSP) culvert replaced by concrete arch bridge with adfreeze piles. There are anticipated challenges with the ground thermal regime that could be affected by the structure, the creek, and future climate change. In this study, detailed 1D and 2D thermal analyses were conducted to simulate the thermal regime prior to and after construction of the arch bridge. The numerical modeling simulations (using Temp/W from GeoStudio) were initially calibrated and developed with historical air temperatures, input values from the literature, and site-specific data from earlier geotechnical investigation. Future climate projection models were used to obtain projected ground temperatures under a number of variations, including the cross-section, creek depth, and climate projections. The results showed that when all thermosyphons are operating as intended, the subsurface temperatures around the piles increase at an average rate of 0.03 °C/year, thus ensuring that the arch bridge will remain fully serviceable for its intended design life. In contrast, when no thermosyphons are functioning, the subsurface temperatures surrounding the thermosyphons increase at a rate of 0.12 °C/year for 4 decades, before gradually slowing due to latent heat. The results of this study highlight the critical importance the thermosyphons will have on the stability and resilience of this foundation design and the importance in ensuring its long-term functionality.

Permafrost Degradation Effects on Seismic Response of Bridge Pile Foundations Along the Qinghai-Tibet Railway*

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With climate warming, widespread permafrost degradation has been found worldwide in recent years. For permafrost regions located in earthquake belts (e.g., the Qinghai-Tibet Plateau permafrost region in China), the effect of permafrost degradation on seismic performance of the bridge pile foundation is worthy of research. In this study, a pile-soil interaction model considering thermalmechanical effect is presented and applied to a case study of bridge pile foundations along the QinghaiTibet Railway. Seismic responses of bridge pile foundations are analyzed with consideration of permafrost degradation. Numerical results show that permafrost degradation can influence the lateral displacement, shear force, and bending moment of bridge pile foundations under seismic actions. The freeze-thaw state of the active layer should be considered when analyzing the effects of permafrost degradation on seismic responses of bridge piles. It can be found that the seismic security of a bridge pier with a pile foundation in permafrost regions should be given more attention under cold conditions (frozen active layer) than under warm conditions (thawed active layer). The seismic security of existing bridge pile foundations along the Qinghai-Tibet Railway is evaluated. It is recommended that the seismic design of bridges with pile foundations in permafrost regions should consider the thermalmechanical effect of pile-soil system and the effects of permafrost degradation.

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Simulating the Thermal Regime of Railway Embankment Structure on The Tibetan Plateau Under Climate Change

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The Qinghai-Tibet Railway (QTR), located in the largest high-altitude permafrost area, is a vital infrastructure linking the west region of China and the Tibetan Plateau (TP). With global warming and its amplifying effect in the TP, the permafrost on the TP has been significantly degraded, manifested by thermokarst subsidence, the decrease of permafrost thickness, and the increase of active layer depth, causing irreversible damage to the infrastructure above it (if built on ice-rich ground). For better understanding and assessing the stability of the QTR in the future, there is a need for physically based model analyses of the thermal regime of the railway embankment and for the evaluation of the risk of railway failure under future climate change scenarios.

In this study, we used a laterally coupled version of the one-dimensional CryoGrid3 land surface model, which adopted a tiling approach to represent different units of the embankment, to simulate the thermal regimes of railway subgrade under present and future conditions and to provide the threshold of subgrade stability under the projected scenarios. Our model results reveal a satisfactory performance with respect to the comparison between measured and modeled thermal regimes. Under the present climate conditions, the crushed-rock embankment structure provides good protection for QTR operations, as our results show less heat penetration into the ground under the railway units as compared to the natural tundra. The thawing depths under the sunny slopes are the largest and reach almost the embankment base under the present climate. This means thaw settlement damage is expected to first occur at the sunny slope with warming air temperature. Furthermore, our results suggest that railway failure depends on the magnitude of warming air temperature. Under conditions typical for our investigated case site at Beiluhe, our simulations suggest that the railway might maintain safe operation until the end of the century under the RCP2.6 scenario. In contrast, inevitably settlement of the subgrade will occur under the strong future warming (RCP8.5) and the permafrost under it will permanently disappear. We hope this paper can mark a step forward in studying the stability of infrastructure located in permafrost areas, especially infrastructure located in the TP.

Quantification of Rut Detection and Height Mapping in Winter Terrains for Off-Road Mobilit*

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Off-road autonomous vehicle navigation in winter environments requires reliable identification and quantification of potential obstacles, such as deep vehicle rutting or buried objects. The advent of consumer-grade LiDAR and Unmanned Aerial System (UAS) based photogrammetry present new avenues for the implementation of change detection algorithms for the purpose of obstacle identification. Few studies have provided a quantifiable statistical method for determining the input parameters of these change detection algorithms based upon user-defined confidence metrics. Previous detection methods also fail to derive the degree of assurance associated with the identification of a perceived obstacle. Here we present an automated method for identification of snow-covered obstacles and vehicle ruts within LiDAR-derived digital elevation models based upon false-alarm probabilities. Probability of detection and accurate height maps are generated for objects by the algorithm to demonstrate the reliability of this method to assist with obstacle avoidance in snowy off-road conditions. The algorithm described here is a reliable and fast method for the identification and measurement of snow-covered obstacles. While this study is concerned with snow-covered terrain, the methods described here may be leveraged to monitor deformation features as a result of vehicle traffic across a variety of terrain types.

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Monitoring Ground Temperatures on Portage Sites Along the Tibbitt-Contwoyto Winter Road to Assess Road Resiliency

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Andrew Troup *Graduate Student*

The Tibbitt to Contwoyto winter road (TCWR) provides critical ground transportation from Yellowknife to several mines in the Northwest Territories. The 400+ kilometer road is predominantly an ice road over water bodies with approximately sixty kilometers of the road on land portages, which consist of snowpack and ice with various subgrades. The TCWR road is typically open for only eight weeks a year thereby the resilience of the road during that operational window is critical. In this study, the performance of varying depths of subgrade at several locations along the winter road were evaluated using numerical modelling techniques to examine their influence on the thermal regime and resulting road resilience. Ground temperatures were measured at three portage locations for the duration of the 2020 winter road season. Preliminary results from the thermistor strings at three portage locations were used to calibrate the numerical models. These thermistor strings had 15 thermistor beads each and were installed in the road to a maximum depth of 1.8 meters. A sensitivity study was used to evaluate subgrade thickness, ice thickness, susceptibility to solar load and slope face direction on the resulting thermal profile. This study found that the south facing slopes and areas with extended exposure to sunlight along the road are the most at risk to thermal vulnerability, almost irrespective of the thickness of subgrade material. For locations with no significant slope, this study found that there were diminishing returns on the thermal performance of the portage when the gravel thickness was increased beyond 0.2 meters. Overall, the results of this study can be used to better manage the construction and maintenance of the portage site, prioritizing the high-risk locations for additional subgrade material and thicker ice cover to maintain roadway integrity.

Recent Experiences with Existing Passively Cooled At-Grade Foundations

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Austen Whitney *Arctic Foundations, Inc.*

Passively cooled at-grade foundations on permafrost rely on cold winter air to remove heat to maintain permafrost and structural stability. As the climate warms in northern latitudes, this natural heat sink is reduced, thus reducing the heat removal capacity of passive systems and jeopardizing the stability of the structures being protected. Three at-grade water treatment plant structures originally constructed between 1995 and 1999 in western Alaska at Eek, Quinhagak, and Nunam Iqua using thermosyphons for subgrade cooling are currently being modified or in the queue to be modified to increase their useful life. Modifications are due to the rapid climatic warming that has occurred and is predicted to continue. At all three sites, the structures are constructed on gravel fills over permafrost soils and use passive thermosyphons to maintain permafrost beneath the insulation within the fill material. The original thermosyphon systems have operated at full efficiency over the existing life of the structures without any deficiencies. Warming from the areas outside of the fills has caused deterioration of the perimeter of the gravel pads and has impacted the stability of the structures. To maintain structural stability, each of the insulated gravel pads is being expanded in areal extent, and additional cooling is being added on the perimeter of the foundations to compensate for the encroaching warming. Additionally, the capacities of the existing thermosyphon systems are being increased, and even converted to hybrid so that they may be actively cooled to maintain structural stability into the future. These three retrofits are but a few that will likely be required in the future to maintain service from similar facilities founded at-grade on passively refrigerated gravel pads as the climate warms.

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Prediction of Climate Change Impact on a Highway in Warm Permafrost*

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A warming climate and its effects on warm permafrost have become increasingly significant, causing persistent problems to the transportation infrastructure, such as roads, airports, and pipelines and threatening their safe operation. Such problems are particularly severe in areas where ice-rich and thaw-unstable permafrost exist extensively. This paper presents the preliminary results of a case study of the Bethel Airport, located in deep warm permafrost in western Alaska. It assesses the climate change influence on the thermal state of warm permafrost and its potential impact on airport runways and roads. It first analyzes the characteristics of the two-meter above-ground temperature predictions for Bethel, Alaska, from 31 models in the Coupled Model Intercomparison Project Phase 5 (CMIP5) for the next century. The air freezing and thawing indices are evaluated from the climate modeling results and compared with historical data. Then a thermal model of an ice-rich site is used to assess the ground temperature variation and permafrost degradation during the next century. Subsequently, the thaw settlement due to thaw and consolidation of the permafrost is predicted, and its potential impact on the built transportation infrastructure is discussed.

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Nondestructive Evaluation of a New Concrete Bridge Deck Subject to Excessive Rainfall during Construction: Implications for Durability in a Cold Region*

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Nondestructive evaluation (NDE) techniques were applied to investigate the effects of excessive rainfall during construction of a new concrete bridge deck in northern Utah. Because excess water can reduce the strength and/or durability of the concrete, testing was necessary to determine whether the portion of the deck affected by rainfall would be expected to still provide satisfactory performance. Given that chloride-induced corrosion of the top mat of reinforcing steel is the leading cause of deck damage in northern Utah as a result of routine deicing salt applications during winter maintenance, evaluating the ability of water and chloride ions to penetrate the concrete and quantifying the overall protection of the reinforcing steel were important objectives. Because the deck was new, the owner specifically requested consideration of NDE techniques that would minimize damage to the deck during the testing process. To that end, resistivity and vertical electrical impedance (VEI) were measured at ten test locations within each of three deck sections (A, B, and C) defined by the contractor based on their exposure to rainfall. To account for potential interactions, concrete cover depth, deck surface temperature, and Schmidt rebound number were also measured at each of the same test locations. Statistical analyses were performed to investigate differences among the three sections. Every significant difference involved section C, which had received the greatest rainfall. Section C had the highest average cover depth, the lowest deck surface temperature, and the lowest average Schmidt rebound number. Although the lowest average resistivity measurement also occurred in section C, the comparatively small differences between section C and either section A or B were not statistically significant. The lowest average VEI value occurred in section A, but the comparatively small differences between section A and either section B or C were also not statistically significant. Although variations in deck temperature and/or cover depth can potentially affect resistivity and VEI, explicitly accounting for differences in these properties among the sections did not change the outcome of the analyses.

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Drivers of Permafrost Degradation Along the Inuvik to Tuktoyaktuk Highway

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Infrastructure construction on permafrost is challenging. Northern regions are undergoing a faster and more intense global warming than the rest of the world, inducing thawing of the permafrost at a global scale. In addition, linear infrastructures such as gravel highways built on embankments to protect the underlying permafrost, favor snow accumulation and produce dust, which can enhance permafrost degradation. The objective of this study was to use satellite (Landsat) and repeat airborne laser scanner observations to explore the physical parameters that drive permafrost degradation in the regions adjacent to the Inuvik to Tuktoyaktuk Highway (ITH) in Northwest Territories, Canada. To test if snow accumulates next to the road, we used digital elevation models produced from airborne laser scanner data collected on one snow-free day in August 2018 and one as the landscape was snow covered in April 2019 over a 3-km road segment located close to Trail Valley Creek (TVC). The zone of enhanced snow accumulation was within 47 m of the road, with maximum snow depths of 1.2 m occurring directly next to the road. The area beyond 47 m was undisturbed with average snow depths of 0.4 m. Despite this finding, our analysis of Landsat images using the normalized difference snow index to discriminate between snow-covered and snow-free areas show that the areas next to the road became snow-free earlier in spring than the areas farther away. The road

construction affected the region in close proximity the most, and the impact decreased with distance from the road to about 400 m. Increased snow cover will increase the thermal insulation, produce higher melt water, and likely promote permafrost degradation at present and in the future of the newly constructed highway. Moreover, earlier melting may trigger other ecological feedbacks such as early greening of the tundra on the long term, highlighting the importance for more observations and additional measurements along the highway.

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Spontaneous Corrugation on Snowy and Icy Road Surfaces Produced by Moving Vehicles in Cold Regions

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In cold regions, as is widely observed, corrugation on snowy and icy road surfaces spontaneously emerges due to repeated moving traffic loads. This phenomenon, also known as a “washboard road,” not only diminishes traffic comfort and produces traffic congestion, but also threatens the safety of running vehicles due to the loss of friction between tires and the road surface. The formation of washboard roads in cold regions is a complicated process, which includes climate factors and traffic influences along with repeated phase changes among water, snow, and ice. To disclose the formation of washboard roads, we first proposed the prerequisite conditions (accumulation of snow, suitable air temperature, and a sufficient amount of traffic) for the formation of corrugation on a snowy and icy road in Hokkaido. Accumulated snow and suitable air temperature are climate factors that are out of our control. Therefore, we investigated the role played by moving vehicles during the formation of corrugation. We designed a series of indoor tests and numerical simulations to clarify the formation and dynamic evolution of corrugation on a snowy and icy road. Then the influences of natural frequency and the touching pressures of the moving vehicles on the corrugation were clarified. This new finding can help us to understand how vehicles promote the formation of washboard roads. On the other hand, this finding shows how adjusting traffic factors can avoid the formation of washboard roads for traffic administrative authorities.

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Upper Silvis Lake Spillway and Powerhouse Failure

James Rooney *Retired, R & M Consultants, Inc.*

In the late 1960s a small hydroelectric project was designed by an out-of-state private consulting engineering firm. The project was completed and operating by 1969. During a heavy rainstorm period, the spillway became engaged with first-time heavy runoff and failed because of erosion of underlying unstable material lying below in the spillway channel. Debris from the failure moved downslope and destroyed the below lying powerhouse. The site is located east and south of Ketchikan on George Inlet. Issues involved included limitations in project financial funds and constraints imposed on the project development effort. This paper is an attempt to identify and document some of the project history and subsequent legal ramifications involved. The project was redesigned and put back into operation and continues to function well.

Use of a Portable Friction Tester on Snow and Ice Pavement*

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Sally Shoop *US Army Cold Regions Research and Engineering Laboratory*
Bruce Elder *US Army Cold Regions Research and Engineering Laboratory*

The purpose of this work was to determine the effect of cold temperatures on the operation and accuracy of commercially available pavement friction measuring tools. We evaluated the consistency of test results for each device and identified any trends in the results. Our tests entailed a series of experiments conducted in a controlled environment at the Cold Regions Research and Engineering Laboratory (ERDC-CRREL). Two portable fixed slip continuous measurement devices were evaluated: the Micro GripTester (mGT) from Findlay Irvine and the T2Go from SARSYS-ASFT. In addition, one deceleration spot measurement device was evaluated: the Dynamic Friction Tester (DFT) from Nippo Sangyo. This series of controlled tests determined that the devices could be operated in conditions as cold as -25 °C. However, care must be taken in interpreting the results of tests conducted at cold temperatures. The ambient temperature and the duration of exposure to these conditions will affect the accuracy of testing. Pronounced changes in the T2Go test results occurred after thirty minutes of exposure to -20 °C and below; for the mGT this occurred after one hour of exposure to -25 °C. The DFT was most sensitive to temperature change with significant changes in friction readings after ninety minutes of exposure to 0 °C or any exposure to temperatures below 0 °C. These devices should not be stored in freezing temperatures prior to testing, and temperature and length of exposure should be monitored and recorded during field testing. Based on the cold room testing, we evaluated the Micro GripTester (mGT) during field tests on packed snow and ice surfaces at the Keweenaw Research Center in February 2020. Several of these tests were run side by side with the SAAB Friction tester, which has been used on cold runway surfaces for many years. The testing showed excellent agreement between the SAAB and the mGT and therefore validating the use of the mGT portable friction tester for snow and ice surface testing.

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Processing and Management of Mountain Permafrost Data

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Sound assessments of climate-related permafrost changes require reliable and comparable data measured at representative sites over decades. Careful standardization and maintenance of field installations are crucial to reduce data gaps and subsequent data processing efforts. However, the production of high-quality permafrost time series does not end with the raw data being collected in the field. It crucially includes secure storage, quality control, data cleaning and gap-filling, and, finally, the derivation of secondary products such as aggregations, warming rates, or creep velocities. The 10th GCOS monitoring principle states that data management systems (DMS) that facilitate access, use, and interpretation of data should be included as essential elements of climate monitoring systems. Best practices for post data-acquisition tasks for permafrost data are hardly available. In part, guidelines for meteorological data can be applied for the processing or quality control of permafrost (temperature) data. However, permafrost data have to be treated with different statistical and gap-filling procedures (e.g., due to the time lag and dampening with depth or during phase change). We present the DMS of the Swiss Permafrost Monitoring Network PERMOS, which developed from an inhomogeneous archive of data files to a DMS in which different types of permafrost time series (i.e., temperature and meteorological data, electrical resistivities, survey points) are stored and processed, and which has been continuously adapted and extended to meet the objectives of GCOS (storage, access, traceability related to raw data, processing, quality control and analyses). For each observation element, database structure and processing routines were developed to derive different levels of data and secondary products, as well as metadata on data manipulations and information on sites, methods, or individual surveys.

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Developing an NWT Permafrost Database

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Territorial governments are among the largest generators of permafrost information in Canada, and the capacity and infrastructure to support data stewardship and analysis are critical to applied permafrost projects. Across the Northwest Territories, various groups and agencies collect permafrost data at a significant expense and for a wide range of purposes. However, there is no standard reporting protocol or repository in the NWT for these data. With an increasing interest in understanding permafrost landscape change and designing and maintaining resilient northern infrastructure, we need to improve how the information generated is transferred and mobilized. A need was identified to develop an NWT Permafrost Database to improve the organization and accessibility of the data, contribute positively to project planning and environmental and regulatory monitoring, and create a culture of data sharing. The NWT Permafrost Database includes a legacy of permafrost data collected through partnerships with academic and government institutions, and industry. Through this project, 537 ground temperature datasets and 194 geotechnical projects, which represent more than 4700 boreholes, have been recovered. This is just the tip of the iceberg for what exists in the NWT. A number of these sites are co-managed by academic and federal collaborators. The NTGS recognizes that interoperability between existing and future databases will be critical for the future of Canadian permafrost data management. The development of the NWT Permafrost Database has successfully supported northern governance, scientific leadership and coordination amongst government departments and indigenous organizations. This presentation will highlight the importance of discoverability and accessibility to permafrost data, the value it provides to support infrastructure planning, maintenance, and adaptation, and innovation in permafrost regions where infrastructure is the most vulnerable to the effects of climate change. It is also critical to support R&D projects, assess future trajectories, and in turn to ensure a repository for new data and research results.

International Database of Geoelectrical Surveys on Permafrost: A New IPA Action Group

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Our new IPA action group (2021-2022) has a main objective of bringing together the international community interested in geoelectrical measurements on permafrost and laying the foundations for an operational International Database of Geoelectrical Surveys on Permafrost (IDGSP). We aim to initiate a database for geoelectrical data and develop guidelines for survey repetition and data processing. We promote and support the repetition of existing legacy geoelectrical measurements to yield the resistivity evolution over time and so detect temperature and ground ice/water changes in response to climate changes. Further aims include raising awareness of the value of geophysical data within the permafrost community and coordinating towards their integration into the Global Terrestrial Network for Permafrost (GTN-P).

International monitoring activities within the GTN-P currently include point-scale measurements of permafrost temperature and active layer thickness (Biskaborn et al. 2019). Geophysical, and especially geoelectrical measurements, have been used for permafrost detection and monitoring for more than fifty years, and are comparatively more cost-effective, faster, non-invasive, and spatially more representative than boreholes. Geoelectrical methods are currently used by countless research groups, government agencies, and industries worldwide to investigate permafrost state. Repetition of old measurements happens seldom, even if it would allow to quantify permafrost degradation on a long-term scale. Exchange of data and expertise exists but is limited or usually done bilaterally. Neither complete information about the existence of geophysical surveys on permafrost nor the data itself is available on a global scale. Given the potential gain for identifying permafrost evidence and for characterizing its changes around the world, there is a strong need for coordinated efforts regarding the exchange of data, metadata, guidelines, and expertise. Eventually, this database will enable monitoring and deciphering the effects of climate change on permafrost environments worldwide (Biskaborn et al. 2019. Permafrost is warming at a global scale. Nat Commun 10, 264 (2019). https://doi.org/10.1038/s41467-018-08240-4).

The Distribution of Dwarf Shrubs and Drought-Resistant Plants Varies with Soil Temperature and Position on Periglacial Patterned Ground at the Goat Flat Alpine Tundra, Montana, USA

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The distribution of N-fixing dwarf shrubs, coniferous tree seedlings, and drought-resistant herbaceous plants differed with soil temperature and position on polygonal and striped periglacial patterned ground of the Goat Flat alpine tundra (2837 m; 46° 3' 17" N, 113° 16' 43" W) in the Pintler Mountains of Montana, USA. We determined the relative percent cover (RPC) of vascular plant species along with a suite of their qualitative functional traits on polygons and stripes, gathered thermographic images with a forward-looking infrared (FLIR) camera, and recorded soil temperatures with in-situ HoboOnset sensors, hourly from 2018-21. Polygon centers and brown stripes were discernable by their low vascular plant cover (< 20 %) while polygon edges and green stripes were visible because of their high vascular plant cover (> 70 %). Thermographic images demonstrated significantly higher surface temperatures on polygon centers than edges. Maximum soil temperatures and ranges were significantly higher on the polygon centers and brown stripes than on the edges and green stripes, and temperature curves suggest later lasting snow on the polygon edges, where dwarf shrubs had significantly higher RPCs. The RPC of the dominant evergreen dwarf shrub, Dryas octopetala (Mountain Avens, Rosaceae), was significantly higher on polygon edges and green stripes than on polygon centers and brown stripes. D. octopetala is symbiotic with N-fixing Frankia soil bacteria, so the presence of D. octopetala likely influences nitrogen dynamics of the periglacial patterned ground. Seedlings of coniferous evergreen gymnosperms were found only on polygon edges and green stripes, indicative of tree establishment. The polygon centers had a significantly higher RPC for the xeromorphic trait of crassulacean acid metabolism (CAM), which confers drought resistance. Patterns of species and functional traits are likely influenced by temperature variations on the patterned ground.

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Machine Learning Analyses of Remote Sensing Measurements Establish Strong Relationships Between Vegetation and Snow Depth in The Boreal Forest of Interior Alaska

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Caiyun Zhang *Florida Atlantic University*

In the diverse vegetative cover of the Interior Alaska boreal forest in Interior Alaska, a warming climate has shortened the winter season by five weeks. Since the seasonal snowpack plays a critical role in regulating wintertime soil thermal conditions, there are major ramifications for near-surface permafrost. Snow depth can be markedly different from one season to another, but there are strong relationships between ecotype and snowpack depth. This can be used to identify how present and projected future changes in winter season processes or land cover will affect permafrost. Though vegetation and snow cover can be assessed rapidly over large spatial scales with remote sensing methods, remotely measuring snow depth has proven difficult. As a consequence, vegetation-snow depth relationships provide a means of assessing snowpack characteristics. We combined airborne hyperspectral and LiDAR measurements with machine learning methods to characterize relationships between ecotype and more than 26,000 snow end-of-winter snowpack measurements. We focused from 2014-2019 at three field sites representing common boreal ecoregion land cover types. These winters represent typical mean snowpacks as well as anomalously low (2016) and high (2018) snowpacks. Hyperspectral measurements account for two-thirds or more of the variance in the relationship between ecotype and snow depth. Among three modeling approaches, support vector machine yields the strongest statistical correlations between snowpack depth and ecotype for most winters. The strongest relationships between ecotype and snow depth come from an ensemble analysis of model outputs using

hyperspectral and LiDAR measurements. Methods used in this study can be applied across the boreal biome to model the coupling effects between vegetation and snowpack depth and to develop more robust means of making standoff measurements of snowpack properties.

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Effect of Slope Topography on Ground Temperature, Hydrology, and Soil Formation: A Case Study At The Seward Peninsula

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Slope terraces 50-200 meters in width with the reasers at two meters high is a widespread feature at the Seward Peninsula. These landforms affect the redistribution of snow during winter seasons and thus control soil temperature and moisture regime. Vegetation and the processes of soil development are also affected. We conducted our research at one such terrace at milepost 28 of the Teller road. Studies included soil, vegetation, and snow surveys along the 70-meter-long transect, biomass productivity assessment, decomposition experiments, and continuous measurements of the ground temperature and soil moisture at three points located in the rear, middle, and front parts of the terrace. According to our results, mean annual ground temperature at the depth of 1.2 meters in 2019 gradually decreased from 4.2°C at the rear part to 0.5°C at the terrace's edge. Such a pattern in the ground thermal regime is mostly caused by the difference in winter temperature due to snow redistribution. The soil moisture regime might be identified as Ustic at the rear and middle parts and Udic at the front of the terrace. Across the tread of the terrace, vegetation changes from the grassland in the rear part to ericaceous tundra in the middle and lichen tundra at the front. Aboveground bioproductivity increases from the rear (449.6 g/m2) to the front part (1099.76 g/m2) of the terrace. But it is necessary to notice that 87% of production in the frontal part is represented by lichens. A significant portion (66.8%) of the total biomass of the ericaceous tundra is composed of woody species, so only about one-third (816.6 g/m2) of it can be involved in the process of annual carbon turnover as litter. The rear part is only a section of the terrace where the whole annual harvest of biomass turns into litter. Thus the amount of annual litter biomass decreases from the rear to the frontal part. The highest rate of litter decomposition during the summer season was recorded at the middle section of the terrace and the lowest at the front. Processes of the organic stabilization were the lowest at the rear part of the terrace. A combination of all mentioned factors and processes explains the pattern in soil sequence. The most developed soil profile (Ustic Haplocryols) can be found at the rear part of the terrace replacing the Typic Humicryepts at the middle and Typic Dystrogelepts/Haplogelepts at the front.

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Active Layer Thickness as a Function of Soil Water Content in Alaska and Canada

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Active layer thickness (ALT) is a critical metric for monitoring permafrost. The influence of soil moisture on ALT is subject to two competing hypotheses: (a) increased soil moisture increases the latent heat of fusion for thaw, resulting in shallower active layers, and (b) increased soil moisture increases soil thermal conductivity, resulting in deeper active layers. To investigate the relative influence of each factor on thaw depth, we analyzed thousands of in-situ soil moisture and thaw depth measurements from the Soil Moisture and Active Layer Thickness (SMALT) dataset, collected at hundreds of sites across Alaska and Canada as part of NASA's Arctic Boreal Vulnerability Experiment (ABoVE). As bulk volumetric water content (VWC) integrated over the entire active layer increases, ALT decreases, supporting the latent heat hypothesis. However, as VWC in the top 12 cm of soil increases, ALT increases, supporting the thermal conductivity hypothesis. Regional temperature variations determine the baseline thaw depth while precipitation may influence the sensitivity of ALT to changes in VWC. Soil latent heat dominates over thermal conductivity in determining ALT, and the effect of bulk VWC on ALT appears consistent across sites.

Explicitly Modelling Microtopography in Permafrost Landscapes in The JULES Landsurface Model

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Microtopography can be a key driver of heterogeneity in the ground thermal and hydrological regime of permafrost landscapes. In turn, this heterogeneity can influence plant communities, methane fluxes, and the initiation of abrupt thaw processes. Here we have implemented a two-tile representation of microtopography in JULES (the Joint UK Land Environment Simulator), where tiles are representative of repeating patterns of elevation difference. Tiles are coupled by lateral flows of water, heat, and redistribution of snow. A surface water store is added to represent ponding. Simulations are performed of two Siberian polygon sites, Samoylov and Kytalyk, and two Scandinavian palsa sites, Stordalen and Iškoras. Tiling tends to result in a warmer lower tile and a colder raised tile. When comparing the modelled soil temperatures for July at twenty cm depth with observations, the difference in temperature between tiles is smaller than observed for Palsa sites (3.2 vs 5.5°C), while polygons display small (0.2°C) to zero temperature splitting, in agreement with observations. Consequently, methane fluxes are near identical (+0 to 9%) to those for standard JULES for polygons, though they can be greater than standard JULES for palsa sites (+10 to 49%). The relative importance of model processes in driving soil temperature and moisture heterogeneity and their sensitivity to the introduced parameters are tested. We also identify which parameters result in the greatest uncertainty in modelled temperature. Varying the modelled palsa elevation between 0.5 and 3 m has little effect on modelled soil temperatures, showing that having only two tiles can still be a valid representation of sites with a large variability of palsa elevations. Lateral conductive fluxes, while small, reduce the temperature splitting by ~1°C and correspond to the order of observed lateral degradation rates in peat plateau regions, indicating possible application in an area-based thaw model.

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Extrapolating Snowpack Properties from Small Temperature Sensors in Two Watersheds on the Seward Peninsula, Alaska, USA

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Understanding changes in snow cover distribution in tundra ecosystems is critical to predicting the future of Arctic climates. Snow acts as an insulating layer in permafrost landscapes during the coldest time of the year. Shrub expansion in tundra ecosystems traps snow—leading to deeper snowpack and increased insulation of frozen soils. Small temperature sensors were deployed at two intensively studied watersheds on the Seward Peninsula of Alaska, USA, as part of the Next Generation Ecosystem Experiments (NGEE) Arctic project. Using small temperature sensors to monitor snowpack conditions provides a cost-effective way to measure a larger spatial and temporal extent than can be measured during a traditional snow survey. The snowpack and air temperature measurements from the sensors were used to extrapolate properties such as snow depth and the insulation effect of snow over the 2020 winter. Spatial and statistical analysis showed that ecosystem types with taller, thicker shrubs had deeper snow for longer during the winter.

Cumulative Impacts of Fire and Climate on Permafrost at Local and Regional Scales, Southern Northwest Territories, Canada

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Climate warming and the growing frequency, severity, and extent of fires in the northern hemisphere are altering post-fire permafrost response. This study examined the impacts of fires from the extreme fire year of 2014 and the more historically typical 2015 at 19 sites along a transect (60.9- 63.1° N) within the sporadic and extensive discontinuous permafrost zones in the Northwest Territories, Canada. Annual field measurements from 2015 to 2019 included ground and air temperatures, snow depths, frost table depths, and repeated direct current electrical resistivity tomography (ERT) surveys. Impacts were evaluated by comparing 16 burned sites to three unburned control sites and by intra-site differences at six sites where burned and unburned areas were contiguous. Permafrost changes occurred in the near surface (40 cm) residual soil organic layer, but vulnerable to thaw at sites with thin organic layers and coarse-textured soils. These findings indicate that permafrost can persist after fire in certain settings, even near its southerly margin, under climate warming to date. This demonstrates the importance of considering the full range of environmental conditions when forecasting permafrost responses to climate warming.

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Distributed Temperature Profiling Networks for Quantifying Soil Thermal Regimes and their Controls Across Discontinuous Permafrost Environments

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Insight into subsurface storage and fluxes of water, heat, and nutrients in permafrost environments is essential to understand and predict how Arctic ecosystems will change under warming temperatures. While the characterization and monitoring of snowpack dynamics and soil thermal regimes and properties is critical for improving the predictive understanding of heat and water fluxes across the landscape, conventional measurement approaches do not deliver sufficient spatiotemporal resolution and coverage. Our research focuses on the design, development, deployment, and use of an innovative Distributed Temperature Profiling (DTP) network, leveraging technological advancements in the field of ultra-low power integrated circuits, sensors, and wireless communication systems. The system consists of a large number of wireless and AA-battery-powered temperature probes with each probe synchronously recording the temperature at 15-minute intervals by sensors distributed vertically with 5 or 10 cm spacing along ~1 m depth. The probes have been deployed at about 100 locations to measure the vertically resolved temperature of soil, as well as snow at some locations, across a ~1.5 × 2 km watershed near Nome, Alaska, which is characterized by discontinuous permafrost and high spatial variability of soil thermal and physical properties. Snow thickness, soil freeze/thaw dynamics, thermal parameters, and other metrics were determined from the temperature time-series over more than one year. We found that the variability in the soil freeze-thaw durations and thickness was strongly impacted by the snow cover dynamics and the soil water content, which were both partly associated with topography and vegetation cover. The study highlights the potentials of the DTP system to monitor the thermal dynamics for improving the predictions of soil hydro-biogeochemical dynamics.

Field Validation of Simulated Permafrost Thaw Depth Across the Vegetation Gradient in Alaska From SIBBORK-TTE Modeling Infrastructure

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In the Arctic, the spatial distribution of boreal forest cover and soil profile sequences characterizing the North American Taiga-Tundra Ecological Transition Zone (TTE) are experiencing rapid transformations, namely alarming and extensive shifts in permafrost thaw and distribution, carbon cycle mobilization, and ecosystem function and composition as a consequence of rising air temperatures and climate change. The complexities and feedback drivers associated with these ecosystem response patterns may be examined with the integration of remote sensing, earth system modeling, and field observations in addition to extensive data assimilation and harmonization techniques, machine learning approaches, and artificial intelligence technology. More specifically, the SIBBORK-TTE model provides a unique opportunity to predict the spatiotemporal distribution patterns of vegetation heterogeneity and forest structure variability, Arctic-boreal forest interactions and ecosystem transition zone transiency, and permafrost degradation with high-resolution scaling across broad domains. Within the TTE, evolving climatological and biogeochemical dynamics such as permafrost thaw and soil turnover facilitate distinct moisture signaling and terrestrial nutrient cycle disruption, thereby catalyzing land cover change and ecosystem instability patterns. This study is an overview of scientifically supported verification and validation metrics of permafrost dynamics throughout Alaska, efforts which reveal distinct historical and future implications within the Alaska boreal and tundra domains (i.e., SMALT and CALM sites within the North Slope, Brooks Range, Yukon Delta, Seward Peninsula, and Interior). To quantify these trends in permafrost thaw variability, in-situ ground measurements for active layer depth (ALD) were collected to evaluate and cross-validate below-ground model simulations between 1996-2018. Shifting trends in derived permafrost thaw variability from these modeling results indicate seasonality biases and were compared statistically to the in-situ data collection. Thereafter, the SIBBORK-TTE model was used to project future below-ground conditions utilizing a CMIP6-integrated climate change warming function generated from four CNRM-CERFACS scenarios. Upon visualization and curve-integrated analysis of the simulated freeze-thaw dynamics, the calculated performance metric from derived annual maximum thaw depth and measured active layer depth yielded a mean error of 0.321. With this novel approach, spatiotemporal variability in active layer depth provides an opportunity for tuning model parameterization for increased simulation accuracy, forecasting permafrost distribution and thaw depth variability, and identifying climate and topographic drivers of earth system feedback mechanisms

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Quantifying Permafrost Soil Micro-Structure with Micro X-ray Computed Tomography

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In permafrost systems, soil micro-structure is largely uncharacterized, and it is unclear what structural elements are prevalent, be it pore structure, soil aggregation, or cryostructure and how they affect microbial ecology and ecosystem function. X-ray Computed Tomography (micro-CT scanning) is often associated with the health industry but

has a wide range of environmental applications. Micro-CT scanning is a powerful technique for analyzing soil physical environments, including pore and aggregate structure, which play a role in shaping soil microbial ecology and biogeochemical processes. However, this knowledge is mostly limited to temperate soils. Here we demonstrate a pipeline for acquiring, processing, and analyzing permafrost micro-CT scanning data. We collected four permafrost cores from above the Cold Regions Research and Engineering Lab (CRREL) permafrost Tunnel in Fox, Alaska, and subsampled as triplicate pucks (~1 cm in height and ~2.5 cm in diameter) 5 cm below the active layer. Pucks were scanned at 20 µm resolution using a Bruker Skyscan 1173 micro-CT at CRREL (Hanover, NH). Slices were reconstructed and corrected for hard beaming and ring artifacts in CTAn image processing software. Then, image stacks were imported into Dragonfly image processing software, filtered for speckle noise, and segmented to regions of interests (ROI). Finally, relevant morphological operations were applied to ROIs to eliminate remaining scanning artifacts and account for resolution limitations. We calculated volumetric composition of air, ice, and soil. Additionally, ice and pore structure were quantified by calculating ice-soil interface surface area, ice and pore connectivity, and size distribution. Characterizing patterns in permafrost micro-structure will give insight into how the physical soil environment influences microbial distribution, abundance, and diversity in permafrost soils

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Modelled Soil Temperature Sensitivity to Variable Snow and Vegetation Conditions in Low-Relief Coastal Mountains, Nunatsiavut and NunatuKavut, Labrador*

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Understanding permafrost vulnerability and resilience to climate warming is critical for predicting impacts on northern communities and ecosystems. The thermal characteristics of near-surface permafrost are largely influenced by effects from overlying vegetation and snow cover, both of which are changing in northern environments. Associations between vegetation and snow cover are particularly important in the coastal mountains of Labrador, northeast Canada, because of high annual snowfall totals and greening tundra biomes. Due to a lack of field studies in the region, relatively little is known about contemporary permafrost and the impacts permafrost thaw may have on infrastructure and culturally significant ecosystems. In this study, we present a series of one-dimensional simulations using the Northern Ecosystem Soil Temperature (NEST) model to characterize ground thermal conditions at two field sites (one northern and one southern) in low-relief mountains along the Labrador coast. NEST simulations were run for the period 1979-2018 using climate data derived from ERA5 atmospheric reanalysis. The NEST simulations were prepared for three ecotypes (tundra, shrub, treed) with three different snow accumulation regimes (wind-exposed, flat, topographic hollow) to provide a range of ground thermal conditions at both sites. At the northern field site (near Nain, Nunatsiavut), the perennially frozen ground was present for all ecotypes when simulated with extensive snow drifting but largely absent for all ecotypes with high snow accumulation. At the southern field site (near Pinware, NunatuKavut), near-surface permafrost was largely absent from simulations for all ecotypes. Scenarios with extensive wind drifting away from the site allowed thin perennially frozen bodies (<1m) to persist in tundra and shrub ecotypes in most years and under treed ecotypes in cooler years. These results highlight the importance of spatial and temporal variability in snow cove for stimulating ground thermal regimes in coastal Labrador.

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Comparison of Satellite-Derived Snow Data Benchmarks with Historic Snow Survey Data from the North Slope of Alaska Using ILAMB Software

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Understanding and modeling the permafrost system, hydrologic cycle, energy balance, and biologic systems along the North Slope of Alaska is dependent, in part, on snow depth and snow distribution. Point-source snow measurements provide ground-truthed observations of snow depth and snow density, although these measurements may be limited in spatial and temporal distribution. Satellite-derived remote sensing products provide spatial coverage of snow cover, but the applicability is affected by the balance of resolution, computational speed, and confidence in the remotely sensed data products. The goal of this research is to assess the suitability of specific satellite-derived snow data products for fine scale modeling in the North Slope of Alaska by using International Benchmarking Project (ILAMB) software. ILAMB works to provide software for modelers to compare model results to internationally accepted benchmarks, such as the Clouds and the Earth's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) radiation dataset and Global Fire Emissions Database (EFED4). The benchmark for North America snow water equivalent encouraged for use by ILAMB is the Canadian Sea Ice and Snow Evolution Network (CanSISE) Observation-Based Ensemble of Northern Hemisphere Terrestrial Snow Water Equivalent, Version 2 data product. Historic snow survey data from the North Slope of Alaska dates from 1901 to the present day. This historical snow data, collected by agencies, academia, and industry, was curated to create a digital catalog of over 2000 observed snow data points from locations across the North Slope of Alaska. The curated snow data is being ingested into the ILAMB software for comparison to established benchmarks and to earth system model simulations of snow water equivalent. In this study, we will present the curated snow survey data as well as initial results in the assessment of the CanSISE benchmark in reference to the curated data.

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Boreal Shrub Water Use in Permafrost and Permafrost-Free Systems

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Shrub expansion in boreal forest ecosystems has received less attention compared to Arctic ecosystems, but the consequences may be just as significant. Alder and willow shrubs are expanding their range in the boreal forest, particularly in areas experiencing permafrost thaw. An understudied aspect of shrub expansion is their water use dynamics. Deciduous vegetation has high levels of water use that dries the soil, impacting the conditions that affect permafrost stability. This study quantifies boreal shrub (alder) water use dynamics (stem water content, transpiration, water stress) in a permafrost ecosystem that is thawing and in a permafrost-free ecosystem. The shrubs in both ecosystems take up snowmelt water prior to leaf out to support early season physiological processes but rely on rainfall as the growing season progresses. Shrubs growing in the thawing permafrost system were more water stressed, had lower stem water content, and transpired less water than the shrubs growing in the permafrost-free system. These findings are surprising because soils underlain by permafrost are generally wetter than soils without permafrost, suggesting that water availability should not be a limiting factor for these plants in permafrost soils. However, the moss and organic layers in this ecosystem become dry because water from thawing soils exits this system via lateral subsurface flow (the site is on a hillside). Although this creates stressful conditions for the shrubs, they have continued to thrive and expand into this area. Additionally, the shrubs use significantly more water than the black spruce and contribute to drying the soil. This study demonstrates that alder shrubs can tolerate a range of soil conditions created by permafrost presence and condition. While the stressful conditions in the system with thawing permafrost reduces shrub water use, they still contribute to soil drying and are potentially more tolerant of thawing conditions than black spruce.

Snow and Canopy Interception Influence on Soil Thermal Regimes

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Precipitation plays a crucial role in shaping ecosystem structures and functions. Snow, specifically, has an outsized influence on the Boreal and Arctic ecosystems' hydrological and thermal energy budgets. When present, snow shields the ground from low winter temperatures. Its arrival and departure have dramatic impacts on the surface and subsurface ground energy balance. In spring and summer, snow provides the majority of the growing season's liquid water. Snow is a key atmospheric, cryospheric, hydrologic, and ecological component that has been largely ignored. Subsequent feedback effects from reduced canopy are augmented by wind and snow cover interactions, leading to increased spatial variability in snow distribution and snow thermal properties. To investigate the snow and canopy interactional influence on soil thermal regimes, we set up a monitoring network with soil temperature sensors in Fairbanks, Alaska, at numerous locations with varying vegetation (black spruce, deciduous forest, tussocks) and canopy cover. In 2018, the soil temperatures, at 5cm depth, at our sites varied between a low of -15°C and a high of 0°C at the end of January, and the range in the summer was 22°C (between 5 and 37 °C). At deeper depths (35 cm), the soil temperatures varied between -6 and 0 °C in the winter and 0 and 17 °C in the summer. At a relatively short (10m) transect with varied canopy cover, displayed the greatest variance in surface soil temperatures with wintertime lows between -21 to -6 °C and summertime highs between 18 to 40 °C. We are currently expanding our monitoring network to include snow depths, snow temperature, volumetric water content, meteorological sensors (air temperature, wind, relative humidity, barometric pressure, solar radiation, precipitation) and soil thermal conductivity. Our study has the potential to greatly enhance our understanding of these changing systems and their delicate interdependence.

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Spatial Patterns of Snow Distribution for Improved Earth System Modelling in the Arctic

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The spatial distribution of snow plays a vital role in Arctic climate, hydrology, and ecology due to its fundamental influence on the water balance, thermal regimes, vegetation, and carbon flux. However, for earth system modelling, the spatial distribution of snow is not well understood, and therefore it is not well modeled, which can lead to substantial uncertainties in snow-cover representations. To capture this influence and define key hydro-ecological drivers, we carried out intensive field studies over multiple years for two small (2017-2019, ~2.3 - 2.5 square km) sub-Arctic study sites located on the Seward Peninsula of Alaska. Using an intensive suite of field observations (>22,000 data points), we developed simple models of spatial distribution of snow water equivalent (SWE) using factors such as topographic characteristics, vegetation characteristics based on greenness (normalized different vegetation index, NDVI), and a simple metric for approximating winds. The most successful model was the random forest, which illustrated the complexity and variability of snow characteristics across the sites. Approximately 86% of the SWE distribution could be accounted for, on average, by the random forest model at the study sites. Factors that impacted year-to-year snow distribution included NDVI, elevation, and a metric to represent coarse microto-

pography (topographic position index, or TPI), while slope, wind, and microtopography factors were less important. The models were used to predict SWE for the whole study area. The characterization of the SWE spatial distribution patterns and the statistical relationships developed between SWE and its impacting factors will be used for the improvement of snow distribution modelling in the Department of Energy's earth system model, and to improve understanding of hydrology, topography, and vegetation dynamics in the Arctic and sub-Arctic regions of the globe.

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TTOP Model Sensitivity and Comparison to Random Forest Permafrost Temperature Modelling Across Western Canada

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The temperature at top of permafrost (TTOP) model is widely used determine equilibrium permafrost distribution due its simplicity and transferability to a variety of permafrost environments. Our study evaluates TTOP model sensitivity to changes in parameters in different permafrost environments across a range of scales, and also examines the importance of variables in the model using random forest analysis. The random forest modelled permafrost temperatures are compared to field observations and those predicted through the TTOP model to assess the feasibility of using a random forest approach to permafrost modelling at both national and local scales. The study area encompasses a substantial portion of northwest Canada with sites extending from the Canadian Arctic Archipelago to northern British Columbia including the Mackenzie Valley and the southern Yukon. The environments sampled range from continuous to discontinuous permafrost with vegetation covers from boreal forest to tundra, and in lowlands and mountains. Preliminary results indicate that the TTOP model is most sensitive to changes in the freezing n-factor (nf) across all the environments sampled. The sensitivity of the model to changes in ground thermal conductivity increases as temperatures approach 0°C, with limited response at the High Arctic sites and a stronger impact in the southern study regions. Preliminary random forest analyses also highlight the importance of nf and the nival offset at High Arctic sites.

Thermal Modelling of Post-Fire Permafrost Change Under a Warming Coastal Subarctic Climate, Eastern Canada*

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Forest fires in permafrost areas have lasting thermal impacts on the underlying frozen ground. These impacts are expected to continue to occur as the frequency and intensity of fire disturbance increases with climate change. This study implemented transient one-dimensional thermal modelling using the TEMP/W program to examine changes in the ground thermal regime at two coastal forest fire sites located in the sporadic discontinuous permafrost zone near Nain (56.5°N) in Nunatsiavut, northern Labrador, Canada. To our knowledge, no previous studies of post-fire permafrost response and resilience have been conducted in the region. Simulations were undertaken for unburned forest and adjacent fire-disturbed sites, which were modelled to have permafrost thicknesses of 15.6-17.5 m in 1965. The simulations incorporated projected climate change modelled under Representative Concentration Pathways (RCPs) 4.5 and 8.5, as well as variation in the regeneration of the surface organic mat. In most scenarios, particularly those with post-fire organic mat regeneration, a suprapermafrost talik developed immediately following disturbance, but frozen ground re-aggraded after several decades before subsequently thinning. Results varied from permafrost thinning by 50% but persisting to 2099 at unburned sites under RCP4.5, to thawing entirely by 2060 when subjected to RCP8.5 and a high severity burn with no post-fire organic mat regeneration. Our findings are broadly consistent with those from climatically dissimilar sites in the western North American boreal forest and demonstrate that fire accelerates permafrost thaw due to climate warming. The results also confirm the importance of considering organic material accumulation in long-term modelling of permafrost change.

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Ground Ice on Terrestrial Worlds: The Importance of Laboratory Data

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Since the mid-1960s, thermophysical and molecular diffusion models have been powerful tools for predicting where buried water ice can be found in the inner solar system. These models predicted the wide-spread occurrence of shallow ice on Mars, as well as regional and local variations in burial depth. They predicted the presence of a global shallow ice table on Ceres and other main belt asteroids. They have also been applied to glacial ice in the Antarctic Dry Valleys and to problems in cometary outgassing. Broadly, spacecraft observations have supported the thermophysical modeling approach that has become standard. However, in every location, there are observational details that are difficult to reconcile with existing models and the limited body of empirical constraints on regolith and ice properties. A general theme of these small inconsistencies is that spacecraft have observed somewhat more ice than expected on multiple bodies over the past twenty years, while at the same time, a small set of laboratory studies has indicated that silicate regoliths are less able to protect ice than had been previously assumed. Ground ice is wider spread (Mars, Ceres), shallower (Mars, Ceres, Antarctica), more concentrated (Mars), and older (Antarctica) than models readily predict. The responsible processes are likely unique to each of these planetary environments; however, a lack of key material properties data is a common theme. We will describe specific areas of friction between models and observations on multiple terrestrial bodies. We will then discuss how laboratory investigations targeted to planetary environments and materials can complement future spacecraft investigations and improve our theoretical understanding of the history and accessibility of water ice in the inner solar system.

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A Sublimation-Based Framework for Generating Protrusion of Marker Beds Within the Icy Martian Polar Layered Deposits

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The polar caps of Mars are mostly composed of the Polar Layered Deposits (PLD), kilometers-tall stacks of water ice layers with variable amounts of dust. These layers are exposed at troughs and scarp faces. Dark-toned layers, sandwiched between brighter (and thus presumably icier) layers that are traceable across large portions of the PLD are known as marker beds. At trough and scarp exposures, these marker beds are found to protrude topographically relative to their surrounding layers, and this protrusion is generally considered a proxy for the layers' resistance to erosion (Becerra et al. 2016). Given that the marker beds have a lower albedo, they should absorb more sunlight than surrounding higheralbedo layers. Thus it could be expected that they would undergo more sublimation (i.e., be recessed), which would make their protrusion confounding. We tested the role of differential sublimation of icier vs. dustier layers and developed a framework for generating protrusion of dustier layers in the PLD. Dust content plays an important role in the amount of lag left behind as the layers undergo sublimation during periods of instability. This lag then insulates the ice from temperature perturbations and can prevent further sublimation. We find that the amount of protrusion observed for the marker beds can be explained completely by differential sublimation and the interplay between dust content, lag thicknesses, mechanical erosion of the lag, and the amount of time that the layers experience sublimation. We also find that the amount of protrusion (on the order of meters) can be generated within a few thousand years, or within one obliquity cycle on Mars. This offers an explanation to the morphology of ice layer exposures within Mars' polar ice caps.

Subsurface-Atmosphere Exchange of Water Vapor in Sublimation Environments

Norbert Schorghofer *Planetary Science Institute*

This presentation will provide an overview of the theoretical framework for near-surface ice on Mars that has emerged over the last two decades, and, where possible, it will draw parallels with near-surface ice in the Dry Valleys of Antarctica. On present-day Mars, the annual mean temperature (160-230K) and the frost point temperature (about 200K) are far below the melting point (273K), and ice exists in a sublimation environment. Ice-rich landforms where melting never occurs are rare on Earth but may be present in portions of the Antarctic Dry Valleys. On Mars, the distribution of near-surface ice is governed by vapor exchange with the atmosphere, whereas terrestrial permafrost processes are dominated by melting and the associated energetics, resulting in two substantially different theoretical frameworks. The diffusion of water vapor in soil is a complex physical process, but theory has provided general insights. A subsurface ice table can be in vapor exchange equilibrium with a humid atmosphere, and that equilibrium is characterized by the frost point associated with the long-term mean of the absolute humidity of the atmosphere. Data from the Dry Valleys illustrate how the vapor pressure on an ice-free and snow-free surface can exceed the vapor pressure of buried glacial ice, due to the decay of the seasonal temperature amplitude with depth. A closely related process, absent from the terrestrial permafrost literature, is thermal pumping of vapor into the subsurface, which can result in the sequestration of ice. Laboratory experiments have revealed that vapor-deposited ice grows in intergrain spaces in the shape of tendrils, and this desublimation ice even includes bubbles, despite the absence of the liquid phase.

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Implications for the Distribution of Brain Terrain in Arcadia Planitia, Mars

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Etienne Godin *Université Laval*

Arcadia Planitia is a flat-lying region in the northern hemisphere of Mars, where significant evidence indicates an ice-rich subsurface. Near-surface ice becomes less stable at lower latitudes under present climate conditions. However, Shallow Radar observations indicate that a 10s-of-meters-thick, relatively pure buried ice deposit, interpreted to be an ice sheet, exists across much of Arcadia extending north from ~38°N. Mid-latitude ice distribution and preservation have important implications for both Mars' past climate and in-situ resource utilization for future human exploration. We are using small-scale (i.e., meters) surface morphologies and their relationship to glacial and periglacial Earth analogues as a means of better understanding the stability of mid-latitude ice in Arcadia Planitia. The surface of our study site in Arcadia is characterized by three distinct morphologies, typically found across the mid-latitudes and associated with subsurface ice, including polygonally patterned ground, polygonally patterned ground with pitted troughs, and brain terrain. Brain terrain is proposed to represent a lag deposit formed atop thick glacial ice as a result of ice sublimation. The Canadian High Arctic is used to investigate an analogous brain-like landform to identify surface-subsurface relationships and formation mechanisms. We document a new landform, termed Vermicular Ridge Features (VRFs), that has a circular, sinuous, and anastomosing morphology, with similar morphometrics to brain terrain observed at Arcadia Planitia on Mars. Aerial drone imagery, digital elevation models, grain size analysis, and field observations of VRFs were used to compare morphology, morphometry, environmental conditions, substrate characteristics, and formation mechanisms to other morphologically similar terrestrial periglacial and glacial features. We interpret VRFs to be of paraglacial origin produced from the passive ablation of buried glacial ice remnants. Using VRFs as an analogue for brain terrain on Mars, we support that brain terrain can form largely via disintegration of underlying glacial ice, likely via sublimation. A latitudinally dependent relationship in brain terrain occurrence in Arcadia Planitia suggests a northward regression of ice stability. However, we propose regions that are indicative of less ice degradation in the lower latitudes of Arcadia Planitia based on surface morphology.

Boulder Halo Rock Distributions on Ice-Rich Latitude Dependent Mantle Indicate Large Role for Cold-Permafrost Cryoturbation Processes at Some Sites on Mars

Joseph Levy *Colgate University*

Boulder halos are rings of large (>25 cm) clasts present on the Martian surface at middle and high latitudes that are arranged in diffuse, quasi-circular annuli. The halos are hypothesized to form when meteorite impacts punch through ice-rich surface soil layers, excavating underlying bedrock. These ice-rich surfaces are portions of the latitude dependent mantle (LDM), a young (10s of ka to a few Ma) ice-rich deposit inferred to have been emplaced through either airfall of ice and dust or large scale vapor deposition into regolith. Regional deflation of ice and/or infilling of the crater result in flattening out of the terrain, leaving only a ring of boulders at the surface. However, questions remain as to whether the boulders represent primary impact ejecta, and whether they are in place or have been reworked by cold permafrost processes (e.g., some form of cryoturbation). LDM surfaces are extensively polygonally patterned, but show little evidence for freeze-thaw processes, as wet active layers are not predicted to have been present outside of steeply sloped surfaces over the past 4 Ma. Here we present boulder sizedistribution counts for boulders in halos. We find that the boulder size-frequency power law exponents are inconsistent with fresh impact ejecta from existing lunar and Martian impact craters. While some boulder halos show nearly size-distance and density-distance relationships that suggest little reworking of the boulders by permafrost processes, other halos have nearly flat density-distance and size-distance curves, suggesting considerable movement and reworking of boulder populations by permafrost processes. Several cold-cryoturbation processes are considered to explain this evolution of boulder densities, including tumbling and slumping of boulders into expanded thermal contraction crack polygon troughs and surface creep associated with seasonal dry ice layers at high latitudes.

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A Review of Terrestrial Analogs for Martian Glacial, Periglacial, and Permafrost Studies

Eric Petersen *University of Alaska Fairbanks*

Terrestrial analogs have been instrumental in developing our modern understanding of the Martian cryosphere. Even the knowledge we obtain from applying geophysical techniques and geomorphic analyses is informed directly or indirectly from terrestrial analogs. Often the analogs employed are enigmatic features in their own right, the study of which leads to advances in our understanding of processes on both planets. In this sense, we can conceive the endgame of terrestrial analog studies to be the merging of Earth sciences and planetary sciences along specific disciplines such as the cryosphere. In this presentation, the use of terrestrial analogs in Martian permafrost and periglacial sciences will be reviewed. Investigated features include terrestrial debris-covered glaciers and rock glaciers as stand-ins for Martian viscous flow features, thermal contraction crack polygons on both planets, various landforms indicative of deglaciated landscapes, and terrestrial debris-covered glacial ice cliffs as possible analogs to Martian icy scarps. The strengths and potential pitfalls of analog research will be investigated, as will potential future avenues for research. Among these is a renewed focus on investigating the processes that occur in the murky regime between glacial and permafrost environs—an arena of historical controversy and persisting questions in the terrestrial literature, but one which is seemingly ubiquitous for the formation of landforms on Mars.

Geotechnical Properties of Frozen Ground at McMurdo Station, Antarctica

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McMurdo Station is built on fractured basaltic frozen ground. The recent plans for the station involve major buildings upgrades. Foundation design for the proposed buildings require an understanding of the geotechnical properties. CRREL assisted in this effort by conducting a series of studies with a goal to improve geotechnical information. These included digging soil pits, radar profiles, laboratory tests, and coring data. Radar surveys conducted up to ten m depth identified the active layer, permafrost, excess ice, fill thickness, solid bedrock depth, buried utilities, construction, and waste debris. Visual profiles from the soil pits were quantitatively corroborated with in situ samples for gradation, moisture content and density tests. Ground profiles indicated a very shallow active layer exists at a maximum depth of 30 cm in the undisturbed ground and 60 cm in the anthropogenic fill, with segregation ice at the bottom from seasonal snowmelt. The undisturbed natural deposits are composed of fractured basaltic boulders, rocks, gravelly sand, and ice. The ice-cemented course-grained materials (less than 300 mm in size) of gravelly sands exist due to sedimentation. Ground ice does occur in these irregular interbedded strata with different cryostructure formation to the Arctic terrains. The lack of precipitation and groundwater generally prevent large-scale development of wedge ice. Laboratory tests from the uniaxial compression tests on remolded frozen gravels tested between 4% and 20% ice content resulted in compressive strength from 0.6 to 1.6 MPa at −7°C and from 2.7 to 6 MPa at −20°C. If these strength values meet the requirements, we can reliably expect for the ice-poor to ice-free volcanic rock to be stable specially as temperatures drop. However, snow, ice from meltwater deposit, and possible debris were anthropogenically buried with fill materials for flat areas. Ground ice or any thaw unstable materials must be removed, especially for shallow footers foundation design options.

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Thaw Consolidation Model for Permafrost Based on the Residual Stress

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The concept of the residual stress has been introduced by Morgenstern and Nixon (1971). It has been defined as the effective stress existing in the soil skeleton when a fine-grained soil is thawed under undrained conditions. In practice, this definition has mostly been applied to bulk soil sample which is only theoretically valid for ice-poor soils. The definition of the residual stress can be generalized to include ice-rich soils by specifying that the residual stress is the effective stress within the soil elements upon thawing rather than the effective stress in the bulk soil. This definition is in theoretical agreement with the historical definition of the residual stress, and it allows us to distinguish between the thaw consolidation behavior of excess ice and of the soil skeleton while using a unique void ratio – effective stress relationship. Morgenstern and Nixon suggested that the residual stress could be an intrinsic soil property. The practical implications of the residual can thus be extended to the development of empirical relationships based on the residual stress. Empirical relationships are developed for the compression index of the thawed soil, the residual stress, the hydraulic conductivity change index of the thawed soil, and the initial hydraulic conductivity of the thawed soil. The liquid limit, the clay content, and the median grain size of the fine fraction are used as predictive parameters. The median grain size of the fine fraction offers the greatest precision.

Measurement Techniques for Soil Freezing Characteristic Curves

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Soil freeze/thaw processes play a role in the hydrology, geophysics, ecology, thermodynamics, and soil chemistry of permafrost systems. In these processes, the temperature of the soil is related to the soil ice content through a soil freezing characteristic curve (SFCC). This mathematical construct relates the soil ice content to a specific temperature for a particular soil. SFCCs depend on many factors including soil properties, soil pore water pressure, dissolved salts (hysteresis in) freezing/thawing point depression, and degree of saturation, all of which can be site-specific and time varying. This has led to the development of many diverse SFCCs for applications in different study sites, fields of study, and for differing research purposes. As the climate warms, much of the earth's frozen ground warms and approaches the freezing/thawing temperature where the choice of SFCC becomes more important, especially in modelling studies that predict changes in ground ice content. Many SFCCs are empirically based and rely on collection of freezing and thawing data for the soil in question. Short of this, SFCCs based on theory alone are highly dependent on soil properties. In many watersheds, these detailed data are not available, and yet hydrological and geophysical models are still necessary and depend on soil freeze/thaw processes. To address this, a synthesis of measured SFCC data from literature is organized into an open-source compilation for the available range of studied soils. Data digitized from previous (historic) lab and field measurements is gathered, and data collection methods are compared. The theoretical basis of each measurement technique is described. Uncertainty bounds are estimated for each measurement technique based on the aggregate data. Future work understanding the propagation of this uncertainty in modelling and creating a data processing tool is outlined.

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Fine-Scale Heterogeneity vs. Large-Scale Models: Effects of Soil Heterogeneity on Simulated Physical Properties - Does It Matter?

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Soil texture (i.e., its composition of clay, silt, and sand, as well as organic material) is often very heterogeneous within small distances. State-of-the-art land-surface models usually cannot capture this due to their coarse grid. However, neglecting small-scale soil heterogeneity may strongly affect the estimated exchange of energy, water, and carbon between land and atmosphere.

This discrepancy is especially problematic when modelling permafrost soils, where the heterogeneity-induced mismatch can make the difference between frozen and unfrozen soil, or waterlogged and unsaturated soil, as soil texture determines physical properties such as heat and water-storage capacity. By that, soil heterogeneity affects the buildup of soil ice and resulting frost heave, determines pond locations, and ultimately influences soil genesis (e.g., by inducing cryoturbation). The determination of soil geophysics also propagates into biogeochemical dynamics, affecting the Arctic carbon cycle by providing the environment for either carbon stabilization or degradation.

To assess the effect of soil heterogeneity in detail and quantify the potential mismatch, we develop a two-dimensional geophysical soil model with a spatial resolution of less than ten cm at the region of interest. We apply our model at permafrost sites, because our ultimate aim is to understand cryoturbation as a permafrost-specific soil process and its relevance for the Arctic carbon cycle, which will finally allow us to improve predictions of the Arctic carbon budget.

Here we present our first results, where we study the effect of fine-scale soil heterogeneity on physical properties (i.e., soil temperature, water, and ice) that directly affect the sensible and latent heat fluxes between soil and atmosphere. By comparing simulations with and without soil texture heterogeneity, as well as with and without lateral fluxes of heat and moisture, we are able to quantify the effect of soil heterogeneity at small scale and discuss the effect on larger scales.

Permafrost Core Characterization Using Gamma Ray Attenuation and Industrial Computed Tomography Scanning

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Alejandro Alvarez *University of Alberta*

The physical properties of permafrost cores are largely measured using destructive methods. These approaches are time-intensive and sacrifice critical samples collected at great expense. The development of rapid, non-destructive methods to quantify permafrost physical properties shows great promise but is still poorly developed. In this study, we assess the potential of gamma ray attenuation and industrial computed tomography (CT) scanning to measure physical properties, including density and volumetric ice content, in a range of permafrost cores in the newly developed Permafrost Archives Laboratory at the University of Alberta. We describe the development of calibration standards and individual capabilities for both a GEOTEK multi-sensor core logger (MSCL; including imaging, magnetic susceptibility, non-contact resistivity and gamma density) and a Nikon XTH 225 industrial micro CT scanner. These results are compared with established destructive methods for permafrost-core analyses. The MSCL has a higher throughput capacity and lower cost per meter of core, compared with the micro CT scanner. MSCL, once calibrated, shows the potential for processing tens of meters per day to generate high quality images, magnetics, and density data. Gamma density data is broadly comparable with CT-generated density measurements (derived from linear attenuation of x-rays) but represents a narrow transit of the core compared with the potential for whole core analyses via CT scanning. CT scanning still remains one of the most useful tools but is limited by the relatively high costs and time required to image cores. We have found that a combination of MSCL for the rapid characterization of cores, complemented by detailed CT imaging and quantitative analyses, provides a useful approach for permafrost projects in our laboratory.

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Material Properties of Advanced High-Strength Cold-Formed Steel Alloys Subjected to Subzero Temperatures

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Advanced high-strength cold-formed steel alloys (AHSS) have been developed, and due to advancements in chemical composition, multiphase microstructures, and other micromechanical changes, AHSS have three to five times the strength of conventional mild steels with yield strengths up to 1250 MPa and ultimate strengths up to 1900 MPa. Originally developed for automotive applications, AHSS have a high potential for application in the building construction industry. For the eventual use of AHSS for structural engineering in cold climates, the material properties must be properly quantified. An experimental investigation was carried out for a series of tensile coupon tests on three different AHSS alloys consisting of one dual phase steel with a nominal yield strength of 580 MPa and two martensitic steels with nominal yield strengths of 1030 MPa and 1200 MPa, in addition to two conventional cold-formed steel alloys consisting of one high-strength low-alloy steel with a nominal yield strength of 700 MPa and a mild steel with a nominal yield strength of 395 MPa, which served as a reference. The test temperatures ranged from ambient to -60°C at an interval of 20°C following the steady-state test protocol for testing at subzero temperatures. The stress-strain relationships and important material properties, including elastic modulus and stresses and strains at the yield, ultimate, and fracture points, were obtained from the tensile tests using an extensometer. Additionally, a grid method was adopted to measure the fracture elongations under various gauge lengths. The results demonstrate that AHSS have larger yield and ultimate strengths and fracture elongation at subzero temperatures than at ambient, and no significant decrease in the elastic modulus was observed, indicating the high potential for adopting AHSS as a building construction material in cold climates. Furthermore, a series of predictive equations on key material properties and stress-strain relationships at subzero temperatures were developed.

An Experimental Investigation of Coupled Thermo-Dielectric Properties of Icy Porous Media

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The freezing temperature of water in porous media is not constant but varies over a range determined by the structural properties of materials. Consequently, the amounts of unfrozen water and ice change with temperature in frozen conditions and varying temperatures, which in turn affects thermal and mechanical properties. Quantification of ice coverage and water content in porous material is challenging. One approach is to indirectly determine from dielectric constant of the porous material using techniques based on electrical measurements. In this study, we first aimed to detangle the coupled phenomena to understand the interactions between thermo-electrical processes to characterize the coupled thermo-dielectrical properties of a porous material at different scales using two different approaches: Time Domain Reflectometry and Impedance Spectroscopy. We performed element-scale and tank-scale experiments to measure dielectric constant of reconstituted inorganic porous material in the laboratory at varying initial water content and temperatures. Although the two methods operated in different frequency ranges, the data generated from these experiments were comparable. The dielectric constant increased with increasing temperatures until all the ice in the pores thawed at different temperatures. The results indicated that the dielectric constant of the porous silt increases with the decrease in frequency. This is due to the increased electrical conductivity of water when it is exposed to a low frequency alternating current. The results from these experiments not only allow us to characterize the response of porous materials with changing environmental conditions, but also to relate the length scales for thermo-dielectrical properties.

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Creep of Marginally Frozen Soils

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Creep of road embankments is a recurring problem in permafrost regions. Important degradations such as shoulder cracking and rotation reduce the functional capacity and lifespan of embankments, which considerably increases the maintenance costs of these structures. The problem, fairly well documented in the literature, is generally attributed to the static weight of the embankment on the underlying permafrost. However, degradations likely due to creep were observed on some portions of the Alaska Highway in Yukon, where the embankment is rather thin. Virtually no documentation is available on creep of thin embankments. Furthermore, little information is available on the effect of the passage of heavy vehicles circulating on these embankments. The main objective of this project is to quantify the effect of repeated loading on the mechanical behavior of marginally frozen soils. A new method was developed to conduct static and dynamic creep tests on frozen soils in a triaxial cell. The main innovations are the optimized control and acquisition of temperature around the sample, and the possibility to conduct drained tests. Creep tests were carried out on reconstituted ice-rich clay. The temperature varied between -3 and -0.5 °C, which simulated the behavior of a warm permafrost. Deformations caused by static and dynamic loading were treated separately, so that a method could be developed to estimate settlements caused by building a 1-meter embankment on the one hand, and settlements caused by the passage of heavy vehicles on the other hand.

Synthesis of Geophysical and Geomechanical Properties of Permafrost-Affected Soils Highlights Complex Processes of Permafrost Degradation in a Geotechnical Context

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Recent permafrost degradation across the high northern latitude regions has impacted the performance of the civil infrastructure. This study summarizes the current state of physical processes of permafrost degradation in a geotechnical context and the properties of permafrost-affected soils critical for evaluating the performance of infrastructures commonly built in the high northern latitude regions. We collected a total of 92 datasets with 3027 data points from 37 journal and conference publications and analyzed the variations of geomechanical and geophysical properties under the effects of permafrost degradation. The datasets represent a range of geomechanical and geophysical properties of permafrost-affected soils with different soil types and compositions under different testing conditions. While the data collected are highly scattered, regression analysis shows that most geomechanical and geophysical properties have strong associations with temperature. These associations highlight that ongoing warming will greatly affect the performance of civil infrastructures at high northern latitudes. These properties include elastic moduli, strength parameters, thermal conductivity, heat capacity, unfrozen water content, and hydraulic conductivity. This paper also discusses other factors, such as soil type, soil composition (e.g., total moisture content, porosity, bulk density, and salt content), and confining pressure, which may further complicate the relationships between temperature and the geomechanical and geophysical properties. Through this review, we identify key knowledge gaps and highlight the complex interplay of permafrost degradation, temperature, soil heterogeneity, and soil geomechanical and geophysical properties. Given the scarcity of certain permafrost properties in addition to the complex processes of permafrost degradation in the geotechnical context, there is a need to establish a comprehensive and curated database of permafrost properties. Hence, we encourage broader collaboration and participation by the engineering and scientific communities in this effort.

Permafrost Discovery Gateway:
Big Imagery Permafrost Science Today and Tomorrow

High-Performance Image Analysis Workflow Designs for Automated Mapping of Icewedge Polygons from High-Resolution Satellite Imagery

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Upsurge of peta-byte scale sub-meter resolution satellite imagery archives has been radically redefining the azimuth of Arctic permafrost research. Data processing challenges combined with clamant quest for pan-Arctic scale permafrost modelling efforts spontaneously creating the vacuum for pursuit of artificial intelligence (AI) algorithms, such as deep learning (DL) convolution neural nets (CNNs). Despite the remarkable performances of DLCNNs in everyday image understanding, bottlenecks still exist when translated to geo-object detection from remote sensing imagery. Among others, image dimensions, multiple spectral channels, spatial reference, seasonality, and most importantly semantic complexity aggregated into multiple spatial scales pose greater friction on the performance of DLCNN model predictions. Scalability of automated analysis over millions of square kilometers comprising heterogeneous landscapes reverberates the need for efficient image-to-assessment workflows that center on high performance computing resources (HPC). We have developed a novel high performance image analysis framework--Mapping application for Arctic Permafrost Land Environment (MAPLE)--that enables the integration of operational-scale GeoAI capabilities into Arctic science applications. The MAPLE workflow is three-fold: image preprocessing, DLCNN prediction, and post-processing. While the first and last segments involve CPU implementations, the prediction operates on GPUs. In this study, we have investigated highly parallelized four different workflow designs to implement MAPLE on heterogeneous HPC systems. It is equally important to understand how different workflow designs interact with underlying service unit (SU) accounting models of HPC systems. We systematically analyzed the execution time of image-pre-processing, DLCNN model execution, geospatial data generation of each design when predicting ice-wedge polygons and water bodies from satellite imagery. Currently, the MAPLE combines DLCNN algorithms with HPC resources to automatically identify icewedge polygons from thousands of commercial satellite imagery at an unprecedented spatial scale and also to detect small scale water bodies in the Arctic permafrost tundra.

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Interactive, Geospatial Visualization of High-Resolution, Pan-Arctic Permafrost Features in the Permafrost Discovery Gateway

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The Permafrost Discovery Gateway (PDG) is a new visualization portal to help researchers understand the extent, spatio-temporal variations, and impact of pan-Arctic permafrost thaw and other phenomena. Geospatial visualization is key to understanding permafrost features but is challenging at pan-Arctic scales for high-resolution permafrost features of interest. We present the PDG portal, an online application that provides interactive visualization, exploration, and access to geospatial permafrost data products derived from high-resolution satellite imagery (Big

Imagery). We incorporate the Fluid Earth Viewer to enable global and regional visualization of Arctic data products over time. We also incorporate Cesium as a tile-based Imagery Viewer that allows exploration of pan-Arctic, sub-meter map products over time and can be exported as publication-quality map images. Workflows will enable a Plot Viewer for interactive data exploration in which researchers can produce their own publication-ready 2D and 4D graphs from aggregated statistics from the geospatial data products. We discuss the initial data layer example of pan-Arctic ice-wedge polygons derived using machine learning from submeter imagery and processed into both raster and vector tiles. Future extensions of the portal platform will enable researchers to create publication quality maps and publication quality plots, as well as the ability to download specific subsets of high-resolution data for further analysis locally. Finally, the data processing pipeline has been built so that it can be extended to create visualization layers for new permafrost features of interest to the research community.

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Permafrost Discovery Gateway: A Project Overview

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The remote and expansive Arctic region is experiencing rapid changes to its permafrost landscapes in response to a warming climate. Simultaneously, more data than ever is created on this region in terms of satellite imagery. The Permafrost Discovery Gateway (PDG) aims to enable the creation of pan-Arctic geospatial data products from sub-meter and monthly scales, while also making the data accessible and discoverable to allow knowledge-generation by scientists and the public. About half-way into our National Science Foundation Navigating the new Arctic funded project, we now have developed operational hybrid machine learning pipelines using Cloud and High-Performance Computing Resources for initial use cases based on Maxxar and Landsat pan-Arctic imagery. Newly developed imagery products include first versions of near pan-Arctic sub-meter mapping of ice-rich permafrost as well as a selection of complementing NASA atmospheric data. In the visualization portion of the PDG, we have integrated examples of coarse permafrost geospatial products into the Fluid Earth Viewer (FEV) global visualization tool and incorporated Cesium as a tile-based Imagery Viewer to allow exploration of pan-Arctic, sub-meter map products over time. In addition to refining FEV and the Imagery Viewer, developments will also include workflows that will enable a Plot Viewer for interactive data exploration in which researchers can produce their own publication-ready 2D and 4D graphs from aggregated statistics from the geospatial data products. This presentation aims to give an overview of the multi-institutional project, while additional presentations will give more in-depth insights of the different components under development within the PDG. We greatly welcome the opportunity to interact with the PDG user community through these presentations.

Developing Hybrid Machine Learning Pipelines Using Cloud and HPC Resources for the Permafrost Discovery Gateway

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The aim of this work is to build interactive scientific gateways to manage extensible pipelines for large scale execution of ML models on satellite imagery using hybrid Cloud and HPC resources. Initial use cases include ice wedge polygon identification from ArcticDEM data (MAPLE) and thaw slump, lake and fire identification from Landsat data via Google Earth Engine (LandSatRes). We leverage the Clowder data management framework to expose the existing models as interactive web interfaces and to visualize intermediate geospatial datasets. Our current implementation leverages the NCSA Radiant OpenStack Cluster and Kubernetes to manage data locally and provide a container-based execution environment for the models. The gateway leverages the XSEDE Bridges2 resource for large scale execution of MAPLE using GPUs (not available on Radiant). Individual files uploaded to the gateway can be submitted for execution directly from the gateway web interface, or a path to existing data available on Bridges2 and moved there off band by the Polar Geospatial Center (in cases where the data cannot be widely shared). Outputs are then uploaded back to the gateway using the Clowder web service APIs. Geospatial visualizations are available in the PDG using Clowder geospatial extractors and previewers and integrate with other PDG visualization tools currently under development, including Arctic-wide visualizations of the results. Our hybrid approach reinforces the idea that a single solution does not often fit all cases, and integration of different solutions is often required.

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Understanding the Effect of Image Augmentation on Deep Learning Convolutional Neural Net Algorithms

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Easy access to sub-meter resolution imagery repositories positions the permafrost science at the precipice of revolution. We now have the imagery-enabled power to map, monitor, and document even individual permafrost features and their change over time. Artificial intelligence (AI) methods such as deep learning (DL) convolutional neural nets (CNNs), demonstrate remarkable success in automated analysis of semantically complex imagery from multiple domains. By design, inferential strengths of CNN models are largely fueled by the quality and volume of hand-labelled training data. Production of hand-annotated samples is a daunting task. This is particularly true for regional-scale mapping applications, such as permafrost feature detection across the Arctic, where landscape complexity would spontaneously inflate the semantic complexity of sub-meter resolution imagery. Additionally, image dimensions, multispectral channels, imaging conditions, seasonality, coupled with multiscale organization of geo-objects pose extra challenges on the generalizability of DLCNN models. Image augmentation is a strategic 'data-space' solution to synthetically inflate the size and quality of training samples without additional investments on hand-annotations. A plethora of augmentation methods have been proposed under the auspices of two general categories: data warping and oversampling. The performances of image augmentations methods largely depend on the image recognition problem in hand and characteristics of underlying data. In this study, we systematically investigate the effectiveness of a spectrum of augmentation methods falling into different cohorts, such as color space, geometrical transformations, feature space, and kernel filter when applied to CNN algorithms to recognize ice-wedge polygons from commercial satellite imagery.

Automated Recognition of Ice-Wedge Polygon Troughs and Human-Built Infrastructure in the Arctic Permafrost Landscapes Using Commercial Satellite Imagery

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Very high spatial resolution (VHSR) satellite imagery affords permafrost scientists the ability to map and monitor both the natural and human environments at finer scales. Geo-AI mapping applications based on the deep learning (DL) convolutional neural networks (CNNs) have been successful in translating big imagery resources into Arctic science-ready products. However, frontline DLCNN models are computationally intensive, which in turn hampers the scalability of imagery-enabled mapping efforts. Automated permafrost feature recognition is further challenged by the scarcity of large amounts of hand-annotated training samples to cope with inherent landscape complexities in regional-scale model applications. In this exploratory study, we investigated the ability of a lightweight U-Net DLCNN to efficiently perform semantic segmentation of VHSR commercial satellite imagery with a limited amount of training data in automated mapping of 1) ice-wedge polygon troughs and 2) human-built infrastructure in the permafrost-affected regions of the Arctic. We conducted a multidimensional experiment to understand how data augmentation, image pre-processing, and imagery-derived indices improve the performances of DL-based semantic segmentation of VHSR imagery. In both tasks, we employed data augmentation and tested the impacts of different types on trough and infrastructure recognition to determine the optimal set of augmentations. In the case of trough recognition, we additionally tasked mathematical morphological operations to exploit the geometric structure of the image. We utilized imagery-derived spectral indices and tested the impacts of normalized difference vegetation index (NDVI) and normalized difference water index (NDWI) on trough recognition. With a relatively low number of model parameters, limited labelled training data, short training time, and high segmentation accuracy, our findings suggest that overall, the U-Net DLCNN, coupled with data augmentation and mathematical morphology, could serve as an accurate and efficient method for mapping both natural and human-built features in the Arctic permafrost environment without compromising spatial details and geographical extent.

Alaska's Transportation Infrastructure in a Changing Environment

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Understanding the interactions between permafrost, climate, and infrastructure is complex, especially in regions like Alaska. The most readily available geospatial data on permafrost and infrastructure do not readily show the interactions. This study aims to evaluate the utility of long-term permafrost and climate data in understanding and predicting infrastructure stability on permafrost for Department of Transportation (DOT) assets in Alaska. First, the number of DOT assets on permafrost were summarized per Alaska climate zone for miles of road, bridges, and airports. Out of the thirteen Alaska climate divisions, eight contain DOT assets with permafrost. Southeast Interior contains the highest number of assets on permafrost. Thirty-year decadal averages were constructed for two different past and projected periods for active layer thickness, permafrost thickness, air temperature, and precipitation using data from the Integrated Ecosystem Model (IEM) project obtained at a 1-km spatial resolution. These results were contrasted against trend- detection approaches including LandTrendr and Mann-Kendall. Finally, projects identified from the Alaska Statewide Transportation Improvement Program (STIP) from 2018 to 2023 were compared to these results to understand if either approach could aid in predicting the location or degree to which infrastructure required capital investment.

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Infrastructure's Adaptation to Climate Change in the Russian Cold Regions Territories*

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Much of the territory of Russia is affected by climate changes, and the consequences of these changes have a significant impact on the socio-economic development of the country, living conditions, human health, and the state of the economy. According to many years of observations by the Federal Service of Russia for Hydrometeorology and Monitoring of the Environment, the average annual air temperature at the Earth's surface in the Russian Federation has, since the mid-1970s, been increasing by an average of 0.47° C over 10 years, which is 2.5 times greater than the growth rate of the average global air temperature (0.18° C for 10 years). Under these conditions, measures to adapt to climate change are simply necessary. The ongoing climate change in Russia creates new opportunities for the country's economy, which also relates to the field of adaptation. The Russian National Plan means that economic and social measures have been identified, and those measures will be implemented by federal and regional authorities in order to reduce the vulnerability of the Russian population, the economy, and natural objects. The plan will take advantage of opportunities arising from climate changes. The solution to the problems of geocryological forecasting as the scientific basis for reducing economic losses associated with the anthropogenic impact on permafrost is an interesting scientific problem, to which we devoted our research.

***For full text, see *Permafrost 2021: Merging Permafrost Science and Cold Regions Engineering*, American Society of Civil Engineers. https://ascelibrary.org/doi/epdf/10.1061/9780784483589**

Regional-Scale Investigation of Pile Bearing Capacity for Canadian Permafrost Regions in a Warmer Climate

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Climate change is being experienced particularly intensely in the Arctic, and therefore adaptation of engineering systems for this region cannot be further delayed. However, one of the major barriers to studies focused on adapting northern engineering systems is the lack of information at the spatial and temporal scales required for engineering applications. This study presents the development of ultra-high resolution (4 km) climate change information using the Global Environmental Multiscale (GEM) model for Canada's northern regions, and subsequent application to investigate pile bearing capacity for different pile material and configurations, for current and future climates. Comparison of the ultra-high resolution GEM simulation with available observations and a coarse resolution GEM simulation demonstrates added value for several variables such as temperature, precipitation and wind extremes, and in surface-related fields such as near-surface permafrost. The estimated adfreeze contribution to the total bearing capacity, for current climate, for a standard cement pile, is found to be of the order of 15% for regions with shallow bedrock and 80% for regions with deeper bedrock. Application of the GEM climate change simulation, for the RCP8.5 scenario, point to projected decreases to adfreeze contribution in the 5-30% range by 2040, with the largest differences noted for regions with deeper bedrock. For steel piles of the same configuration, although the adfreeze contributions are only about 70% of that for cement piles, the projected percentage changes are of similar magnitude. Further downscaling of results to 250 m resolution for important transport corridors, using simulations performed with the land surface model of GEM, provides many useful insights. The results of this study, including the ultra-high resolution climate change information, will form the basis for additional detailed investigations on climate-infrastructure interactions and climate resiliency studies.

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Developing a Framework for Assessing the Vulnerability of Infrastructure on Permafrost to Climate Change

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Observed permafrost warming and increase in the active-layer thickness are having significant detrimental effects on sustainable development in high latitudes. An increase in permafrost temperature decreases the ability of the frozen ground to carry a load imposed by infrastructure, which can potentially cause deformation and collapse. Active layer thickening, especially in regions underlain by ice-rich permafrost, promotes differential thaw subsidence, which undermines the stability of linear infrastructure (roads, railroads, pipelines, airstrips). Climate projections indicate that amplified Arctic warming will persist through the 21st century, causing pronounced changes in permafrost conditions. Moreover, permafrost changes are likely to be more evident in areas where the ground thermal regime is significantly modified by intensive urban and/or industrial development, causing negative impacts to Arctic socio-economic systems. In this study, we employ a subset of CMIP6 models using the SSP585 scenario to compare present (2015-2024) and future Arctic climate conditions (2055-2064). Daily temperature and precipitation were used as inputs for a permafrost-geotechnical model to estimate changes in permafrost temperature, active layer thickness, subsidence, and bearing capacity. Simple interpolation techniques were used to estimate changes within cities and other centers of economic activity. A circumpolar infrastructure geodatabase was assembled to determine locations and infrastructure types particularly threatened by changing climatic and permafrost conditions. Costs associated with projected damages were then estimated for all Arctic states using country-specific construction statistics. The framework presented can be used to translate complex climatic inputs into a series of accessible graphics and interactive maps for stakeholders to examine and communicate potential impacts of climate change and permafrost degradation from national to municipal scales. An online version of this diagnostic tool is currently being developed.

A Spatially Consistent Account of Infrastructure across the Entire Arctic

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Infrastructure and anthropogenic impacts are expanding across the Arctic. A consistent record is required in order to quantify the changes and to assess climate change impacts, including permafrost thaw, on the communities.

Satellite data offer spatially continuous coverage, but the separation of infrastructure from natural environments is challenging due to spatial resolution and spectral similarities with natural features. Sentinel-2 provides an advance in this context compared to Landsat (10m versus 30m). We used Sentinel-1 (Synthetic Aperture Radar) in combination with Sentinel-2 (multispectral) observations covering the entire Arctic coastal region to identify areas impacted by humans. Machine learning techniques are implemented in a first step. Manual post-processing has been carried out for two different classification type results and eventually they have been merged. Due to the size of the study area, several editors have been involved in the manual postprocessing step. To evaluate the comparability of the results, the performance of individual editors has been assessed through a benchmarking exercise.

Mapped objects include roads, buildings, and other areas such as gravel pads or open pit mining areas. These represent only part of relevant infrastructure for Arctic communities, but a consistent database can be obtained. In total, 0.02% of the land area within the 100-km buffer was identified as human-impacted.

As an example, results are combined with ground temperature trends derived from the ESA CCI+ Permafrost time series (1997-2019). If trends continue as observed during this time period, the majority of areas with human presence will be subject to thaw by mid-21st century.

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Early Warning Frost Detection System*

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Occurrence of freeze/thaw conditions in rural roadway subgrades over the years resulted in significant labor efforts by Whatcom County Public Works engineers to monitor and evaluate conditions for implementing road restrictions. Extended periods of frost conditions followed by warmer temperatures can result in extensive damage to the road system if restrictions are not applied. Previously, manual subsurface temperatures were measured at various locations throughout the county to assist with evaluation of roadway conditions. Recently, a network of automated measurement and remote communication systems was designed and implemented to facilitate improved monitoring and response for the County engineers. Sixteen remote monitoring locations were selected throughout the county and at each site a 1-meter-long tube with 18 thermistors at 50 mm spacing was installed into the roadway subgrade. Additional instrumentation at each site included ambient air temperature sensors and moisture sensors for the datalogger enclosures. Data is collected and transmitted to a web-based data management system for county personnel to access. The data also provides alarm notifications to county personnel with indications as to when temperature thresholds are exceeded. Having the automated system allows the county to monitor the thaw process more accurately and be more confident in when road restrictions are applied and the duration. The current monitoring system has increased the effectiveness and efficiency of the county's rural roadway management process during freeze/thaw cycles, resulting in significant savings in operating and maintenance costs.

***For full text, see *Permafrost 2021: Merging Permafrost Science and Cold Regions Engineering*, American Society of Civil Engineers. https://ascelibrary.org/doi/epdf/10.1061/9780784483589**

On The Influence of Complex and Changing Arctic Conditions on Historic and Future Waste Disposal Sites: A Multi-Criteria Risk Assessment

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Management of waste from both human settlements and mining activities has been a major challenge in the Arctic region. Historically, practice has relied on permafrost conditions in the soil to stabilize waste and to prevent contaminants from being released into the environment. Increased temperatures in Arctic regions, due to climate change might result in mobilization of contaminants from historic waste. In addition, traditional approaches to the handling of mine waste are no longer valid, and new solutions need to be developed.

To address these challenges, we developed a multi-criteria risk assessment approach that considers the various processes that can apply pressure on Arctic waste site systems:

- Climate change-induced increases in temperatures and changes in precipitation patterns can lead to increased erosion.
- Permafrost is expected to lose its role as a geological barrier for the containment of environmental contaminants.
- Landslides and avalanches could impact stability and safety on-site.
- Changes in geotechnical stability will impact stored waste and potentially lead to the release of contaminants.
- Hydrological conditions guide the functioning of barriers between the waste and its environment.
- Properties of the deposited waste fractions are drivers for the release of contaminants and therefore require a clear classification.

All of these factors are interrelated, and the risk they pose can be addressed by combining their probability of occurrence and the consequences in a risk matrix. This integration allows both a qualitative and a quantitative approach of the involved risks to humans and the environment. Thereby, it is possible to find solutions that will be sustainable under future climate change scenarios in the Arctic. In our presentation, we show how this multi-criteria risk assessment approach can be applied to historic and future waste disposal sites on Svalbard, Norway.

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Understanding the Changing Natural-Built Landscape in an Arctic Community: An Integrated Sensor Study in Utqiaġvik, Alaska

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Arctic communities face many challenges in the context of a rapidly changing environment. These challenges include coastal erosion, permafrost thaw, and ecosystem change. Arctic cities need to prepare for critical decisions in the future, which traditional geochemical approaches alone are unable to address adequately. Instead, an interdisciplinary, community-based approach is necessary. This project is developing and deploying a network of terrestrial and aquatic sensors, in addition to conducting geophysical surveys, within the community of Utqiaġvik, Alaska, in order to improve our understanding of the interactions between the built and natural environments in the Arctic. Community collaborators are involved in the planning process for sensor and surveying locations and the ongoing maintenance and interpretation of the data. At peak thaw this summer, we conducted ground-penetrating radar and electrical resistivity tomography survey along transects throughout Utqiaġvik and placed the first two of twenty proposed meteorological stations. This research will investigate two essential challenges for the Arctic city of Utqiaġvik: 1) the impacts of existing community infrastructure practices on the surrounding tundra, coastal, and lagoon landscapes within and around the city, and 2) the impacts of a changing environment on the design and future planning of community infrastructure and buildings. The process of co-production of knowledge among researchers and community collaborators is also being studied to better understand how these relationships can successfully build and maintain equitable sharing of knowledge and data and provide benefits for the residents of Utqiaġvik and the broader scientific community.

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Performance of Climate Projections Used for Engineering Design in Yukon and Adjacent Northwest Territories, 1991-2020

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Permafrost foundation design recognizes the potential impact of climate change on soil bearing capacity so that foundation integrity is maintained throughout the intended service life of structures. Canadian scientists and engineers have published a guideline for considering climate change in foundation design (CSA PLUS 4011-19). However, there is no guidance as to the climate scenarios most prudent to adopt. In 2003, climate change scenarios were outlined for the Mackenzie Gas Project in consideration of its proposed 30-year service life. In this paper, we ranked these projections and compared them with Environment and Climate Change Canada (ECCC) data to determine the scenarios most representative of the 1991-2020 climate record. The greatest climate change in Canada during the last 50 years has been measured in the western Arctic, where annual fluctuations in air temperature are regionally correlated. The rate of change in mean annual air temperature (MAAT) has ranged from 0.72 °C/decade at Inuvik, NWT to 0.43 °C/decade at Dawson, YT. The warming has been concentrated in winter. No statistically significant trends in precipitation have been observed for 1971-2020, and these records are poorly correlated among regional stations. Twenty-nine ranked climate projections from SRES scenarios derived using seven global climate models (GCMs) were examined for the region. The observed regional climate change in 1991-2020 has surpassed the upper MAAT and winter air temperature projections. For example, at Inuvik the 2.0 °C increase in MAAT between 1961-1990 and 1991-2020 already exceeds the median projection of +1.6 °C and is approaching the upper value of +2.4 °C for projected change by 2011-2040. No consistent relations between observed and projected precipitation have been determined. These observations indicate that future projections for regional temperature change may prudently adopt higher or more extreme scenarios. Projections for precipitation exhibit less systematic behavior with respect to the record.

Spatial Variability in the Relative Influence of Permafrost on River Bank Erosion Rates

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Arctic watersheds are undergoing and/or are predicted to undergo significant changes in hydrology, sediment loading, and the rates and patterns of permafrost thaw. All of these changes may impact river migration rates and the exchange of materials between rivers and their surrounding floodplains. To establish a baseline of Arctic river erosion rates and evaluate the relative influence of hydrology, sediment, and permafrost on bank erosion, we used both field and remotely sensed observations to quantify rates of river bank erosion. We find that bank erosion along rivers with both discontinuous or continuous permafrost exhibits significant spatial and temporal variability. Along individual rivers, temporal variability in hydrology exerts the strongest control on erosion rates over time. Along tens to hundreds of kilometers of individual rivers bounded by discontinuous permafrost we see some evidence of lower erosion rates along banks with permafrost, but the correlation between the presence of permafrost and erosion rates appears to be confounded by local controls in both bank material properties and local hydrodynamics. Compiling erosion rates from across the pan-Arctic, we do observe mean erosion rates that are lower relative to non-Arctic rivers with similar magnitudes of total stream power (a product of river discharge and slope). The difference in normalized erosion rates between permafrost- and non-permafrost-affected rivers increases with increasing river size. Both local field observations and pan-Arctic remotely sensed observations suggest that the presence of permafrost may set an upper limit for bank erosion rates. This control only infrequently influences small rivers with generally abundant thawed sediment and relatively fewer days above the threshold for sediment transport. On larger river systems, longer durations of higher flows and smaller more readily transported bank sediments combine to make erosion rates on these river systems more strongly controlled by thaw rates of frozen bank material.

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Process-Based Thermal-Mechanical Numerical Modeling of Coastal Erosion on Tuktoyaktuk Island, Northwest Territories

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Erosion of Arctic coasts is promoted through warm air temperatures and storm surges impacting permafrost coastal bluffs during the open-water season, resulting in erosion rates varying from 1 to 20 m/yr across the region. The Inuvialuit community of Tuktoyaktuk, Northwest Territories, located along the Beaufort Sea coast, has been dealing with the consequences of coastal change for many decades and will likely be displaced due to accelerating rates of erosion. Tuktoyaktuk Island lies to the east of the community, sheltering the harbor and shores from the impact of waves. It is retreating at a rate of ~2 m/yr and is expected to be breached by 2050. In this study, a process-based thermalmechanical numerical model was developed for Tuktoyaktuk Island to investigate erosional processes commonly impacting ice-rich permafrost bluffs including thermal denudation of the cliff face through soil-climate interaction, thermal abrasion at the cliff toe through the formation of a thermoerosional niche under a storm surge, and the impact of permafrost sediment properties on rates of erosion. It was found that erosion rates vary significantly between stratigraphic units, where sandy silt sediments have higher rates than ice-rich clayey silt layers due to latent heat effects, and therefore they should be considered on a site-specific scale for engineering purposes. The consideration of permafrost sediment properties improved our understanding of erosion rates on Tuktoyaktuk Island, thus

allowing future detailed consideration of mitigation strategies. It was found that a storm event of extreme duration or surge level is required to reach a critical niche depth capable of triggering block failure on the island. Lastly, it is expected that erosion rates will increase under climate-driven change such that the drivers of accelerated erosion are relative sea level rise, decrease in sea ice extent, and increase in surface air temperatures.

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Functional Delta Connectivity and Impacts on Lake Ice in the Colville Delta, Alaska

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Within Arctic deltas, surficial hydrologic connectivity of lakes to nearby river channels influences physical processes like sediment transport and ice phenology as well as biogeochemical processes such as photochemistry. As the Arctic hydrologic cycle is impacted by climate change, it is important to quantify temporal variability in connectivity. However, current connectivity detection methods are either spatially limited due to data availability constraints or have been applied at only a single time step. Additionally, the relationship between connectivity and lake ice is still poorly quantified. In this study, we present a multitemporal classification and validation of lake connectivity in the Colville River Delta, Alaska. We introduce a connectivity detection algorithm based on remote sensing of water color that is expandable to other high-sediment Arctic deltas. Comparison to validation datasets suggests that detection of high vs. low connectivity lakes is accurate in 69.5–85.5% of cases. Connectivity temporally varies in about 20% of studied lakes and correlates strongly with discharge and lake elevation, supporting the idea that future changes in discharge will be drivers of future changes in connectivity. Lakes that are always highly connected start and end ice breakup an average of 26 and 16 days earlier, respectively, compared to lakes that are never connected. Because spring and summer ice conditions drive Arctic lake photochemistry processes, our research suggests that surface connectivity is an important parameter to consider when studying biogeochemistry of Arctic delta lakes.

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Intra-Ice and Intra-Sediment Cryopeg Brine Occurrence in Permafrost Near Utqiaġvik, Alaska

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Shelly Carpenter *University of Washington*
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Cryopeg is a volume of permafrost with a significant amount of cryotic unfrozen water as a result of freezing-point depression by dissolved salt content. Cryopeg and saline permafrost have been reported for coastal areas of the Arctic seas, and their current distribution and future changes are a great concern for the warming Arctic, as the state of permafrost controls ground stability and the functioning of ice cellars in Arctic villages. To describe the distribution and segregation of cryopeg lenses, and to explore the origin and development of the cryopeg and associated brines found near Utqiaġvik, we conducted extensive sampling campaigns in the Barrow Permafrost Tunnel during May of 2017 and 2018. We found two types of cryopeg brines based on their distinctive spatial occurrences: 1) intra-ice brine (IiB), entirely bounded by massive ice, and 2) intra-sediment brine (IsB), found in unfrozen sediment lenses within permafrost. In our study, the IiBs were at roughly atmospheric pressure and situated in small pockets of ellipsoidal or more complex shape (dimensions of up to about 30 cm wide and 3 cm height) within 17–41 cm above the underlying sediment layer. Several individual IiB pockets may have been connected by porous ice of low permeability. Radiocarbon dating suggests that, at the earliest, the IiB was segregated about 11 ka BP from IsB-bearing cryopeg underneath. IsB lenses were interpreted as having developed through repeated evaporation and cryoconcentration of seawater in a lagoonal environment, then isolated at the latest when the surrounding sediment froze up and became covered by an upper sediment unit around 40 ka BP or earlier. An increase in permafrost temperature invariably will result in expansion of cryopeg lenses and may change movement of liquids within the permafrost, which potentially become threats to Arctic coasts, infrastructure, and food security.

Demonstration of the ACE (Arctic Coastal Erosion) Model at Drew Point, Alaska, During a Permafrost Bluff Block Collapse Event in Summer 2018

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The erosion of permafrost coastlines is accelerating in many arctic locations, threatening infrastructure and putting native communities at risk. Predicting rates of land loss remains challenging, if not impossible, using current tools. Permafrost coastlines can erode by a variety of mechanisms such as slumping, block erosion, and thermo-denudation, which is driven by ocean activity, atmospheric processes, and permafrost thaw. In this presentation, we introduce the ACE (Arctic Coastal Erosion) Model, a new, multi-physics numerical tool which couples oceanographic and atmospheric conditions with a terrestrial permafrost domain to capture the thermo-chemo-mechanical dynamics of erosion along permafrost coastlines. The ACE Model is based on the finite-element method and solves the governing equations for conservation of energy (via heat conduction including phase change), and the stress and displacement fields using a mechanical plasticity material model. Oceanographic and atmospheric boundary conditions force the evolution of a terrestrial permafrost environment, which consists of porous media made of sediment grains and pore fluid. An oceanographic modeling suite (consisting of external software packages Wave Watch III, SWAN, and Delft3D) produces time-dependent water level, temperature, and salinity boundary conditions for the terrestrial domain. Atmospheric temperature is obtained from the ECMWF (European Centre for Medium-Range Weather Forecasts) Reanalysis v5 (ERA5) dataset. Driven by these boundary conditions, 3-D solutions of temperature, stress, and displacement develop in the terrestrial domain in response to the material plasticity model that is controlled by the frozen water content. Material is removed when the stress within an element exceeds the yield strength of the material and is followed by grid adaptation that captures the new geometry. This modeling approach enables failure from any allowable deformation (e.g., block failure, slumping, thermal denudation) and can treat erosion behavior over single events (hours/days), seasonally, or over several years. A demonstration of the ACE Model will be presented for a portion of the summer 2018 conditions at Drew Point, Alaska, during which a block collapse event was documented with thermistor data and time-lapse photography. We demonstrate that the ACE Model is capable of reproducing the observed erosion behavior, including niche formation/geometry, thermal denudation, and block collapse timing. This model can be used to rigorously investigate erosion drivers and how climate change will influence future erosion behavior at Drew Point, as well as a typological assessment of erosion along the North Slope of Alaska to enable estimates of shoreline change at the coarse scale of Earth system models.

Permafrost Thaw and Coastal Erosion Between 1950 and 2100 at Three Coastal Communities in Arctic Alaska: Past Observations and Future Projections

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Permafrost thaw and coastal erosion are expected to cause widespread land loss, infrastructure damage, the re-routing of tundra and snow travel corridors, and the destruction of important cultural sites across many communities within the next century. We use a combination of remote sensing, digital elevation analysis, and ground temperature modelling to explore past and future permafrost dynamics and shoreline change at Wainwright, Point Lay, and Kaktovik on the North Slope of Alaska. Geophysical Institute Permafrost Laboratory (GIPL) results suggest that by the year 2100, under Representative Concentration Pathway (RCP) 8.5, ground temperature could increase by 6 to 8°C (from ca. -5°C to ca. +1°C) under natural conditions (i.e., tundra) and by 7 to 9°C (from ca. -6°C to ca.+ 1°C) in areas covered by 1 m of gravel (e.g., roads and runways). The projected increase in ground temperature at 1 m depth will result in above-freezing conditions at all sites. Due to the prevalence of ground ice, this will lead to widespread subsidence and thermokarst development both within and around all three communities. The difference in ground temperature change between natural and gravel conditions highlights the potential for accelerated permafrost thaw within the built environment. Maximum historical average rates of shoreline change between ca. 1950 and ca. 2020 were -1.34 m/yr, -1.67 m/yr and -4.3 m/yr at Point Lay, Wainwright, and Kaktovik and their adjacent coastlines respectively. We analyze historic rates of change to explore different shoreline change scenarios (a conservative increase vs. an amplified increase in erosion rates) and create coastal erosion projections through 2100 for all three communities in order to quantify land loss and identify cultural sites and infrastructure that will likely be lost or damaged during this time period.

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Floating Ice and Riverbed Permafrost in the Lena River Delta

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Arctic deltas and their river channels are characterized by three components of the cryosphere -- snow, river ice, and permafrost -- making them especially sensitive to ongoing climate change. Thinning river ice and rising river water temperatures may affect the thermal state of permafrost beneath the riverbed, with consequences for delta hydrology, erosion, and sediment transport.

In this study, we use optical and radar remote sensing to map ice within the Arctic's largest delta, the Lena River Delta. The ice floating on river water is known as serpentine ice and tends to form in the deeper sections of river channels, beneath which unfrozen sediment is often found (called a thaw bulb or talik). Conversely, when river water freezes all the way down to the river bottom, the ice stretches out and covers across a large area, forming bedfast

ice. With optical data, we distinguished elevated floating ice from bedfast ice, which is flooded ice during the spring melt. The radar data were used to differentiate floating from bedfast ice during the winter months.

As an example, the accompanying animated figure shows the mouth of the Olenekskaya Channel at the southwestern edge of the Lena Delta, where Lena River water discharges into the western Laptev Sea. The optical imagery shows land cover and surface water color. Superimposed on this image in white is the position of the serpentine channel based on spring optical imagery, which correspond to channels deep enough to be navigable for small-draught vessels. The black and white radar image shows the region of the river channel with high winter backscatter from a floating ice interface.

We tested our observations with methods that allowed us to investigate the temperature field and sediment properties beneath the riverbed: numerical modeling of heat flow and field surveys of sediment bulk electrical resistivity. Our results show that regions of serpentine ice identified with optical and radar remote sensing corresponded to one another. The serpentine ice regions coincided spatially with the location of thawed riverbed sediment observed with in situ geoelectrical measurements and as simulated with the numerical model of heat flow through the ice, river and sediment. Our remote sensing approach provides a means of investigating seasonal changes in delta connectivity, since the channel network open to flow in summer is greatly reduced by river ice in winter, when flow is restricted to open channels below the ice. Furthermore, our results provide viable information for the summer navigation for shallow-draught vessels.

For river channels such as the Lena River Delta of Russia the consistent location of floating serpentine ice from year to year suggests that unfrozen permafrost lies beneath and that permafrost beneath bedfast ice regions may stabilize channel position. Thinning river ice and rising river water temperatures can affect the stability of permafrost beneath these riverbeds, with consequences extending into erosion, sediment movement, ice jams and related flooding, damage to local infrastructure, and increasingly dynamic channel morphology, making navigation less certain.

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Permafrost Investigations Below the Marine Limit at Nain, Nunatsiavut, Canada*

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Discontinuous permafrost located within municipal boundaries of northern communities presents a unique challenge for existing and future infrastructure. Warming and thawing of permafrost beneath built structures can cause differential subsidence, and mitigation of permafrost hazards can be costly. These issues are particularly pronounced in Nunatsiavut communities in coastal northeastern Canada, where glacially carved topographic relief constrains the potential for community expansion. The coastal Labrador (northeast Canada) community of Nain, Nunatsiavut, is in the sporadic discontinuous permafrost zone and is undergoing significant changes due to rapid population growth and expansion of community housing. A community hazard assessment, led by the Nunatsiavut Government, identified major infrastructural issues including subsidence and settling, particularly within the lower sections of the community underlain by marine and glaciomarine deposits. Owing to an overall lack of baseline permafrost studies in Labrador, there is a paucity of local permafrost information to guide infrastructural development like those in Nunatsiavut. In this study, we characterize permafrost distribution in a subset of the community of Nain, Nunatsiavut, using geophysical and field data collected in 2014 and 2018. DC electrical resistivity tomography (ERT) is used with validation data to estimate frozen ground likelihood for seven ERT transects collected in marine and glaciomarine deposits. Permafrost was inferred to be present at six transects, with permafrost bodies of at least 15 m in thickness at four transects, including those performed across the construction pad of the recently completed Illusuak Cultural Centre. The ERT results also suggested the presence of supra-permafrost taliks in certain developed sections of the community, including beneath a local convenience store that has undergone extreme structural subsidence. Despite uncertainties in geophysical interpretation due to a history of local site disturbance and the presence of near surface backfill in some locations, these results have important implications for future development in Nain, Nunatsiavut.

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Characterizing Lake Spatial Distribution to Understand Permafrost Processes on Arctic River Deltas

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River deltas ringing the Arctic Ocean coastline are characterized by thermokarst lakes (i.e., perennially depressions that grow by the thaw of ice-rich soil). These lakes trap and store riverine freshwater, sediment, and nutrients, thereby modulating the timing and magnitudes of riverine fluxes to the Arctic Ocean. Average lake size has recently been reported to be inversely related to mean annual air temperature on Arctic deltas, suggesting a projected reduction of mean lake size under global warming with implications for delta morphology and Arctic ecohydrology. In this study we extend our analysis to include the spatial patterns of lake spacing expecting that local lake density (i.e., "local lake packing") can provide physical insight into delta evolution in permafrost environments. We present an assessment of lake packing at the individual lake, island, and delta scale on 12 Arctic deltas across Siberia, Alaska, and Canada, and we document marked heterogeneity within and across deltas. We identify coherent areas (i.e., clusters) of lakes with similar packing within individual deltas, and attribute clusters of highly packed lakes to ice rich-soils, while differences in geomorphic processes (i.e., fluvial, wave, and tidal activity) also play an important role. Our results indicate that under projected warming and permafrost thaw, lake cover will generally transition from finely to coarsely packed across all deltas, with variability within and across deltas driven in part by differences in local geomorphic processes. These findings bear importance for projecting the future of delta morphology in regions prone to permafrost thaw, with implications for riverine freshwater, sediment, and carbon flux delivery to the Arctic Ocean.

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Ground Temperature Responses to Climatic Trends in a Range of Surficial Deposits Near Kangiqsualujjuaq, Nunavik*

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This paper examines ground temperature responses to recent climatic trends in a range of environments within the community area of Kangiqsualujjuaq (George River) in Nunavik. The municipality straddles the tree line, encompasses surficial deposits of a range of origins, and currently has a mean annual air temperature of -3.43 ºC. Sixteen thermistor cables, extending to depths ranging from 2.9 to 20.05 m, were installed in various geomorphological settings, including bedrock, till, glacio-fluvial, marine sand and gravel, lithalsas in marine silt, and palsas consisting of 1-m-thick peat over marine silt. The longest series available is from a cable installed in bedrock that has been monitoring ground temperatures since 1989 and is still active. Another cable has been recording temperatures in the marine clays of a palsa for almost as long (since 1993). Spatial variations in ground temperature responses to air temperature trends were examined with the support of high-resolution mapping of surficial geology, GPR surveys and mapping of ground ice, and analysis of time-lapse aerial photographs and recent imagery. The assessment of thermal profiles and time series reveal a strong correlation between ground temperatures and regional climate variations, which was clearest in the longest series available, in bedrock with a high thermal conductivity. At some sites with fine-grained deposits, ground temperatures have become isothermal near 0 ºC, reflecting the effects of latent heat as unfrozen water content increases and permafrost progressively thaws along the profile. One of these isothermal sites is in a lithalsa on the coastline that is surrounded by sea water during large tides. Several other sites in marine deposits, such as palsas and lithalsas, and sandy deposits with a substantial fine fraction, are now close to isothermal as well. Lithalsas and palsas are slowly degrading and surrounded by thermokarst ponds while coarse soils show little change.

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Permafrost Dynamics Related to Channel Migration in the Colville River Delta, Alaska

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Permafrost dynamic of Arctic deltas involves a wide range of processes. Erosion may directly impact communities and local ecosystems, while there may be consequences at the global scale such as the release of greenhouse gases. Channel migration affects talik and cryopeg development, yet our knowledge of their configuration, properties, and rate of freezeback has remained limited. Here we integrated subsurface data from 79 boreholes with a remote sensing analysis to measure channel changes in 1948-2013 along a main channel of the Colville River Delta, Alaska, and the impact on permafrost. We also measured erosion rates, and ground loss (areas, volumes) by terrain unit. The longterm maximum erosion rates from 1948 to 2013 averaged 0.9 m y-1 and ranged from 0.4 to 3.3 m y-1. The inactive- and active-floodplain cover deposits experienced the highest erosion (269,960 m2 and 150,830 m2, respectively); however, the alluvial terrace in the Gubik Formation had the largest ground loss volume due to banks being over twice higher, on average. Eroding the older ice-rich terrain units forming the floodplain toposequence, such as the inactive-floodplain cover deposits, resulted in ground loss volumes of about 208,357 m3 as soil solids and about 833,429 m3 as ground ice. We identified closed taliks under the active channel that extended into intrapermafrost cryopeg layers under the riverbed/riverbar and active floodplain. Cryopegs as isolated small pockets were also identified at depths in older terrain units. Permafrost growth occurred at a rapid rate in the land exposed following channel migration, likely due to the low and delayed release of latent heat as the freezing front progresses downward in the coarse-grained soils of increasing salinity but decreasing temperatures. As the deposits keep cooling, ground ice will continue forming, therefore increasing further the salinity of the remaining unfrozen soil pore-water and likely preventing the complete freezeback of the cryopegs developed in relation to channel migration.

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The Influence of Thermal Erosion on Riverbed Deformation in Permafrost Areas*

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The major two differences between channel deformation processes in rivers in permafrost zone and beyond it are due to the considerable effect of thermal erosion and the non-simultaneous effects of the melting of channel-forming ground and flood wave. Laboratory and numerical experiments were carried out to study the effect of water flow on riverbed deformations in the permafrost areas. The results are compared with data of other research, including field observations. The study shows that a comprehensive and adequate model of river channel deformations should take into account not only ablation, but also other factors, including heat transfer in the soil, sediment transport, and bank slope collapses. Numerical experiments with an improved mathematical model, applied to long time intervals, have shown that the differences between the averaged deformations, calculated by a model of ablation alone (i.e., ignoring bank slope collapses and sediment transport) and a comprehensive model can be considerable. Experiments in a hydraulic flume were good enough to reproduce the effect of delayed collapse, consisting in non-simultaneous impacts of channel-forming rock melting and a freshet.

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The Permafrost Monthly Alert (PMA) Program: Informing Engineers, Scientists, Educators, and the Public of Current Permafrost Literature

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The Permafrost Monthly Alert (PMA) Program is a bibliographic compilation of recently published and newly archived permafrost literature that is brought to the public every month. The PMA allows its users – including permafrost engineers, scientists, educators, and the public– to have one location for abstracts and links to the most recent national and international additions to permafrost studies. At the same time, it provides access to the one-stop search of the world permafrost literature dating back to the early 1900s.

References are compiled by the American Geosciences Institute (AGI), which hosts databases including GeoRef and COLD. Monthly accessions are compiled and uploaded to the AGI publicly available database, COLD, which contains over 33,500 recent and historical permafrost references. Currently, the ten-year PMA collection (2012-June 2021), available on the USPA website, includes 113 monthly and special updates containing approximately 8600 citations. Average annual usage of the PMA acquisitions exceeded 11,700 inquiries (views by readers) for 2018 through 2020, and since its inception in 2012 is over 89,000 inquiries.

Our presentation provides results of the recently developed Python code, titled "PMA Query", which analyzes each PMA in order to better understand trends in the permafrost literature. The script collects information on the sources and types of references. In addition, it has a graphical user interface (GUI) and is searchable for any word of interest. Key findings from our analysis show that the majority of publications are sourced from conference papers and abstracts (5285 references) and journals (3061 references). Of these conferences, recent AGU Fall Meetings (1549 references), proceedings of the International Conference on Permafrost (1400 references), and recent EGU Annual Conferences (565 references) have been the top three sources. For journals, the top five represented are Permafrost and Periglacial Processes (213 references), The Cryosphere (138 references), Cold Regions Science and Technology (102 references), Journal of Geophysical Research: Biogeosciences (98 references), and Geomorphology (95 references). Prevalent permafrost terms such as carbon (in 994 references) and methane (in 335 references) have been mentioned more frequently in the past five years. Details are provided in the conference presentation.

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Enhancing STEM Education and Soil Monitoring with a Durable DIY Low-Cost Soil Temperature Data Logger

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Many STEM fields rely on automated data logging systems to measure and understanding environmental change. However, commercially produced devices are often costly, and users often struggle with troubleshooting when these devices malfunction. Here we provide a two-pronged solution to this problem by designing a low-cost open-source "Do-It-Yourself [DIY]" temperature data logger and producing a series of online videos that allow even novice users to construct and deploy these devices in the field. The DIY data logger was designed around the Arduino platform, allowing users to tap into a vast pre-existing collection of educational materials. In comparison to other DIY data loggers, our design is intended to be robust and therefore uses a printed circuit board. The online video series provides a step-by-step tutorial on how to order equipment, assemble, program, and deploy the soil temperature data loggers. We tested the efficacy of the tutorials on college students with minimal experience in electronics and tested the durability of the data loggers by deploying them in permafrost soils on the North Slope of Alaska. Data loggers built by novice users performed well in the field and were able to monitor soil temperature for three years without a battery replacement. Our soil temperature data logger system could easily be scaled to provide greater spatial coverage at an extremely low price point when compared to commercial systems. The low cost and effectiveness of these data loggers position them as a tool that can both increase access to soil temperature monitoring across the globe and train the next generation of scientists and engineers.

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Engage the Public in Science and Embrace Future Change with Human-Centric Stories, Art, and Imaginings*

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Current human-interest stories with interwoven scientific data effectively engage the public in environmental issues that do not yet directly affect them. Science fiction with artistically rendered futuristic scenarios unleashes the imagination and is a lens to explore and plan for the technological, social, and cultural aspects of transitioning to clean energy. Cultures with strong oral history traditions use stories to record history, pass on environmental lessons, and prepare for future change. Stories, art, and emotional connection are effective ways to engage people, disseminate scientific information, and prepare ourselves for future transitions. Ever-increasing amounts of scientific data do little to engage the public and can lead to disconnected helplessness. To share the relevance of Arctic change effectively and make information accessible to enable discovery and public knowledge-generation, scientists should start with art and narratives, real and imagined. We explore these methods by tracing the specific histories of two Inupiaq homes on Alaska's North Slope that are threatened by erosion and permafrost degradation. We use human-centric narratives interspersed with data that illustrate ecosystem processes. Next, we report on a collaborative, interdisciplinary workshop and book project (NREL and Arizona State University) that is creating narratives of hope and visions for the future through inspiring art, short stories, and essays. We discuss the surprising potential of cli-fi and the research behind emotion/imagination-driven engagement in science and futurescapes. We describe various methods that help people visualize their future well-being by creating emotional connections to their future selves, and we explore opportunities to spread those methods.

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Alaska Voices: Building Bridges of Knowledge Through Shared Conversations

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Dr. Bob Bolton and I co-founded Alaska Voices (originally a science-based storytelling project) after we attended the American Geophysical Union meeting. I felt overwhelmed at the conference and just wanted someone to tell me a story about their research. We partnered with StoryCorps – the leading organization in collecting and sharing stories as conversations between two people – and received funding from the Alaska Climate Science and Adaptation Center. Our year-long StoryCorps partnership included training 12 story-recording facilitators and archiving conversations with StoryCorps and the Library of Congress. While the initial idea was to focus on conversations between scientists about science, we decided to be more inclusive of people with different perspectives and experiences of the Alaskan environment, including Alaska indigenous peoples, local community members, policy makers, and students. To date, we have recorded over 60 conversations that include findings from science collaborations, experiences of women in science, different perspectives on changes in the Alaskan landscape, climate change and policy, and some indigenous perspectives. Consent and trust are at the core of Alaska Voices, wherein a participant

may retract a conversation at any point. The conversations were edited from 40 minutes to 5-8 minutes by a culturally sensitive audio producer (Kelsey Skonberg) who collaborated with the participants in the editing process. The stories have been shared via our website (www.alaskavoices.org), other podcasts, and a 6-episode series on local public radio. The stories have reached national and international audiences. Through Alaska Voices, we have observed the power of storytelling and conversation for learning about different scientific findings in an engaging way and different perspectives on environmental change, while experiencing each other as whole people. Stories are powerful for the storytellers, the facilitator, and the listener. Conversation and storytelling allow space for nuance, connection, and inclusivity that is often lost in traditional scientific communication

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Towards a Standardization of Soil Cryogenic Structure and Cryostructure Terminology for the Field Description of Permafrost-Affected Soils

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Freeze-thaw processes and ice segregation in permafrost-affected soils result in unique structures of soil aggregates (cryogenic soil structure) and ice (cryostructures). The morphology of these soil and ice structures together give important clues to soil formation, hydrology, and ecosystem function. However, in the soil science literature and USDA standardized soil field sampling procedures, there is yet to emerge a standardized scheme for describing both soil cryogenic structures and cryostructures in individual horizons which can be utilized in the morphological description of permafrost-affected soils. Here, we outline one potential standardized scheme for describing both cryogenic soil structures and cryostructures for use in soil morphological descriptions. We propose rules for standardizing the unification of these descriptions that align with both the cryostratigraphic literature and established standards for the field description and sampling of soils.

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Towards a Revised Version of the Glossary of Permafrost and Related Ground-Ice Terms

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The Glossary of Permafrost and Related Ground-Ice Terms has been an essential reference for the Canadian and international permafrost community for more than three decades. It was authored by the Permafrost Subcommittee of the Associate Committee on Geotechnical Research of the National Research Council of Canada and first published in 1988. The IPA's Multi-language Glossary, virtually unchanged with regard to terminology, was compiled in 1998 and revised in 2005 by Robert van Everdingen. An edited version of the latter is available on-line as part of the Cryosphere Glossary at the US National Snow and Ice Data Center. The Permafrost Terminology Action Group (PTAG) of the Canadian Permafrost Association was formed in January 2021 to update the glossary. Most of the 400 existing entries are based on knowledge and usage from 1988 or earlier. Using a consensus-based approach, these entries and their associated definitions, comments, and references are being systematically reviewed in relation to current use and their suitability for controlled vocabularies and ontologies. Significant advances, reflecting the explosive growth in permafrost research over the past 30-40 years as well as the increasing diversity of scien-

tific disciplines involved, underline the need for a revision. An illustrated plain-language version, focusing on key terms, will also be developed for use in education and by non-specialists and the media. The members of PTAG are reviewing the formulation of each term, its definition, the associated comment and references. PTAG is committed to operating transparently, and all changes will be traceable. Certain terms may be removed because they have been superseded or are formulated as phrases, whereas more than 40 new terms are under consideration. Suggestions for additional permafrost-related entries or for revisions to existing terms are welcome. Over the next three years, proposed revisions and their justifications will be disseminated for comment to the permafrost community and to those in cognate disciplines with the goal of obtaining the widest possible acceptance. The revised version of the glossary and the plain-language version are planned for completion prior to the International Conference on Permafrost to be held in Whitehorse in 2024

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An Interactive Website to Visualize and Communicate How the Arctic is Changing

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The Arctic, comprising the tundra and boreal biomes, is warming more rapidly than anywhere else on the planet, prompting scientific endeavors to increase in recent years. As the body of scientific knowledge continues to grow, so too does the challenge of communicating these findings. This is of particular concern because changes in the Arctic will have implications on local, regional, and global scales. Despite far-reaching implications, most people who live in lower latitudes are unaware of the state of the Arctic or how rapidly it is changing. To increase awareness of the rapidly changing Arctic, scientific information needs to be shared beyond academic publications into compelling stories that resonate with broader audiences. To this end, we created a science communication and data visualization website using the Esri Hub platform. We combined compelling photos of the Arctic with informative maps and statistics to showcase how climate change is affecting Arctic ecosystems, permafrost, fires, and carbon. We include interactive mapping applications that encourage users to engage with the data more effectively by, for example, comparing the rate of warming in their location to that in the Arctic region. The website is designed to engage different types of audiences, including the general public, students, policymakers, and media. In addition to the clear language and emphasis on visuals that will resonate with the general public, we include maps with long-term monitoring of key variables for geospatial specialists and other scientists, and we distill complex information into stories that are relevant to policymakers. In the future, we plan to expand our community and data availability components to include two-way information sharing and comprehensive data sets. Our site provides broad audiences with engaging information and helps them to better understand the Arctic and the local to global impacts of climate change in the North.

Polar Explorer: An Immersive Virtual Learning Environment that Teaches Students about the Impacts of Thawing Permafrost on Society

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Lisa Thompson *University of Arizona*
Ariel Anbar *Arizona State University*
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Kevin Schaefer *University of Colorado Boulder*
Geoffrey Bruce *Arizona State University*
Joseph Tamer *Arizona State University*
Victor Leshyk *Northern Arizona University*

Scientists at Northern Arizona University, Arizona State University, the University of Arizona, and the University of Colorado at Boulder recently received funding from the National Science Foundation to develop a new digital learning environment called Polar Explorer. Through innovative learning design and virtual reality technologies, Polar Explorer will provide a novel and transformative approach for improving STEM education. It will cultivate a sense of curiosity and connection-to-place and will generate new knowledge about STEM teaching and learning. Polar Explorer will consist of a suite of Learning Experiences (LXs) built around interactive Virtual Field Trips (iVFTs), connected via a high-resolution rendered landscape generated from real Arctic terrain data. Seven place-based LXs will teach students about permafrost dynamics, indigenous perspectives on changing landscapes, and impacts of permafrost thaw on infrastructure, climate, and human health. Students will have autonomy in choosing their learning path through the LXs, which will leverage virtual reality technology, an engaging narrative, real scientists, and real-world data and places to provide context to student learning. An intelligent tutoring system will individualize the student experience and help address conceptual gaps in knowledge. Polar Explorer's iVFTs will effectively promote active, inquiry-based learning and resolve the substantial accessibility challenges inherent to polar science. It is predicted that students will 1) increase their polar science disciplinary knowledge, 2) learn to recognize and work across multiple scales, and 3) improve their comprehension of transdisciplinary connections in polar science. Polar Explorer will run on HTML5 and target students in critical undergraduate introductory STEM courses, such as geology, earth science, climate, and biology. This project will also provide much-needed metrics on the degree to which iVFTs and adaptive digital learning environments, and the associated approach to learning design, promote STEM learning.

Holocene Thermokarst Lake Dynamics in Northern Interior Alaska: The Interplay of Climate, Fire, and Subsurface Hydrology

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Mark Shapley *University of Minnesota*
Bruce Finney *Idaho State University*

Thermokarst processes in permafrost landscapes often lead to widespread lake formation, and their spatial and temporal evolution reflects the combined effects of climate, ground conditions, vegetation, and fire. This investigation of thermokarst lake sediments of Holocene age from the southern loess uplands of the Yukon Flats includes bathymetry and sediment core analyses across a water depth transect. The sediment core results, dated by radiocarbon and 210Pb, indicate early basin development through inferred thermokarst processes followed by permanent onset of finely laminated lacustrine sedimentation at deepest water depths by ~8,000 cal yr BP. Thermokarst expansion to modern shoreline configurations continued until ~5000 cal yr BP and may have been influenced by increased fire. Between ~5000 and 2000 cal yr BP, the preservation of fine laminations at intermediate and deep-water depths indicates higher lake levels than present. At that time, the lake likely overflowed into an over-deepened gully system that is no longer occupied by perennial streams. By ~2000 cal yr BP, a shift to massive sedimentation at intermediate water depths indicates that lake levels lowered, which is interpreted to reflect a response to drier conditions based on correspondence with Yukon Flats regional fire and local paleoclimate reconstructions. Other contributing mechanisms include the possible influence of catastrophic lake drainages on down-gradient base-flow levels that may have enhanced subsurface water loss, although this mechanism is untested. Comparison with regional paleoclimate trends indicates that after thermokarst lakes formed, their size and depth has been affected by North Pacific atmospheric circulation in addition to the evolution of permafrost, ground ice, and subsurface hydrology. Results provide a framework for future investigations of paleoclimatic signals from similar lake systems of thermokarst origin, which characterizes large regions of Alaska and Siberia.

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Seasonal Freeze-Thaw Dynamics under and around Streams in the McMurdo Dry Valleys, Antarctica

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Thaw of streambeds and ground adjacent to streams provides the opportunity for hyporheic exchange and related biogeochemical cycling in permafrost landscapes. However, there are few direct examples of thaw and freeze dynamics in these systems. Here we present data and findings from novel subsurface sensor arrays that measure temperature, salinity, and soil moisture under and adjacent to glacial meltwater streams in the McMurdo Dry Valleys, Antarctica. Streams flow for 8-12 weeks per year and hyporheic zones represent critical locations of nitrogen storage and rapid weathering in these ecosystems. For example, we find that the subsurface directly under streams, hyporheic zones are more consistently thawed during the flow season than lateral subsurface locations. We also note that lateral locations tend to have higher salinity, on average, than locations directly under streams. These findings help us to constrain the extent to which hyporheic processes can contribute to downstream evolution of water quality and biogeochemical fluxes to downstream parts of the ecosystem.

The Lake Agnes Rock Glacier as a Climate Resilient Cold-Water Reservoir Within the Colorado Front Range

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Daniel McGrath *Colorado State University*

In Colorado, rock glaciers vastly outnumber traditional ice glaciers and cover a larger spatial extent, suggesting that they may contain a larger volume of ice than glaciers themselves. In certain basins, the reduced climate sensitivity of rock glaciers and their sustained cold-water input to mountain streams will likely provide a refuge for cold-water aquatic species in a warming climate. The Lake Agnes rock glacier is a transitional rock glacier located in the Never Summer Mountain Range of northern Colorado, and ranges from 3260 to 3520 m asl. This study incorporates geophysical, hydrochemical, and remote sensing data from summers 2019, 2020, and 2021 to quantify the hydrologic contribution to late-season streamflow, ice presence, and the displacement rate of the Lake Agnes rock glacier. Hydrochemical results (pH, temperature, ion concentrations, δ18O) of stream samples distinguish between rock glacier, non-rock glacier, and mixed source streams, with an increase in proportion of late season basin outflow from rock glacier-fed sources. Geophysical surveys in the upper portion of the rock glacier indicate ice presence and suggest an active layer depth of ~3 m. Photogrammetric analysis indicates that the upper, active part of the rock glacier is moving at a rate up to ~20 cm/year, though the lower lobe remains inactive. Comprehensive characterization of the Lake Agnes rock glacier is a first step in understanding the role of rock glaciers in alpine basins within northern Colorado, features which are an often-disregarded component of the alpine water budget.

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Modeling Arctic Lakes with the LAKE2.0 Model

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Lakes in the Arctic are important reservoirs of heat with much lower albedo and larger absorption of solar radiation than surrounding tundra vegetation. Under climate warming scenarios, we expect Arctic lake heat balance to shift, thawing underlying permafrost. Previous studies of Arctic lakes have focused on ice cover and thickness, the ice decay process, catchment hydrology, lake water balance, and eddy covariance measurements, but little work has been done in the Arctic to model lake heat balance. We applied the LAKE model to simulate water temperatures in three Arctic lakes in northern Alaska over several years. The LAKE model is a one-dimensional finite-difference model that explicitly solves vertical profiles of water state variables on a finite-difference grid, using a k-ε parameterization to calculate turbulent fluxes. We used a combination of meteorological data from local and remote weather stations, as well as data derived from remote sensing, to drive the model. We validated simulated water temperatures with data of observed lake temperatures at several depths. Our validation of the LAKE model completes a necessary step toward modeling changes in Arctic lake ice regimes, lake heat balance, and thermal interactions with permafrost.

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Hydrogeology and Permafrost Dynamics of a Degrading Lithalsa Near Umiujaq (Nunavik, Canada): Insights From Long-Term Monitoring

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Nathan L. Young *Laval University*
Michelle A. Walvoord *US Geological Survey*
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Simulations of climate-driven permafrost degradation typically consider simple or idealized groundwater conditions due to the limited availability of hydrogeologic data in permafrost environments. However, in order to better understand the evolution of these highly non-linear systems, and to properly characterize the impact of groundwater flow on permafrost degradation, robust cryohydrogeological conceptual models are needed. This study uses long-

term, high-temporal-resolution observations from an extensive network of monitoring equipment to characterize the thermal and hydrogeological regimes of a permafrost mound located in the discontinuous permafrost zone near Umiujaq (Nunavik, Canada). This instrumentation includes thermistor cables, groundwater monitoring wells, temperature and water content sensors in the active layer, heat flux plates, and a snow cover monitoring system. Data indicate that ice-rich permafrost is restricted to a 15-m-thick unit of marine silt, which is overlain by a 4-m-thick layer of sand. The active layer encompasses the full extent of the surficial sand layer, as well as the top 2 m of the silt unit. Depending on climatic and surficial conditions, the furthest extent of the freezing front in a given year may not reach the permafrost table, resulting in the formation of a sporadic talik between the active layer and the permafrost table. Data further indicate that the surficial sand layer acts as an unconfined aquifer, and that infiltrating precipitation flows downward to the permafrost table before flowing radially toward the sides of the mound. A downward hydraulic gradient was observed across the low hydraulic conductivity silt unit. These observations were synthesized into a cryohydrogeological conceptual model to provide insight into the physical processes that govern local permafrost dynamics at the study site in order to guide future field campaigns and modelling projects.

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Impact of Lateral Groundwater Flow on Hydrothermal Conditions of the Active Layer in a High Arctic Hillslope Setting

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The hydrothermal state of the active layer in permafrost landscapes is largely influenced by the presence of water. It greatly influences vertical conduction and advection of heat in areas with little topography. In a hillslope system, lateral water transport introduces additional effects on the hydrothermal state of the subsurface through water and moisture redistribution along the hillslope. In a semi-generic modeling study, we analyze the effect of groundwater flow in two hillslopes (steep and medium) in a high Arctic setting in comparison to a flat control case. We find that ground temperatures within the active layer uphill are generally warmer than downhill in both slopes (with a difference of up to 0.8°C in the steep, and 0.6°C in the medium slope). Further, the slopes are found to be warmer in the uphill section and colder in the base of the slopes compared to the flat control case. As a result, maximum thaw depth increases by about 5 cm from the flat (0.98 m) to the medium (1.03 m) and the steep slope (1.03 m). Uphill warming on the slopes is explained by overall lower heat capacity, additional energy gain through infiltration, and lower evaporation rates due to drier conditions caused by subsurface runoff. The major governing process causing the cooling on the downslope side is heat loss to the atmosphere through evaporation in summer and enhanced heat loss in winter due to wetter conditions and resulting increased thermal conductivity. On a catchment scale, these results suggest that temperature distributions in sloped terrain can vary considerably compared to flat terrain, which might impact the response of subsurface hydrothermal conditions to ongoing climate change.

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Measurement and Modeling of Wildfire-Initiated Talik Development in Boreal Alaska

David Rey *US Geological Survey*

As the Arctic warms and wildfire occurrence increases, talik formation in permafrost regions is projected to expand and affect the cycling of water and carbon. Yet, few unified field and modeling studies have examined this process in detail, particularly in areas with cold mean annual air temperatures. We address this gap by presenting multimethod, multi-seasonal geophysical measurements of permafrost and in situ liquid-water content that reveal substantial talik development in response to recent wildfire in continuous permafrost of boreal Alaska. Results from observation-based cryohydrogeologic model simulations suggest that pre-disturbance subsurface conditions are key factors influencing thaw response to fire disturbance and air temperature warming. Our high-resolution integrated study illustrates enhanced vulnerability of boreal continuous permafrost, with observed talik formation that exceeds coarse-scale model projections by ~100 years even under the most extreme future emissions scenario. Results raise important scaling questions for representing extreme permafrost thaw phenomena of growing widespread importance in large-scale predictive models.

Hydrologic Implications of Supra-Permafrost Taliks in Disturbed Landscapes of Boreal Alaska, USA

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Recently, there has been focused attention on the development of supra-permafrost taliks (perennially unfrozen zones in permafrost) that follows active-layer thickening in the sequence of top-down permafrost-thaw progression in high latitudes. Talik formation can substantially influence geomorphic, hydrologic, and biogeochemical processes in permafrost landscapes, thus motivating efforts to understand current talik distribution and provide constraints on future evolution under changing climate. Here we present examples of talik formation in contrasting field sites in upland and lowland boreal forest ecoregions in interior Alaska, USA. Sites are located near the broadly mapped transition between continuous and discontinuous permafrost. Multiple lines of geophysical data provide support for enhanced talik development in response to disturbance, including wildfire and ice jam river flooding, superimposed on atmospheric warming. Drawing from results of cryohydrogeologic model simulations, field measurements, and additional analytical assessments, we discuss hydrologic implications for talik development and permafrost thaw acceleration at our contrasted sites. We identify and explore landscape characteristics and initial thermal conditions that control the propensity for talik development. Field investigations show localized examples of rapid talik development that outpace current coarse scale talik projections under the most extreme greenhouse gas emission scenario by ~ 100 years. Though large-scale extrapolation of localized extremes is not advised, our research raises questions regarding the potential for aggregated localized thaw to evolve toward regional importance as widespread wildfire activity and flooding intensify in the future.

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Are Concentration-Discharge Relations in Arctic Rivers Different from Temperate Rivers?

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Despite the impact of solute exports from the six largest Arctic rivers on the biogeochemistry of the Arctic Ocean and its surrounding ecosystems, the long-term relationships between concentration and discharge from these river systems have been sparsely studied. Relationships between solute concentrations and river-discharge are important controls on intra-watershed transfers and exports of materials. In temperate watersheds, most geogenic (water-rock interaction controlled) solutes behave chemostatically (e.g., the log concentration versus log discharge patterns follow a near zero slope). Sufficiently long hydrological residence times are critical to this behavior, enabling kinetic source limitations to be overcome, as well as activation and mixing of different hydrological stores during wet up. Permafrost environments have not been well studied in a chemostatic context, but because permafrost limits deep groundwater flow paths and hydrological storage, chemodynamic (flushing or dilution) and non-systematic (high coefficient of variation ratio) behaviors may be dominant. We analyzed concentration-discharge data for twenty solutes from the six largest Arctic rivers using the Arctic Great Rivers Observatory (ArcticGRO) database. We found that, while chemostatic behavior is common, chemodynamic behavior frequently occurs for both geogenic and non-geogenic (e.g., nitrate and dissolved organic carbon) species. We also found many differences in the distribution of chemostatic, chemodynamic, and non-systematic behaviors between the different rivers, suggesting that physical and biogeochemical attributes of these basins controlling concentration-discharge vary substantially. This study provides an important baseline for comparison to other Arctic streams and rivers. In addition, by establishing the current trends of concentration-discharge relations we can monitor Arctic rivers for future changes that might occur through further permafrost degradation or other anthropogenic perturbations.

Long-Term (2000-2017) Response of Lake-Bottom Temperatures and Talik Configuration to Changes in Climate at Two Adjacent Tundra Lakes, Western Arctic Coast, Canada*

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Lakes are principal agents of disturbance to permafrost. Key variables which control these thermal disturbances are permafrost temperature, lake size, and lake-bottom temperature. Many Arctic lakes are shallow and well-mixed. Consequently, the lake-bottom temperature is closely associated with atmospheric conditions in summer. In winter, thermal regimes of the atmosphere and lake-bottom are distinct until the water column freezes to depth. Canada's western Arctic has experienced considerable climate change since 1970, dominantly in autumn and winter. Mean annual air temperatures at Inuvik, Northwest Territories, increased from -9.7 °C to -6.0 °C between 1960-69 and 2010-19. We present long-term measurements of lake-bottom temperatures at two adjacent tundra lakes near the western Arctic coast to determine responses in lake thermal regime to climate variation. Temperatures have been monitored on shallow near-shore terraces and in deep central pools between 2001-10 for one lake and 2000-17 for the other. In total, there are 25 lake-bottom-years for shallow water and 17 for the central pools. Air temperatures have been reconstructed from several years of monitoring and with reference to records at Tuktoyaktuk, Northwest Territories. Annual mean lake-bottom temperatures have varied (2000-17) between -5.7 and 2.8 °C in shallow water and between 1.1 and 4.5 °C in the deep central pools. Annual mean air temperatures have varied between -11.2 and -6.8 °C in the same period. The coefficient of determination (R2) between seasonal thawing degree-days at the lake bottom and in the air for three shallow sites ranged between 0.85 and 0.94. For two deep sites, comparable values are up to 0.79. For seasonal freezing conditions, R2 ranged up to 0.21 for shallow and had no correlation at deep sites. The data suggest that the greatest effects of climate change on lake taliks will likely occur through adjustments to permafrost in the littoral terraces of tundra lakes.

***For full text, see *Permafrost 2021: Merging Permafrost Science and Cold Regions Engineering*, American Society of Civil Engineers. https://ascelibrary.org/doi/epdf/10.1061/9780784483589**

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The Uncertainty in Insar-Based Active Layer Soil Water Storage Estimates over the Arctic Foothills

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Recent studies show that groundwater flow through the topmost portion of permafrost soil, known as the active layer, has a significant contribution to the export of carbon in permafrost terrain. Because the Arctic covers continent-sized areas that are mostly inaccessible, remote-sensing has become a critical tool for observing continuous permafrost. Particularly, the density difference between liquid water and ice causes seasonal ground surface deformation that can be detected over large spatial scales using Interferometric Synthetic Aperture Radar (InSAR). Here, we analyzed L-band ALOS PALSAR scenes acquired between June and October from 2006 to 2010 (Path 255, Frame 1370-1380) near Toolik Lake and solved for the seasonal thaw subsidence and frost heave associated with the active layer freezethaw cycle. We confirmed that the maximum thaw subsidence is proportional to the total soil water content in the active layer using in situ measurements of the hydraulic properties and stratigraphies at over 200 sites across the Arctic foothills. We found that the average seasonal thaw subsidence increases along a geomorphic-ecohydrologic transect starting with heath vegetation on the drier ridgetops, transitioning into tussock tundra on hillslopes, and draining into lowland riparian zones with wet sedge tundra. We also quantified the uncertainty in the InSAR measurements. We found that the misregistration between the Arctic DEM and a subset of SAR images

leads to a DEM error in InSAR phase measurements. This is the dominant error source in the ALOS Toolik InSAR data, particularly in areas with large slope angles (> 7.5%). We developed a mitigation strategy, that reduces the uncertainty in the InSAR-based soil water estimates from > 20 cm to < 10 cm. Our study suggests that InSAR has greater observational capabilities than previously assumed for monitoring changes in hydrological and ecological characteristics above continuous permafrost and estimating large-scale soil moisture.

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Simulating Arctic Hydrology with WaSiM

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Climate change leads to rapid landscape change in the Arctic regions. Many aspects of those changes are related to hydrological processes. Arctic landscapes are dominated by ice where it is present in many forms from snow to glaciers and below ground with a variety of ground ice present in permafrost. All the ice depends on cool atmospheric conditions to remain frozen, but in many cases that is currently changing. Ice can be considered long-term storage in the Arctic hydrological system and the water is often decades to centuries old.

Ground ice degradation leads to changes in the topography resulting in modified surface runoff and watershed response to precipitation events. Surface water changes due to permafrost collapse both as the water accumulates in thermokarst pits or lake drainage due to thermal erosion events. Snow is of particular importance as the feedback to subsurface temperatures is strongly dependent on snow depth and density. With warming conditions also comes a change in vegetation and its effects on active-layer temperatures and double feedbacks related to snow trapping as the shrub advance continues in the Arctic.

Over the past years we have made progress in the development of the water Balance Simulation Model (WaSiM) toward an Arctic hydrological simulation model. Some of the highlights are soil temperature with freezing and thawing, snow temperature in the snow pack, efficient surface runoff, snow distribution variability, and soil surface temperature effects of vegetation through n-factors. We are currently working on the development of a dynamic soil surface collapse module based on known ground-ice content and warming conditions. Surface vegetation conditions are dynamic and simulated by the Arctic Vegetation model (ArcVeg). We are implementing feedbacks from ground-ice melt to soil surface collapse affecting surface runoff, local drying and wetting effects on the vegetation. Secondary affects are also considered through preferential snow accumulation in troughs and shrub establishment.

The model is centered on hydrology, and it is therefore uniquely suitable for the simulation of processes on a watershed scale. It is highly efficient and can be used on a high-resolution grid that includes the processes of ice wedge polygon collapse and preferential snow accumulation on a meter scale. In our developments, we focus on the most important hydrological events in Arctic watersheds.

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The Thermal Response of Permafrost to Coastal Flooding

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Permafrost warming is projected everywhere in the Arctic. Increases in air temperature directly drive permafrost warming, but flooding also indirectly contributes to permafrost warming by changing the surface reflectance of solar insolation. For example, more shortwave radiation is more likely to be absorbed when the ground is inundated. Historical data show that coastal regions of the North Slope of Alaska experience frequent flooding events due to spring snowmelt, summer storms, river ice-break-up, and Arctic Lake drainage. However, the impact of flooding on permafrost in the continuous permafrost environment has not been tested and remains poorly understood. To address this knowledge gap, we used a combination of available flooding data on the Ikpikpuk delta and a numerical model of permafrost conditions. We first constructed the four most common flood events based on water level data on the Ikpikpuk: high spring snowmelt flood, equally distributed flooding events over the whole summer, early-summer floods, and late-summer floods. The impact of these flooding events on permafrost was simulated on one-dimensional permafrost columns using the Advanced Terrestrial Simulator (ATSv1.0) fully coupled permafrost-hydrology numerical model. The results of our simulations show the extent of permafrost thaw and active layer deepening depend on the timing, duration, and frequency of flood events. Preliminary results suggest that shorter and more frequent summer flood events have a greater effect on permafrost thaw than longer snowmelt-driven floods.

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Spatial Distribution and Temporal Dynamics of the Suprapermafrost Subarial Taliks in Eastern Siberia

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The research aims at the assessment of the spatial distribution and temporal dynamics of subaerial suprapermafrost aquifer taliks in Central Yakutia, Eastern Siberia, using geophysical methods, drilling, and geothermal and hydrogeological monitoring. Subaerial suprapermafrost taliks are not anticipated in the continuous permafrost zone and extreme continental climate of Central Yakutia. We revealed a relatively high proportion of the suprapermafrost subaerial taliks on a small catchment of the Shestakovka river near Yakutsk and in the western part of the region between the Lena and Viluy rivers. The thickness of the seasonally frozen layer above the taliks is 1.7-3 m, and the thickness of the thawed layer is 3-20 m. The depth of zero annual amplitudes is 5-6 m, and the temperature at the depth of zero annual amplitudes is 0 °C. Taliks could include several thawed troughs oriented along the slope where water filtrates down the slope. In winter, taliks break up into separate closed water-saturated thawed areas and the talik water level can be higher than the surface due to the cryogenic pressure. In the warm period taliks, groundwater, and water of the active layer form a single aquifer. The seasonal dynamics of the spatial distribution of taliks is more pronounced than the interannual ones. An approximate assessment of the suprapermafrost taliks fraction in the western part of Central Yakutia using GPR methods and key sites can be more than 6% only due to the subaerial taliks. This estimate does not include lake and channel taliks and is at least one and a half times higher than the previously published estimates. Suprapermafrost subaerial aquifers taliks can be used as a year-round source of water supply.

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Hydrologic-Land Surface Modelling of the Canadian Sporadic-Discontinuous Permafrost: Initialization and Uncertainty Quantification

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Permafrost is a critical feature in cold regions that significantly impacts hydrological processes, energy flux partitioning, plant communities, and carbon dynamics. Permafrost thaw has been observed in recent decades in the Northern Hemisphere and is expected to accelerate with continued global warming. Predicting the effects of climate warming on permafrost requires proper representation of the surface/subsurface thermal and hydrologic regimes. Land surface models (LSMs) are well suited for such predictions, as they couple heat and water interactions across soil-vegetation-atmosphere interfaces and can be applied at large scales. However, the long-term thermal and hydraulic memories of permafrost pose a major challenge for modelling. Historical records are too short to represent these dynamics under transient climate conditions; hence model initialization is problematic. Moreover, the significant interactions among the underlying processes in LSMs for model validation add further difficulty for model development. This study addresses the challenge of model initialization by characterizing the impact of initial climate conditions and initial soil frozen and liquid water states on the simulation length required for model warm-up.

Further, we quantify how the uncertainty in model initialization propagates to simulated permafrost dynamics. We report model experiments conducted with the Modélisation Environmentale Communautaire – Surface and Hydrology (MESH) modelling framework and its embedded Canadian Land Surface Scheme (CLASS) to investigate permafrost simulations for sporadic and discontinuous permafrost regions. The study area is in the Liard River basin in Canada's Northwest Territories, where soil temperature/texture profiles are available at two sites. Results confirm that uncertainty in model initialization dominates the simulated permafrost attributes, especially the active-layer thickness, which can change by 1-1.5m depending on the initial condition chosen. The least spin-up time to reach equilibrium was achieved with initial soil moisture near field capacity. We advise an extended spin-up of 200-1000 cycles to ensure proper model initialization under different climatic conditions and initial soil moisture contents.

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Fine-Resolution Measurement of Soil Moisture from InSAR Phase Closure

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Acquiring high-resolution soil moisture data over large swaths of remote permafrost-covered areas is difficult due to the high cost of manual coverage and relatively coarse resolution of spaceborne passive radiometric observations. Here we test how well fine-resolution interferometric synthetic aperture radar (InSAR) phase closure measurements match in situ soil moisture data. Phase closure refers to the net phase when linking three interferograms formed from three acquisitions so that the net phase in single-look interferograms is zero. The phase closure often becomes nonzero when regions of pixels are averaged spatially (in multi-looked images) before the net phase is computed. Here we show cases in which the discrepancy in phase closure corresponds to changes in soil moisture. Our data reduction approach includes an integration of the phase closure over time and subtraction of a random walk component to relate the differential phase values to soil moisture level. We find that for a large, simple test region of Oklahoma, the integrated phase closure using Sentinel-1 data tracks the soil moisture observed in the field. We also analyze results from a more complex region of permafrost in Alaska, with less straightforward results. In other cases, the match is less than good. If we can determine under what circumstances the InSAR measurements provide a good match to soil moisture, we have a potentially valuable utility to remotely estimate soil moisture at high resolution in remote permafrost areas.

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Modelling Water Release from Degrading Permafrost in Arid Mountain Environments

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Numerical cryo-hydrogeology models can be useful tools for understanding thermal and hydrological feedbacks that influence water flow in periglacial environments. With climate change expected to modify permafrost distribution globally, there is growing interest in developing such models for planning purposes, particularly in arid mountainous environments where headwaters can be important water sources to downstream users. In the arid Central Andes, permafrost is ubiquitous and debated as a possible resource to moderate water scarcity under climate change and drought. At many locations in the region, permafrost is in disequilibrium with existing climate and therefore expected to degrade even if current air temperatures are maintained. The coupled finite element codes TEMP/W and SEEP/W were used to explore a range in hydrologic outcomes from degrading permafrost within a typical watershed for such an arid region, subject to a suite of characteristic permafrost distribution, ground ice content and hydrogeologic conditions. A 3-km-long 2D cross-sectional numerical model was developed using simplified

topography (altitude up to ~6000 m), and ground temperatures representative of the region. The model uses constitutive relationships that consider conductive and advective heat transport, as well as unsaturated water flow and includes surface boundary conditions derived from local monitoring data. Predictive simulations were performed to estimate changes in water quantities and flow-paths should current temperature conditions in the watershed persist. Preliminary results for a continuous permafrost case suggest an overall decrease in downstream discharge as ground ice thawed. As permafrost degraded laterally and the active layer thickened, supra-permafrost water migrated downward through the unsaturated zone toward the regional ground-water system. It is noted that these results are strongly subject to the assigned initial conditions and simplified topography. Future efforts will explore scenarios with more complex landform topography and permafrost distribution, under climate change influences.

Quantification of Permafrost Degradation Using Calibrated 4D-ERT and Consequent Deformations in Alpine Bedrock

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Slope failure from warming permafrost rockwalls is a hazard in alpine environments. For assessing the instability of permafrost-affected rockwalls, quantitative monitoring techniques are necessary to repeatedly and spatially measure permafrost distribution and link this with rock kinematics. We applied 4D laboratory-calibrated Electrical Resistivity Tomography along five parallel transects combined with mechanical deformation measurements using a tape extensometer across a permafrost-affected rock ridge in the Swiss Alps between 2006 and 2021. Resistivity of saturated field samples was calibrated in a freezing chamber ranging from 20°C to −3°C. Resistivities above 13.25±1.75 kΩm indicated frozen rock. A 3D inversion was applied to field data, and the frozen volume was calculated by mesh filtering and integration (Scandroglio et al., 2021). All inversions confirmed a drastic degradation in the last 13 years with up to 65% less permafrost volume, well in agreement with the recorded air temperature increase. Inversion settings influenced the volumetric estimation on average by ±10%. The largest permafrost degradation was obtained without time-lapse constraints, and data error estimation had a strong influence on results. Resistivity trends in the active layer show good correlation in time and space with kinematical changes recorded on the surface. Clear patterns could be distinguished between different slope orientations; while the summit of the ridge suffered small or no changes, the south slope showed important consistent deformations. Our applied techniques enable an accurate quantification of permafrost degradation dynamics and show that this is in strong connection with rock kinematics. Therefore, they are a key tool in alpine permafrost rockwalls for detection of hazards that are likely to be enhanced by future global warming.

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Sedimentological Investigations at the Hickory Run Boulder Field, Carbon County, Pennsylvania

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Boulder (block) fields are open-work clast accumulations that occupy low-sloping surfaces. These features are thought to be the result of periglacial (cold, but nonglacial) mass-movement processes, many of which were active during the Last Glacial Maximum (~20-12 ka). There are two diverging hypotheses for the formation of boulder fields in both current and former cold regions. The periglacial interpretation emphasizes repeated cycles of mechanical weathering (e.g., freeze-thaw cycling and frost shattering) and periglacial mass movements (e.g., frost creep and gelifluction). Non-periglacial hypotheses emphasize weathering during the warmer and wetter conditions of the Neogene (~23-2.5 ma). The Hickory Run Boulder Field (HRBF), located in northeastern Pennsylvania, is the largest feature of its type in the eastern United States. The research presented here uses relative weathering indices (clast dimension, fabric, and hardness) collected at the HRBF to investigate its geomorphic origins. Preliminary analyses of weathering indices show significant trends with distance downslope from local bedrock outcrops. Fabric analysis revealed the dominance of clast long-axis orientation parallel to the local slope, indicating a flow-type depositional environment. The size (120 x 550 m) and proximity (~1.5 km) of the HRBF to the Wisconsin glacial border and results of relative weathering indices support a periglacial interpretation for the formation of this striking boulder field.

Identifying Slope Instability in Mountain Permafrost Terrain: A Case Study in Colorado and Alaska

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Climate change and associated air temperature warming continues to offset equilibria in nature, including permafrost affected mountain slopes. Studies have shown an increase in the magnitude and frequency of mass movements in periglacial environments that are attributed primarily to permafrost degradation. Permafrost thaw-induced weakening of bedrock and colluvium poses a threat to human lives and critical infrastructure in periglacial environments. We aim to determine mechanisms of slope destabilization triggered by permafrost degradation and map thaw-vulnerable slopes to constrain the timing of future mass movement events. This study comprises two phases. First, we developed a GISbased 3-D virtual model for landslide susceptibility in the San Juan Mountains (SJM). We applied a weighted-overlay method integrating six terrain variables: slope angle, slope length, aspect, lithology, vegetation, and soil drainage. This 3-D model was enhanced with a surficial-landform map constructed at a scale of 1:5,000. Our findings indicate that 1) aspect, slope, and geology have the greatest relative influence on slope failure, 2) east- and west-facing slopes are highly susceptible to landslides, 3) class 2 slopes (22.01°- 44°) are highly susceptible to landslides, and 4) talus and landslide deposits are the most widespread surficial deposits in the SJM. For the second phase of this study, we will examine how permafrost thaw may be impacting the susceptibility of mountain slopes to mass movement events in the central Alaska Range. We propose to implement the following interdisciplinary approach: 1) conduct field surveys at key road-accessible mass movements, 2) use a range of remote sensing techniques to map the location of mass movements across the study area, 3) establish a permafrost monitoring network across a suite of representative sites, and 4) integrate terrain parameters to model mountain permafrost applying the same approach used for the SJM region combined with the GIPL permafrost model.

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Mountain Permafrost in the Tropical Andes of Peru: The 0°C Isotherm as a Potential Indicator*

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In the tropical Andes of Peru, very little is known about occurrence and extent of permafrost. Only recently more systematic studies, which focus on the high elevation sites of the mountain ranges (cordilleras) in Peru, have been initiated. In the framework of the first pioneering studies, and with the objective to improve the understanding of permafrost occurrence and characteristics, including occurrence of rock glaciers, we analyze here how mountain permafrost in Peru is correlated with the altitude of the O°C isotherm (ZIA). Climate change has generated an increase in air temperature and in the ZIA. These variables are associated with the state of mountain permafrost, and any variation could cause changes in the presence of mountain permafrost. We focus on two different zones studies: The Cordillera Central (CC) and the Cordillera Volcanica (CV). The first located in the central zone and the second in the south zone of Peru. The study used air temperature data from 133 weather stations (2002-2016) to calculate the mean annual air temperature (MAAT), interpolated using a Multiple Linear Regression Model (MLRM) and digital elevation model (MERIT DEM). Occurrence and extent of 46 intact rock glaciers (IRG) and the global model of permafrost (Permafrost Zonation Index) were used to validate the results. The MAAT of CC has a minimum value around -0.6°C (R2 = 0.8) and a ZIA average of ~5152 m a.s.l. 56% of IRG are located above the ZIA. On the other hand, the MAAT of CV has a minimum value around of -4.4°C (R2 = 0.8) and a ZIA average of ~4861 m a.s.l. 60% of IRG are located above of the ZIA. The results show a greater variation of the ZIA in CC respect to CV, which could indicate a possible degradation of mountain permafrost in this mountain range.

***For full text, see *Permafrost 2021: Merging Permafrost Science and Cold Regions Engineering*, American Society of Civil Engineers. https://ascelibrary.org/doi/epdf/10.1061/9780784483589**

Accelerated Motion Rates of Frozen Debris Slopes in the Brooks Range, Alaska, USA

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The Alaska Brooks Range supports a variety of periglacial mass movement features, including rock glaciers and frozen debris lobes (FDLs); yet few studies have focused on Brooks Range slopes and movement rates. These studies include initial investigations of rock glaciers near Atigun Pass in the 1970s and 1980s – with measured surface deformation rates of 0.03 to 0.1 cm/day – and detailed field investigations and remote sensing of FDLs beginning in 2008. Typical FDL surface movement rates from 1955 into the 1970s were 0.5 cm/day, with increasing rates of movement over the last 65 years. Here we present results of preliminary satellite-based interferometric synthetic aperture radar (InSAR) analysis for 1) FDLs, 2) rock glaciers, and 3) a variety of slopes demonstrating evidence of movement expressed by transverse cracks or scarps. Using differential interferograms from L, C, and X-Band sensors from 2009 to 2017, we outlined areas of demonstrated movement with polygons in a GIS environment. We assigned characteristic movement rates based on measured displacement over the return period for a given satellite, and we corrected the movement rates for satellite line of sight. During the years for which InSAR data were available, the average rates of surface movement for FDLs, rock glaciers, and other deforming slopes were 1.5 cm/day, 0.5 cm/day, and 0.4 cm/day, respectively. This preliminary analysis indicates that both FDLs and rock glaciers are moving faster now than in the past; and rates continue to increase, with some FDLs demonstrating velocities up to 5.8 cm/day, as determined through field measurements. These trends warrant a more comprehensive investigation, such as determining the increase in spatial extent of unstable slopes with time. Such findings will help to inform public and private agencies about ongoing changes and potential hazards related to warming and degrading permafrost slopes.

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An Increase of Rockfall Activity Due to Elevation-Dependent Paraglacial and Periglacial Processes

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Rockfalls are important agents of erosion and a hazard in mountain regions. A compilation of rockfall erosion rates from the European Alps indicates that erosion rates increase with elevation. Previous studies have hypothesized one or more explanations for this relationship, such as an elevation-dependent increase in paraglacial processes such as debuttressing, or periglacial processes such as permafrost thaw or frost weathering. Herein we consider all of these processes in the first quantitative evaluation of the elevation dependency on rockfall erosion rates.

Within a glaciated alpine valley in Switzerland, we quantified the relationships between rockfall erosion rates to frost weathering, permafrost distribution, and deglaciation. We monitored rockwall thermal regime using rock temperature loggers between 2016 and 2019 and used these data to run a thermomechanical frost cracking model and a permafrost distribution model. We reconstructed glacier retreat using historical images and glacial landforms. The volumes, and equivalent erosion rates, of rockfalls between 2016 and 2019 were assessed using repeat terrestrial laserscanning. Principal component analysis demonstrated that frost weathering, permafrost distribution, and deglaciation all strongly influence the rockfall erosion rates measured. We found that erosion rates increase with increasing elevation, decreasing modelled mean annual rock surface temperature (MARST), and decreasing deglaciation age. Integrating the spatial distribution of MARST and deglaciation revealed that both periglacial and paraglacial rockfall drivers increase with elevation.

The observed spatial erosion patterns at our case-study site correspond well to our compilation of regional rockwall erosion data for the European Alps. Therefore, our data suggest that a combination of paraglacial and periglacial processes drives rockfall activity and that both exert a primary control on erosion in high mountain areas. Our research contributes new understanding of alpine rockfall processes and informs efforts to mitigate rockfall hazards in a changing climate.

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Development of Early Soviet Ideas about Cryoplanation Terrace Genesis

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Cryoplanation terraces (CTs) are underrepresented in the world geomorphological literature. This area of investigation appears to have been forgotten in contemporary Russian-language geomorphological and periglacial literature. The heyday of this topic was the period extending from the 1930s to the 1980s. It is associated with the names Obruchev, Boch, Krasnov, Bashenina, Sukhodrovskiy, Chaiko, and others who conducted field studies of these relief elements and incorporated them into process-oriented development theory. A primary source of early information are the papers of S.V. Obruchev, who described CTs in detail in his work in Chukotka and summarized both his own field materials and the accumulated experience of other scientists. Obruchev emphasized the division of genetic theories largely on terrace appearance. Here, we expand Obruchev's overview by treating theories developed during the 1940-1980 period.

Theories of terrace appearance can be divided into two main categories. The first and more archaic of these considers CTs as relics of past epochs associated with severe climatic regimes. Like many early 20th-century investigations, these interpretations were usually qualitative and not supported with substantial field data. This type of work attempted to explain observed phenomena largely through inference. Scientists attributed the formation of terraces to rivers, glaciers, and desert processes. The second category involved detailed field studies and is associated with Boch and Krasnov, Obruchev, and Suhodrovskiy. These studies involved ideas closer to the modern point of view typified in a 1969 monograph by the Czech geographer J. Demek, who worked closely with Soviet scientists. This viewpoint holds that terraces can be formed under contemporary climatic and geomorphic conditions and should simply be divided into active and non-active groupings. Terminological concerns have been the subject of controversy throughout the history of cryoplanation research. The last major Russian-language study of cryoplanation landforms was a 1985 review monograph by M. Chaiko.

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Early North American Investigations in Cryoplanated Uplands

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Cryoplanation terraces (CTs) are series of large staircase-like landforms widespread in unglaciated uplands of the world's cold regions. They are especially prominent in unglaciated Beringia and are distributed zonally in uplands between the Lena and Mackenzie Rivers. Early U.S. Geological Survey and Geological Survey of Canada investigators charged with general geological and geographical surveys of Alaska and Yukon associated with the gold rush of the very early 20th century found the characteristics of these landforms to be inconsistent with the Davisian "normal cycle of erosion," then the prevalent geomorphological theory in North America. In particular, the lack of elevational accordance, the absence of alluvium on summits, and a dearth of residual soil on level upland surfaces were not consistent with criteria specified by W.M. Davis for the recognition of peneplain remnants. The publications of the early investigators such as Prindle and Moffit in Alaska reflect the confusion generated by these contradictions. After introduction and diffusion of the nivation hypothesis (erosion by late-lying snow patches) by Matthes and the periglacial concept by Lozinsky, a unified theory of CT formation was published in 1912 by Cairnes in Yukon and, apparently independently, by Prindle in Alaska in 1913. These papers outlined hypotheses of CT development consistent with current geomorphic theory, although the landforms remained controversial for many decades. In the mid-1930s Mertie employed altimetric evidence to assert the existence of a theoretical climatically determined geomorphic surface, analogous to the climatic snowline, which slopes gently from the Alaska-Yukon border to the vicinity of the Bering Sea. Russian CT literature did not have an appreciable effect on North American thought until the publications of Boch and Krasnov in the 1940s and 1950s. In the late 1960s the Czech geographer Demek surveyed the world literature, resulting in a consistent, unified view of CT development.

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First Evidence of Rock Wall Permafrost in the Pyrenees (Vignemale peak, 3298 m a.s.l, 42°46'16" N / 0°08'33" W)

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Permafrost is a relevant component of the Pyrenean high mountains, triggering a wide range of geomorphological cryogenic processes. While in the last decades, there has been an increase in frozen ground studies in the Pyrenees, there are no specific studies about rock wall permafrost, its presence, distribution, thermal regime, or historical evolution. This work combines measured rock surface temperatures (from August 2013 to April 2016) along an elevation profile (four sites) on the north facing rock wall of the Vignemale peak (3298 m a.s.l, 42°46'16" N / 0°08'33" W), and temperature modelling (CryoGRID2), in order to ascertain the presence of permafrost and to analyze its evolution since the mid-20th century. Simulations are run with various RST forcings and bedrock properties in order to account for forcing data uncertainty and varying degrees of rock fracturing. Results reveal that warm permafrost may have existed down to 2600 m a.s.l. until the early 1980s and that warm permafrost is currently found at around 2800 m a.s.l and up to 3000 m a.s.l. Cold permafrost may exist above 3100-3200 m a.s.l. Systematic investigations on rock wall permafrost must be undertaken to refine those results in the Pyrenees. The elevation shift of warm permafrost suggests the imminent degradation of permafrost in the Vignemale peak.

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Ground-Ice Content Loss in Different Mountain Permafrost Environments Inferred from Repeated and Re-Processed Geophysical Measurements Data

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Permafrost is currently warming on a global scale including not only polar but also mountain permafrost occurrences; many of these changes are operationally documented in national permafrost networks such as the Swiss permafrost monitoring network PERMOS. However, the warming trend is not uniformly distributed, as permafrost occurs in a large variety of complex landforms with different ground-ice contents, surface material, and therefore different thermal regimes (e.g., Etzelmüller et al. 2020). Geophysical techniques have been used for a long time to spatially extend singular borehole data and add quantitative information about important permafrost properties other than temperature, such as ground-ice content. From the large variety of geophysical properties, electrical resistivity, especially, has been proven capable of accurately distinguishing between frozen and unfrozen soil due to its partic-

ular sensitivity to the presence of liquid water content. In combination with seismic P-wave velocity, quantitative estimates of ground-ice and liquid water content have been presented for several permafrost environments using co-located electrical resistivity and refraction seismic tomography data (Mollaret et al. 2020). These approaches can also be applied in a monitoring context (Klahold et al. 2021, Steiner et al. 2021), however so far only for singular and/or synthetic permafrost examples. Within a current pilot study funded by GCOS Switzerland, a focus is on the systematic archiving and reprocessing of historical geophysical measurements in permafrost regions with the aim of repeating these measurements and analyzing them in a climate context. This contribution summarizes first results of this study showing up to 20-year-long ground-ice content changes in several permafrost occurrences in the Swiss Alps.

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Mountain Permafrost in the “Ojos Del Salado” Volcano, Chile: Advances And Challenges

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The Andes Mountain range and the Atacama Puna are ideal environments for mountain permafrost and their associated landforms (i.e., rock glaciers, protalus lobe, etc.). These landforms were mapped for this study. However, during the fieldwork it was possible to identify in pits many more permafrost zones with ice content that do not present morphological expression. Therefore, it is imperative to have spatial distribution and behavior models in order to understand mountain permafrost. The Cryosphere and Water Research Laboratory (LICA) of the University of Atacama has begun measurements that allow a better understanding of the mountain permafrost surrounding the Ojos del Salado Volcano (-27.11°S,- 68.54°W). Since January 2017, the monitoring of the soil surface temperature (Sst) and at 10 centimeters depth (Dst), in altitudinal bands, at 5,000, 5,500, 6,000 and 6,500 m a.s.l., the temperature records were sampled every two hours. Additionally, studies have been carried out using geophysical surveys: ground penetrating radar (GRP), refractive seismic, and electrical resistivity tomography (ERT), in the Llano de Piedras Pomez (-27.02°S,-68.69°W) near the volcano and at 5,000 m as.l. The results show that at 5,000 m a.s.l the average temperature for the entire period was 0.1 ° C (Dst) and -2.7 ° C (Sst), and at 5,500 m a.s.l. it was -1.6 ° C (Dst) and -1.9 ° C (Sst). From the studies carried out with GPR, ERT, and seismic, it appears that the permafrost layer with ice content could be more than 50 meters deep, with a potential aquifer under this layer. Considering the presence of ice in this mountain permafrost, it is an important water reserve due to its ice content, even more so in areas where it is the only water reserve. Therefore, it is essential to advance a better understanding of the impact of mountain permafrost on the water resources available downstream.

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Surface-Based Temperature Inversion Characteristics in Dissimilar Valleys, Yukon

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There is an interfingering of elevationally controlled and latitudinal permafrost in high-latitude continental mountainous regions of Yukon, Canada. This is related to the occurrence of surface-based temperature inversions (SBIs) which significantly modify surface lapse rates (SLRs) annually. Therefore, it is essential in permafrost science to understand and quantify spatial and temporal variation in how SLRs are modified by SBIs annually. Particularly there is a need to review the modification of SLRs by SBIs on local valley-to-valley scales. In this research, we aim to identify and quantify patterns of SBI characteristics in two proximal yet dissimilar central Yukon valleys. Investigation utilizes Elevational Transect Analysis (ETA) using sensors in valley bottoms and 100 m up slope to determine in situ SLRs. Data from downscaled climate reanalysis products (GlobSim and ClimateNA) almost entirely

missed hyper-inversions which produce SLRs that range from 0.46 °C 100 m-1 to 1.2 °C 100 m-1 annually. The magnitude of these hyper-SBIs was substantially underpredicted by recent modelling of surface air temperatures in this region as SLRs were predicted to be annually a maximum of 0.1 °C 100 m-1. Furthermore, assumptions of normal SLRs in valleys above tree line were found to breakdown in this terrain, although SLRs were more gently inverted than the treed valley. Assessment of SLR variation and microclimatic variability between the valleys yielded significant relationships of SLRs with wind speed, incoming solar radiation, and surface air temperatures. Whether these relationships between microclimate and SLRs in the two valleys are causal or covariant remains unknown. Finally, from monitoring of ground and depth temperatures at each site, permafrost is present at all locations except for the south-facing slope location. Presence of hyper-SBIs frequently throughout the year alongside the south-facing aspect drove this recently conceptualized pattern of permafrost distribution.

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Surface Temperatures and their Influence on the Permafrost Thermal Regime in Steep High Arctic Rock Walls on Svalbard

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Permafrost degradation and the effect on slope stability have been studied increasingly in recent years, especially in mountainous and sub-Arctic regions. However, the thermal regime of high-Arctic rock walls is still poorly understood and a better understanding of the occurring thermo-mechanical processes is needed.

This study presents four years of rock surface temperature measurements in steep rock walls on Svalbard, comparing coastal and non-coastal settings. For evaluation, we applied the surface energy balance model CryoGrid 3, taking into account modified radiative forcing in vertical rock walls.

Our results indicate that monthly RST in coastal cliffs are increased up to 1.5 °C compared to non-coastal rock walls, which can be traced back to higher air temperatures at the coast compared to inland locations, as well as long-wave emission by relatively warm seawater. Ice coverage on the fjord counteracts this effect. Consequently, sea ice loss might lead to higher RST in coastal cliffs during winter.

We calculated a surface energy balance of both coastal and non-coastal settings. The fluxes in summer and fall show just slight differences, while they differ significantly in winter and spring, when the water body of the fjord acts as an additional energy source for the coastal settings.

In this study, we present a unique data set of rock surface temperature measurements in steep rock walls in the high Arctic. With the surface energy balance model CryoGrid 3, we can analyze the influencing factors in coastal and non-coastal settings and the associated fluxes of the surface energy balance.

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A Continental Permafrost Distribution Model for the South American Andes

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Currently, there is very limited information available on the spatial extent (horizontally and vertically) of permafrost in South America. However, as climate change has significant impacts on glaciers and associated diminishing effects on runoff during droughts, the potential role of permafrost as a substituting regulator and contributor of runoff through the thawing of potentially ice-rich ground, is controversially debated. To quantify this potential and evaluate whether permafrost degradation may even contribute to runoff, the spatial extent of permafrost in the South American Andes must be better modeled. We introduce a new continental scale probabilistic permafrost distribution model that utilizes publicly available rock glacier inventories and parameters derived from the publicly available SRTM digital elevation model. Based on more than 14,000 rock glaciers mapped by the DGA in Chile and IANIGLACONICET in Argentina, a multi-parameter analysis was completed to formulate correlations between the probability for permafrost to exist and topography related parameters, such as elevation, slope angle, potential solar radiation, aspect, latitude and longitude. We run the model on more than 3.5·109 raster points using cloud computing to cover the full, >4000 km long extent of the South American Andes. The initial output was then upscaled to a raster resolution of approximately 300 m, subdivided into five probability classes (very low, low, medium, high and very high), representing different spatial probability ranges, and cleaned by applying filters within the ArcGIS package. While the model should not be used on individual watershed scales, this new permafrost distribution model now allows users to estimate the potential extent of permafrost more accurately on a regional or national scale. For example, the model suggests that in Chile, north of 36°S, the area in which one of the five permafrost probability zones was identified covers about 5.5%. By applying the spatial probability classes used, it can subsequently be concluded that in this northern region of Chile, about 1.5 – 2.7% of the land area is underlain by permafrost.

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Topographic and Geologic Controls on Frost Weathering in Alpine Rock Walls

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Frost weathering is a periglacial process and a major control on rock wall erosion in alpine environments. To quantify climatic control by frost weathering on mountain erosion by frost weathering and potential effects of climate change on future erosion, topographic and geologic controls on frost cracking need to be unraveled. Therefore, we installed six temperature loggers along an elevational gradient ranging from 2500 to 3200 m in crystalline rock walls in the Swiss Alps and 35 loggers ranging from 1600 to 3000 m in rock walls of the North-calcareous Alps (NCA) including permafrost-affected rock walls. We used recorded rock temperature data to run thermo-mechanical frost cracking models and compare resulting simulated frost cracking to quantified fracture patterns. Our results from the Swiss Alps show the highest frost cracking occurs in permafrost-affected north-facing rock walls, which is consistent with observed fracture and rock strength patterns (Draebing & Mayer, 2021). In contrast, the model results indicate an even higher frost cracking in all south-exposed rock walls, which is contrary to measured rock properties and could be an effect of overestimated rock moisture availability in the model. Our data suggest that elevation and exposition of rock walls affects rock temperature and permafrost distribution and, therefore, controls topographic frost cracking patterns is strongly depended on elevation and exposure of rock walls, which affects temperature and permafrost distribution. As climate change potentially increases rock temperature influences this dependency, frost cracking and therefore resulting rockfall will shift to higher elevations (Draebing & Mayer, 2021). To unravel topographic effects due to aspects and geology, we are currently quantifying frost weathering patterns in the NCA combined with rock moisture measurements on south- and north-exposed rock walls in the NCA. We will also gain higher resolution in elevation dependency of frost cracking patterns towards permafrost-affected rock walls in more detail.

First Experiences from a High-Arctic, Off-Grid, Solar-Powered Time-Lapse ERT System

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After rock slope failures in the Karrat fjord of West Greenland led to a tsunami with catastrophic consequences for nearby settlements, there has been an increased focus on rock slope-related geohazards in Greenland. As part of these efforts, the Thawing Mountains project aims to improve our understanding of the thermal regime and permafrost distribution in rock slopes in the Vaigat area of central West Greenland. This talk presents the first experiences from a completely off-grid, solar-powered Electrical Resistivity Tomography (ERT) system installed in the summer of 2021 on a basaltic plateau and vertical rock face to collect time-lapse resistivity and IP data. The purpose of the experiment is to assess the feasibility of operating such a system under remote, high-Arctic field conditions, to obtain insight into the resistivity-temperature relationship for the basaltic rocks in the region, and to evaluate to which extent such resistivity and IP datasets are useful in the evaluation of freeze-thaw processes in the rock mass. The field site is located on the northeast coast of Disko Island, on a plateau at approximately 1000 m elevation. The established profile has a total length of 160 m, with the first approximately 30 m installed down a vertical rock face. Electrodes are equidistantly spaced 2 m apart and consist of expansion bolts with a bentonite slurry to improve contact. The instrumentation is powered by solar panels with a total rating of 960 Wp connected to a battery bank of 550 Ah. The station measures daily profiles during summer but is scheduled to gradually reduce measurement frequency over the fall as daylight becomes scarce. Basic results and health data are transmitted from the station regularly over a cellular connection which also allows modification of collection settings. However, full data download will only occur upon station visits.

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20-Year Long Permafrost Evolution at the Long-Term Monitoring Site, Stockhorn, Swiss Alps, by Combining Borehole Temperature, Electrical, and Seismic Monitoring Data

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The Swiss Permafrost Monitoring Network (PERMOS) collects routinely the surface and subsurface temperatures, meteorological data, and geoelectric measurements at different sites in Switzerland to observe and monitor the state and the change of the permafrost (PERMOS, 2021). The Stockhorn plateau, an east-west oriented crest located at an elevation of around 3410 m a.s.l. in the Swiss Alps, belongs to this network. The bedrock plateau is covered by a thin debris layer (Marmy et al., 2016) and shows considerable small-scale variability with up to 1°C differences in permafrost temperatures evidenced by results from two boreholes that measure temperature since 2000 to a depth of 17m and 100m (PERMOS, 2021). In addition to standard borehole temperature monitoring, regular geoelectric and seismic surveys are performed since 2005. The particularity of this site is a continuous increase of temperatures at depth and an increase of the active layer thickness by 2m during the past twenty years. Within the uppermost ten meters, the geoelectric data show a decrease of resistivities of more than 30% in 13 years, suggesting a substantial thawing of permafrost during this period. The advantage of the additional collocated seismic measurements is the ability to quantify ground-ice content and its changes over time (Wagner et al., 2019; Mollaret et al., 2020). Coupling geoelectrical and seismic data can therefore improve the differentiation between the different phases (rock, ice, water, and air) present in mountain permafrost if suitable petrophysical relationships are used. Using this combined electrical and seismic data set, we will estimate the ground ice content losses over the past 1-2 decades and discuss the potential reasons for the pronounced spatial variability over comparatively small spatial scales.

Preliminary Interpretations from a Landslide Inventory in Interior Alaska*

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Landslides are geologic hazards that threaten human life, infrastructure, and property. To mitigate these threats, a landslide inventory map must first be developed. We present preliminary interpretations – as related to permafrost – of the first landslide inventory in the Fairbanks North Star Borough (FNSB) in Interior Alaska. The inventory was developed using Light Detection and Ranging (LiDAR) digital elevation models (DEMs), and it was validated with field checks of landslides accessible on public lands along the road system. The inventory provides a landslide spatial distribution that we can correlate to types of soil and/or bedrock, slope, aspect, and permafrost distribution. Future work will include sampling of selected landslides to determine age using radiometric dating. Without that in-depth analysis, however, we are able to determine relative age of landslides using morphology, vegetation, and cross-cutting relationships with infrastructure. Field checks indicate that most of these landslides are prehistoric (predating the first significant anthropomorphic surface changes that occurred approximately 100 years ago in Interior Alaska). Some are historic, and others exhibit on-going movement as evidenced by leaning and split trees, and fresh cracks and scarps. One currently moving landslide has a morphology and surface features characteristic of frozen debris lobes in the Brooks Range of Alaska, suggesting that movement within the permafrost is tied to temperature and water pressure. Many of the prehistoric landslides that occurred within Quaternary loess deposits often lack clear head scarps and flanks due to excessive gullying, yet they retain distinct toe deposits. We provide examples of landslides of 1) different ages, 2) mechanisms of movement, and 3) morphology as seen in LiDAR and during field checks, and we explore potential triggers of the prehistoric landslides.

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Characteristic Periglacial Terrain: Multi-Scale Hypsometric Analysis of Cryoplanated Uplands in Eastern Beringia

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Frederick Nelson *Northern Michigan University*

Cryoplanation terraces (CTs) are large step-like erosional landforms conveying the impression of giant staircases. They are thought to be formed through locally intensified sediment production and transportation associated with late-lying snowbanks. CTs are ubiquitous in unglaciated Beringian uplands and are found on ridgecrests and hillsides throughout the region. They are surrounded by cryopediments, beveled lower-angle surfaces of sediment transportation dominated by periglacial fluvial and mass-movement processes. Viewed as an integrated landscape, these landforms impart a distinctive geomorphic form that can be described by the term "cryoplanated terrain."

General geomorphometry is concerned with the geometric form of the continuous land surface and can be useful for identifying topographic "signatures." Hypsometry, a branch of geomorphometry concerned with area-elevation relationships, has found numerous applications in several subfields of geomorphology, but has not been used extensively in published periglacial work. In this study, hypsometric analysis was applied to several unglaciated and glaciated locales in Alaska's Yukon-Tanana Upland and Indian River Upland physiographic sections, areas of eastern Beringia in which cryoplanation landforms are extensive. At local and intermediate scales, never-glaciated areas in this region have hypsometric signatures distinctly different from those of glaciated areas. Comparison with terrain in the southwestern USA revealed substantial differences between the upland periglacial terrain of Beringia and warm-desert geomorphic landscapes, casting doubt on a published suggestion that cryoplanation landforms in high-latitude mountains are inherited from past intervals of warm and arid environmental conditions. At local and intermediate scales cryoplanated terrain exhibits a distinctive convex-upward hypsometric signature very different from the concavity of typical fluvial, desert, or glaciated terrain. We conclude that characteristic upland periglacial landscapes exist in unglaciated areas of Beringia and can be recognized through objective, quantitative methods.

Alyeska's 40-plus Years of Experience with Heat Pipes on the Trans-Alaska Pipeline*

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Frank Wuttig *Alyeska Pipeline Service Company, Fairbanks*
Chuck Shulz *Alyeska Pipeline Service Company, Fairbanks*

Heat pipes (thermosyphons) were installed in the vertical support members (VSMs) of the Trans-Alaska Pipeline where the pipeline is elevated in areas with warm non-thaw-stable permafrost. More than 124,000 heat pipes were installed during pipeline construction in the mid-1970s to thermally stabilize the permafrost surrounding the VSMs. Shortly after pipeline construction non-condensable gas (NCG) began to occur in some of the heat pipes, affecting their performance. Alyeska conducted an extensive research effort to identify the root cause for the occurrence of NCG and performed a test program on the degradation in heat pipe performance with the build-up of NCG. Two procedures have been used to repair underperforming heat pipes due to NCG issues: (1) Using "getter devices" and (2) recharging the heat pipes with carbon dioxide. Using getter devices was not a permanent solution to the NCG problem, and experience has shown recharging to be a successful repair option. This paper describes several heat pipe options Alyeska considered prior to construction and the choice and development of the heat pipes that were used on the pipeline along with the operational experience during the last 40-plus years. This paper presents findings from the test program on the degradation in heat pipe performance with buildup of NCG, and the use of heat pipes as a thermometer to monitor end of thaw season ground temperatures at the base of VSMs.

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Initial Performance of Sloped Thermosyphons for Stabilization of Massive Ground Ice Beneath the Alaska Highway, Yukon Territory

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The Dry Creek Highway Section is located along the Alaska Highway in the Yukon Territory of Canada. The site was identified as a key highway section that required stabilization due to warm (>-0.5°C), degrading ice-rich permafrost and massive ground ice in excess of 9 m thick. The thermal design for permafrost stabilization was based on a 30-year design life and incorporated sloped thermosyphons installed beneath the existing highway embankment to passively cool the permafrost foundation. The design specified 58 thermosyphons installed every 7 m on center beneath the existing highway embankment, with evaporator pipes 34 m in length that were installed in a cased borehole at an ~11° incline beneath the embankment. A vertical riser pipe with a 19.5 m2 surface radiator was installed for each unit. The inclined boreholes were drilled from the embankment toe to limit the need for excavation and to maintain integrity of the existing embankment, allowing for unimpeded use of the vital cross-border transportation route between Alaska and the Yukon Territory. Numerical thermal modeling was used to verify performance of the design and optimize thermosyphon radiator size and evaporator pipe distance in the ground to reduce project cost and ensure long-term performance with consideration of climate change. This presentation will cover the thermal design and initial performance over the first two years since construction. Temperature measured at two monitoring sections have confirmed initial cooling of the foundation by several degrees Celsius in response to seasonal heat extraction by the thermosyphons. The most notable change in ground temperature from the baseline period has occurred beneath the centerline where the embankment thickness is the greatest. At some sideslope positions, the permafrost table has begun to aggrade upward into thaw-stable material. The Dry Creek Permafrost Stabilization project contributes to evaluation of sloped thermosyphons for the adaptation of surface infrastructure to climate change in permafrost environments.

Effects of Foundation Performance on TAPS from Changing Thermal Conditions

Andrew Daggett *Golder Associates Inc.*
Christopher Valentine *Golder Associates Inc.*
Thomas Krzewinski *Golder Associates Inc.*
Frank Wuttig *Alyeska Pipeline Service Company, Fairbanks, Alaska*

The Trans-Alaska Pipeline (TAPS) has been impacted adversely by the changing climate over the last forty years of operation. This paper will discuss the performance issues due to thermal changes of underlying permafrost soil at a location along TAPS, near Pipeline Milepost (PLMP) 680. This site has been closely monitored, and design for the repair options is underway. The site is located near the southern end of the pipeline in an area of discontinuous permafrost. The change in climate has caused permafrost degradation impacting the foundations of the Vertical Support Members (VSM) supporting the pipeline. PLMP 680 has a history of continued vertical and lateral movement, which has accelerated in the last twenty years. Despite the passive cooling installed in the VSM's during construction, permafrost degradation has continued at these sites leaving only a frozen bulb around the VSMs. The thermal changes at PLMP 680 have caused significant vertical and tilt movement of the VSMs. Starting in the 1990s, the VSMs had heave up to three feet causing lateral tilting of the VSMs. The heave appears to have been caused the by formation of a vertical ice lens along the VSM. The heat pipes were covered at one of the supports to minimize the heat extraction and reduce the heave rate. Since then, movement at the VSMs has continued with tilting up to 10% since construction. Current movement at the site now appears to be primarily due to permafrost degradation and expansion of the wetlands. Recent lateral movement at the site is believed to be caused by consolidation of the newly thawed fine-grained soils around and below the VSMs.

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Centrifuge Modelling of Steel Piles in Frozen and Thawing Ground

Chris Clarkson *Royal Military College of Canada*
Greg Siemens *Royal Military College of Canada*
Ryley Beddoe *Royal Military College of Canada*

Northern climates create an increased complexity in soil-foundation interactions compared to temperate regions. The continuous and discontinuous permafrost that varies throughout the Arctic has a crucial role in pile foundation design. The uncertain quality of frozen soil, and its interaction with an ad-freeze steel pile provides a strong motive to further understand the strengths and bearing capacities of foundations in frozen soil. Centrifuge modelling was used to simulate in situ forces acting on steel ad-freeze piles in frozen soils. A centrifuge allows for the experimentation of small-scale models in a laboratory to be interpreted with real world parameters. By increasing the magnitude of gravity, a miniature pile foundation in a frozen soil can be modelled at full size for its entire design life in a fraction of time and space of the full-scale equivalent. The model pile was designed to recreate the soil-structure interface of ad-freeze piles used in permafrost region foundations. The piles and surrounding soil were instrumented and frozen prior to testing. Thermistors placed at specific locations in the test apparatus provided the changing thermal profiles of the soil before, during, and after testing. A load cell measured the axial load applied. Inclinometers detected the small factored displacements that occurred within the frozen soil. The steel piles had allocated small expected displacements due to initial loading. Initial load-displacement responses were recorded, as were secondary settlements that occurred during the re loading. The purpose of these centrifuge experiments was to provide further insight through experimental validation on the strength, bearing capacity, and initial stiffness of soils in frozen and increasingly thawed conditions. This was documented by measuring the load-displacement response of varying thermal soil-pile interfaces. Results quantify the ability of piles to sustain intended loads in frozen and thawing permafrost.

Using Airborne LIDAR to Assess Elevation Trends on the Alaska North Slope

Karl Kyzer *Hilcorp Alaska, LLC*

Measuring elevation changes of Arctic infrastructure is labor-intensive by means of conventional survey methods. This talk describes techniques using airborne LIDAR surveys to improve efficiency. Topics include:

1) Real-world application for subsidence mitigation.
2) Collection parameters for airborne lidar surveys.
3) Deliverables.
4) Accuracy and precision expectations.
5) Quality control.
6) Analysis methods and tools.
7) Advantages and disadvantages vs. conventional survey methods.

Overall, the use of airborne LIDAR has been a successful tool used to efficiently assess trends in elevation changes enabling timelier mitigative measures to be put in place on the Alaska North Slope.

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Slope Stabilization along a Buried Crude-Oil Pipeline in Ice-Rich Permafrost*

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Oliver Hoopes *Shannon & Wilson, Inc., Seattle*
Frank Wuttig *Alyeska Pipeline Service Company, Fairbanks*
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The Trans-Alaska Pipeline System (TAPS) transports warm oil through a 48-inch-diameter pipeline (mainline) 800 miles from Prudhoe Bay to Valdez in Alaska. The system traverses continuous and discontinuous permafrost and is supported aboveground or belowground, depending on permafrost and ground conditions. The study site is in the discontinuous warm permafrost of the Copper River Basin in the southern interior of Alaska. Subsurface conditions in the Copper River Basin consist of locally ice-rich glaciolacustrine and glacial deposits. The mainline at the site is buried in thaw-unstable permafrost and actively refrigerated to allow for animal crossings. Thermistor strings were installed in 2001 to monitor subsurface temperatures. In 2012, Alyeska Pipeline Service Company (APSC) observed evidence of ground movement at the study site threatening to uncover the mainline. Instrumentation showed movement related to a combination of permafrost thawing, groundwater seepage, and creep near the top of permafrost. We used coupled 2-dimensional (2D) and axisymmetric finite element thermal simulations to evaluate and develop mitigation. Mitigation consisted of an array of thermosyphons and woodchip surface insulation designed to freeze and buttress movement. APSC installed mitigation and additional instrumentation in fall 2017. Slope inclinometer and thermistor string data indicate freezeback and significant cooling of frozen soils in the treatment area arresting slope movement adjacent to the mainline. This paper demonstrates how geotechnical hazards are being managed along TAPS and how the Alyeska Pipeline Service Company is adapting to changing environment and permafrost conditions. We evaluate our thermal modeling approach and mitigation design by comparing predicted and observed subsurface conditions at the study site. We base our evaluation on thermal modeling results and slope inclinometer and thermistor string data between 2017 and 2020.

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Climate Change Adaptation: Saving our Critical Infrastructure

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William Fraser *Alaska Native Tribal Health Consortium, Department of Environmental Health and Engineering*
Bailey Gamble *Alaska Native Tribal Health Consortium, Department of Environmental Health and Engineering*
John Warren *Alaska Native Tribal Health Consortium, Department of Environmental Health and Engineering*
Mattias Flander *Flander Engineering*
Lindsay Panigeo *ASRC Energy Services*

The Problem

Soils with high moisture content and massive ice can exist in permafrost and can be relatively warm. When permafrost melts, the soils subside and the structures founded on the permafrost can experience significant settlement. Heat transmitted into the ground from warm structures must be removed to prevent the ground from thawing. This is often done through passive thermosiphons. Warmer winter air temperatures are preventing passive cooling systems from working as designed and may render many facilities unusable if not properly addressed in time.

The Solution

ANTHC-DEHE is developing an easy-to-install, relatively inexpensive refrigeration collar. It adds active cooling to the existing passive thermosiphon, keeping the foundation stable. The system can be installed as a retrofit to existing thermosiphons or new construction. The refrigeration collar is expected to be less expensive than a new thermosiphon installation and can avert costly damage. Potential applications exist in remote communities and industrial centers across the Arctic.

Thermal Refrigeration Collar

The refrigeration collar is a clamp-on cooling system. It is ruggedized for Alaska's climate. Installation requires mounting on a thermosiphon, plugging in a power source, and turning it on. Each unit can deliver over 500 W of cooling, which has been demonstrated with lab work. Each unit can be powered with solar panels and a 24V battery bank.

The unit consists of two parts: an insulated evaporator enclosure that mounts at the base of the thermosiphon, and a compressor and condenser assembly that mounts on the evaporator enclosure. The unit uses quick connects to allow connection of the compressor and evaporator in the field without losing refrigerant.

Testing is underway for the second prototype and field evaluation on the North Slope of Alaska is planned for 2022.

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Problems Associated with Construction on Permafrost

Jeff Miller *Cruz Construction, Inc.*

Cruz Construction is willing to be a part of a discussion focused on the means and methods of construction in permafrost as it applies to construction for the oil and gas and mining industries. Our primary focus as a company is to construct heavy civil projects in remote Alaska. We face the challenges of permafrost all year long as we construct jobs in both summer and winter. We have used many types of methods to deal with the effects of destabilized permafrost and/or eroding conditions. This includes insulation, shot rock, thermosiphons, and various other methods. Due to project-specific constraints and funding limitations, there is no one-size-fits-all answer. We would appreciate the opportunity to share and learn in a discussion format on this subject matter. The following is a brief summary of a recent project that had various elements of this topic associated with it. If there is interest, we would be willing to drill down in more detail on the specifics of this project and discuss any associated questions.

Brief Project Summary

Project Name: Newtok, Alaska, Airport Relocation, 2021-2022. The client is the Alaska DOT/PF. The village of Newtok has been on national news due to its emergency need to be relocated because it has been rapidly eroding into the Bering Sea. Cruz Construction has been contracted to construct a new runway at the new village site. The project site and mine site have many challenges due to poor aggregate quality and soils conditions. This project is a summertime build in a challenging environment. The project quantities include 63 acres of clearing; 110,000 CY of excavation; 350,000 SY of geotextile; 15,000 tons of porous backfill and ditch lining; 1.15 million tons of borrow; 75,000 tons of subbase; and 60,000 tons of surface course. The project staff includes Cruz Construction staff Jeff Miller (Contract Manager), Greg Miller (Project Manager), and Kyle Motsko (Superintendent). The project cost is $25- $30 million.

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Concrete Construction in Cold Regions: Quantifying the Impact of Daily Temperature Variations on Required Frost-Protection Measures

Danielle Kennedy *US Army Cold Regions Research and Engineering Laboratory*
Benjamin Watts *US Army Cold Regions Research and Engineering Laboratory*

In cold temperatures, fresh concrete can be irreversibly damaged by internal formation of ice before adequate strength has developed. Industry-standard protection measures, prescribed in ACI 306, are frequently laborious, expensive, and time-consuming. The USACE ERDC Cold Regions Research and Engineering Laboratory (CRREL) has developed ARCTEC (Additive Regulated Concrete for Thermally Extreme Conditions) to enable the use of standard concrete additives as alternative freeze protection in cold conditions.

A core component of ARCTEC is guidance to recommend additive dosage required for a successful concrete placement. This recommendation depends upon multiple aspects of a concrete placement, including geometry, mixture proportions, ambient temperature, and placement time. The number of unique cases implied by these parameters precludes physical testing of every possibility, so a transient finite-element thermal model was created to simulate and quantify the degree of frost protection required for concrete placed over a wide range of environmental and spatial configurations. Inputs for this model were obtained through laboratory characterization of the thermal and mechanical behavior of concrete at multiple curing temperatures and additive dosages.

Daily ambient temperature profiles were synthesized based on regional average minimum and maximum air temperatures, as well as day of year and latitude. Temperature profiles were used to simulate the impact of concrete placement hour on the degree of freeze protection measures required for flatwork of varying thickness. Results indicate that even in winter months, selection of the proper time of day for concrete placement can result in substantial savings in the cost of freeze protection measures. The results define a pathway to development of guidance for successful implementation of additive-based freeze protection measures regardless of time of placement or ambient conditions.

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Permafrost Test Sites: A Summary of Alaskan Pipeline Industry Efforts in Addressing Frozen Ground and Related Technical Issues*

James Rooney *Retired, R & M Consultants Inc.*

This paper is an attempt to identify and provide a brief summary of some industry efforts that I was involved with or aware of during the late 1960s through the mid-1980s,. All of the test sites were focused on evaluating terrain conditions and assessing potential pipeline impacts that would be involved while dealing with frozen ground conditions. The efforts included various organizations and participation by government agencies that occurred during both the Alyeska Pipeline Service Company (APSC), Artic Gas Pipeline and Alaska Northwest Natural Gas Transmission System early project activities. There were at least 11 test sites having locations in various parts of Alaska. These included Barrow, Prudhoe Bay, Prospect Creek, Hess Creek, the Fairbanks area, and Glennallen. They addressed concerns relating to thermal modelling of a hot-oil 48-inch pipe buried in frozen ground, thaw settlement/ frost heave effects, trench excavation methods, and testing vertical support solutions for the designated above-ground pipeline segments. Access to published information on these test sites is varied, and the concern is that some of this past history on early pipeline studies, related design input, and the possible influence on eventual construction (at least for APSC) be recorded.

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Construction and Structural Analysis of an Arched, Cellulose-Reinforced Ice Bridge for Gap Crossing by (Military) Vehicles

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Kiera Thompson Towell *US Army Cold Regions Research and Engineering Laboratory*
Eoghan Matthews *US Army Cold Regions Research and Engineering Laboratory*
Olivier Montmayeur *US Army Cold Regions Research and Engineering Laboratory*
Devin O'Connor *US Army Cold Regions Research and Engineering Laboratory*

As the potential for conflict in the Arctic rises, the US military has a renewed interest in using ice as an indigenous material. While ice covers have been leveraged to traverse water bodies during cold months, ice has seen little use as a stand-alone bridging material for vehicle mobility. To address this knowledge gap, an arched bridge made from ice reinforced with 0.3 wt% cellulose was constructed using a spray deposition method. The bridge was built over a dry gap (3 x 3 m) in a temperature-controlled facility and was able to support the static and dynamic loading of military-grade vehicles (up to 3,000 kg) with no visible damage to the bridge. Flexural and compression testing of ice specimens extracted from the bridge post traverse indicated that the cellulose reinforced ice is almost 2x greater in strength compared to pure ice. Microstructural analysis showed a layered structure with smaller ice grains in layers with more cellulose. A computational model that incorporated the measured material properties was used to probe the effect of ice thickness, gap width, and arch curvature on the strength of ice bridges. The model results predicted that the bridge as built could support up to 16,800 kg of static loading, which is safely in the range of military tactical vehicles (e.g., M1083, 13,480 kg). Increasing the curvature of the bridge effectively increases the load capacity of the bridge by approximately 50%, while larger gaps and widths are still able to support military-grade vehicles up to 3,000 kg if the ice is thickened by 50%. The versatility of this new approach is of high impact to both civilian and military mobility in cold regions, adding a critical new tool to the cold regions engineering toolbox.

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Design and Construction of an At-Grade LNG Storage Tank on Warm Permafrost in Fairbanks, Alaska

John Thornley *Golder Associates, Inc.*
Andrew Daggett *Golder Associates, Inc., Member of WSP*
David Prusak *Stantec*

To improve air quality in interior Alaska, Fairbanks Natural Gas (FNG) has invested in the development of a new liquefied natural gas (LNG) storage facility. The site is in an area of warm, discontinuous permafrost in Fairbanks, Alaska, where there is concern over continued permafrost degradation. An innovative shallow foundation system was selected because of the cost of deep foundations, due to the high seismic conditions and need for long-term foundation cooling. Long-term performance and constructability were two major issues for this foundation system. The LNG is stored at a temperature of -160°C, the permafrost soils extend only approximately 40m deep, and the site is adjacent to the Tanana River. The aggradation of permafrost was considered unacceptable over a 75-year design life. The delicate balance of maintaining warm permafrost was evaluated, modeled, and designed to allow for the construction of an at-grade foundation system. The shallow foundation system is designed to balance the cold from the LNG within the storage tank to maintain the permafrost but not significantly lower the temperature of the permafrost. In addition to design, construction issues arose due to the tight timeline for construction, weather, and the need to compact structural fill soils during the winter. Historically, compaction has shown time and again to be challenging during wintertime placement, often with poor results. The LNG storage tank construction timeline provided very few options for excavation and backfill activities to occur during warmer months. Careful consideration was given to key parameters required for compaction during the winter in Fairbanks, where the average winter temperature is -15°C. Air temperature, wind, soil temperature, and moisture conditioning constraints were defined prior to the start of winter compaction efforts. Careful execution of the plan and attention to the weather and soil behavior allowed for a successful structural backfill compaction effort.

Linking Climate Change and Human Systems: A Case Study of Arctic Pipelines

Nina Blahut *Pacific Northwest National Lab - Joint Global Change Research Institute*
Meredydd Evans *Pacific Northwest National Lab - Joint Global Change Research Institute*
Nazar Kholod *Pacific Northwest National Lab - Joint Global Change Research Institute*
Cathy Wilson *Los Alamos National Laboratory*

This case study estimates the potential economic risk from permafrost thaw on oil and gas pipelines in the Russian Arctic as part of a larger effort to better understand complex interactions between human and earth systems in the Arctic. Pan-Arctic simulations of permafrost thaw-depth from the Community Land Model version 4.5 and ground ice characteristics were used to generate thaw-induced ground subsidence projections over the period 2020 to 2040 with a quantification of uncertainty. Engineering analysis and expert input were used to estimate the magnitude of ground subsidence likely to cause significant pipeline damage. Russian oil and gas transmission pipeline networks were then overlaid on the ground subsidence projections in ArcGIS to identify pipelines vulnerable to damage from permafrost thaw. Recent pipeline construction costs were used to estimate the total replacement costs for at-risk pipelines under several thaw scenarios. The results indicate that permafrost thaw poses a major threat to pipeline infrastructure, especially gas pipelines, in the Russian Arctic. Over the twenty-year study period, total replacement costs for oil and gas pipelines were estimated at $110 billion in 2020 USD. The study also includes an uncertainty analysis on the range of possible replacement cost estimates due to combined uncertainty from permafrost projections, pipelines' subsidence tolerance, and Arctic construction costs. Reduced economic viability of pipelines under climate change could trigger major shifts in the Russian oil and gas industry, which would have impacts on global markets, emissions, and geopolitics.

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Improving Construction and Performance of a Runway in Nuiqsut, Alaska*

Doug Simon *HDL Engineering Consultants, LLC, Anchorage*
Jeremy Dvorak *HDL Engineering Consultants, LLC, Anchorage*
Mark Swenson *HDL Engineering Consultants, LLC, Anchorage*
Erik Jordt *HDL Engineering Consultants, LLC, Anchorage*

Airports provide the only means of reliable access to many Arctic communities in Alaska and are essential for goods, transportation, and medical care. Despite being surfaced with gravel, the runways must provide reliable access year around. Many of the runways in the North Slope region were constructed in the 1980s, when conventional engineering design indicated 1.3-meter to 2-meter embankments were adequate to protect the runways from thermal degradation of the underlying permafrost and subsequent settlement. Global climate change has resulted in thaw instability of many runways. Short, wet, cold construction seasons make construction of Arctic runways challenging. In addition, gravel surfacing is difficult to produce locally and generally of poor quality. This paper presents the solutions developed to address the challenges for resurfacing the gravel runway in Nuiqsut, Alaska. Insulation was installed in the runway embankment to limit the potential for future global warming to thaw the underlying permafrost. Wicking fabrics accelerated drainage during reconstruction of the embankment fill over the insulation. Dust control additives were blended into the gravel surfacing to increase strength and performance. This paper also presents lessons learned through design and construction. Recommendations are provided for design of future runways, and the value of the insulation, wicking fabric, and dust control blending is discussed.

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Embankment Fill Slope Movement on Thaw Sensitive Permafrost: Movement Mechanisms and Thermal Conditions at Lost Creek along the Trans-Alaska Pipeline System (Lost Creek – Part 1)*

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Oliver Hoopes *Shannon & Wilson, Inc, Seattle, WA*
Frank Wuttig *Alyeska Pipeline Service Company, Fairbanks, AK*
Wendy Mathieson *Shannon & Wilson, Inc, Seattle, WA*

The Trans-Alaska Pipeline System transports warm oil through a 48-inch-diameter pipeline (mainline) 800 miles from Prudhoe Bay to Valdez, Alaska. The system traverses continuous and discontinuous permafrost and is supported aboveground or belowground, depending on permafrost and ground conditions. The Lost Creek site is about sixty miles northwest of Fairbanks in discontinuous permafrost on a northwest-facing cut and fill slope. The permafrost is warm with temperatures between 30 and 31.5°F. The embankment fill is up to 45 feet thick and was placed over frozen colluvium along the hillslope and ice-rich peat and silt near the base of the slope. The mainline is supported aboveground by thermal vertical support members (VSMs) which were installed in 1976 and consist of drilled pipe piles fitted with thermosyphons. In 1990, Alyeska Pipeline Service Company first noted ground cracking at the site. Starting in early 2000, shoe displacement indicated VSM downhill movement and maintenance activities increased. APSC advanced exploratory borings in 2006, 2009, and 2010 and instrumented the site with three thermistor strings and three inclinometer casings to study movement mechanisms. In 2017, University of Alaska Fairbanks researchers advanced four shallow borings using a handheld Snow, Ice and Permafrost Establishment (SIPRE) drill in peat deposits adjacent to the embankment to obtain samples for laboratory creep and thermal testing. This study presents our interpretation of geotechnical site conditions based on geotechnical instrumentation monitoring, soil and permafrost observations, and laboratory creep testing results. Movement and deformation mechanisms at the site consist of 1) longitudinal creep movement within a shear zone concentrated in ice-rich organic (peaty) permafrost and 2) transverse shoulder rotation due to thaw settlement. We integrated creep, thermal, and slope stability analyses and developed mitigation options to control ground movement and present our approach in a separate paper within these proceedings (Lost Creek – Part 2).

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Embankment Fill Slope Movement on Thaw Sensitive Permafrost: Combining Creep Testing and Thermal Simulations to Develop Mitigation Options at Lost Creek along the Trans-Alaska Pipeline System (Lost Creek – Part 2)*

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Frank Wuttig *Alyeska Pipeline Service Company, Fairbanks, AK*
Chuck Shulz *Alyeska Pipeline Service Company, Fairbanks, AK*
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The Trans Alaska Pipeline System transports warm oil through a 48-inch-diameter pipeline (mainline) 800 miles from Prudhoe Bay to Valdez, Alaska. The system traverses continuous and discontinuous permafrost and is supported aboveground or belowground, depending on permafrost and ground conditions. The Lost Creek site is about sixty miles northwest of Fairbanks in discontinuous permafrost on a northwest-facing cut and fill slope. The embankment fill is up to 45 feet thick and was placed over frozen colluvium along the hillslope and ice-rich peat and silt near the base of the slope. The mainline is supported aboveground by thermal vertical support members (VSMs) which were installed in 1976 and consist of drilled pipe piles fitted with thermosyphons. APSC observed fill slope movement beginning in 1990. Movement mechanisms at the site consist of longitudinal creep movement along a shear zone in ice-rich permafrost and transverse shoulder rotation due to thaw settlement. The movement causes lateral pile

loading, VSM tilt, VSM downhill displacement, and extensive embankment cracking and displacement. Frequent maintenance activities include adjusting crossbeams, shoe positions, and pipeline position, and regrading the drivelane and embankment slopes. APSC plans to replace VSMs and mitigate slope movement at the site to maintain pipeline integrity. We combined creep testing laboratory results, thermal modeling design simulations, and slope stability design analyses to establish relationships between temperature, shear load, and creep rate based on Glen's Flow Law and developed mitigation options. Based on our analyses, APSC selected a thermal improvement strategy consisting of passive ground cooling and woodchip insulation to mitigate permafrost degradation and to slow creep movement. We present our interpretation of site conditions based on instrumentation readings, site observations, existing condition thermal modeling, and creep testing laboratory results in a separate paper (Lost Creek – Part 1).

***For full text, see *Permafrost 2021: Merging Permafrost Science and Cold Regions Engineering*, American Society of Civil Engineers. https://ascelibrary.org/doi/epdf/10.1061/9780784483589**

Distribution and Kinematics of Rock Glaciers in the Southern Alps of New Zealand

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The Southern Alps of New Zealand is an elongated mountain range, around 800 kilometers long and 80 kilometers wide, crossing almost all the South Island from north-east to south-west. The climate is strongly influenced by the atmospheric perturbations coming from the west. Consequently, the glacier coverage is extensive in the western part of the mountain range and decreases strongly towards the east, allowing the presence of rock glaciers. These landforms are widespread in the Southern Alps of New Zealand but have been only marginally studied. In this study we inventoried and mapped the active rock glaciers of the central part of the Southern Alps using Sentinel-1 InSAR data and following the guidelines produced by the IPA Action Group Rock Glacier Inventorying and Kinematics. We used a total of 43 interferograms acquired between 2015 and 2019 with time intervals between six days and two years along with orthoimage analyses. A total of 115 active rock glacier have been identified. However, only 33 of them can be qualified as strictly active, (i.e., displaying velocities higher than 10 cm/y). The remaining landforms are considered as transitional, with velocities below 10 cm/y. Besides, hundreds of rock glaciers are relict. The mean annual air temperature at the rock glacier locations is between +1.4°C and +4.3°C, with values higher for transitional landforms. This indicates a strong climatic control on rock glacier kinematics; air temperatures are too warm for allowing faster velocities. Moderate altitudes in the dryer eastern part and humidity of the climate in the western part, which allows low ELA, hinder the presence of rock glaciers at higher and more favorable elevations. Rock glaciers in the Southern Alps are thus in a degrading phase, which is expressed by typical morphologies such as stable fronts.

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Tracking Active Rock Glaciers in Utah with Satellite-Based InSAR

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Rock glaciers are a common landform in many alpine landscapes that play an important role in alpine hydrology and landscape evolution, principally through the release of seasonal meltwater and the downslope transport of coarse material. Here we use satellite-based interferometric synthetic aperture radar (InSAR) to identify and monitor rock glaciers in the Uinta and La Sal Mountains, Utah, between 2015 and 2021. Using the new framework established by the IPA Action Group community, we identified 255 active and transitional rock glaciers in the ~10,000 km^2 Uinta Mountains, and 45 active and transitional rock glaciers in the ~350 km^2 La Sal Mountains. In the Uintas, we found that the rock glaciers are 10.8 ha in area on average and located at a mean elevation of 3290 m, where mean annual air temperature is 0.12 ˚C. In the La Sals, the rock glaciers are 9.5 ha on average and located at a mean elevation of 3150 m, where mean annual air temperature is 2.5 ˚C. The mean line-of-sight (LOS) velocities for individual rock glaciers in both mountain ranges are ~1 to 6 cm/yr. We also examined the time-dependent relationship between the motion of select rock glaciers and local climatic drivers such as temperature and precipitation. We found that rock glaciers exhibit seasonal velocity changes, presumably driven primarily by snowmelt, with motion that is more than five times faster during the late summer compared to the rest of the year. Our findings demonstrate the ability to use satellite InSAR to monitor rock glaciers over large areas and provide insight into the environmental factors that control their kinematics.

Repeated Annual UAV-Based Measurement of the Surface Creep Velocity of Leibnitzkopf Rock Glacier (Austrian Alps) Without the Use of Geodetically Measured Ground Control Points (GCPs)

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The kinematic state of a rock glacier is best described by its surface velocity field. Rock glacier monitoring often includes annual measurements of the surface creep velocity. Due to time constraints and, in recent years, accessibility, in-situ geodetic measurements (total station, GNSS-based) are usually restricted to a limited number of observation points. In contrast, UAV-based rock glacier mapping allows the flow velocity field to be remotely derived, without stepping on the rock glacier’s surface. Nowadays, the georeferencing of UAV-based aerial images is facilitated by measuring camera positions using RTK/PPK-GNSS techniques. However, UAV images taken with consumer-grade cameras generally require camera self-calibration during bundle block adjustment. Consequently, around 3-4 GCPs are commonly used to model systematic offsets and to eliminate strong correlations between unknowns. The present study is based on a field campaign planned for August 2021 and comparison with last year’s UAV-based aerial survey of the highly active Leibnitzkopf rock glacier in the Austrian Alps. We will use a hexacopter twinFold Geo carrying a Sony Alpha ILCE-6000 and a PPK-GNSS module for data acquisition. However, this time we will not use any GCPs. Georeferencing of the 2021 UAV-based image data will be done using the PPK-GNSS-measured camera positions, and the UAV-based images from the 2020 aerial survey which have already been georeferenced. We intend to carry out a bi-temporal (2020-2021) joint bundle block adjustment, connecting both the reference and the follow-on image data using stable ground in the surroundings of the rock glacier. We are also investigating whether the 2021 image data can be georeferenced using plain co-registration and completely disregarding the 2021 PPK-GNSS-measured camera positions. The accuracy of the obtained creep velocities for 2020-2021 will be assessed using contemporary geodetic measurements. A further quality control will be to compare the digital orthophoto and digital elevation models with older ones obtained from previous aerial surveys, both conventional and UAV-based. This study emphasizes that annual (in-situ) geodetic measurements on highly active rock glaciers such as the Leibnitzkopf rock glacier can be replaced by UAV-based aerial surveys without the use of GCPs where high-quality UAV-based image reference is available.

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Internal Structure, Dynamic Behavior, and Hydrological Characteristics of a Rock Glacier in the Semiarid Andes of Argentina

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This work aims to present the analysis of the internal structure, dynamics, and hydrogeology of a large-sized, complex, multi-lobate and multi-root rock glacier located in the southwest of the San Juan province (31°52’59.75””S; 70°15’8.62””W), Central Andes of Argentina. The study was conducted combining electrical resistivity tomography (ERT), Differential Interferometry Synthetic Aperture Radar (DInSAR) and hydrochemical data. A total of eight ERT profiles have been carried out in the El Gigante rock glacier, which have been distributed to be representative for various lobes. ERT surveys show a marked irregular geometry for the upper sector of the permafrost with electrical resistivity values ranging from 7 to 142 kΩm. These low electrical resistivity values recorded could be influenced by the high metallic concentration present in the environment, reflecting ionic enrichment to varying degrees during water circulation and subsequent re-freezing.

The horizontal displacement from October 2014 to April 2017, exhibits its greatest magnitudes in the upper sector of both tongues, reaching speeds of up to 150 cm/year. The active frontal sector shows a displacement rate of 2 to 4.5 cm/year. The analysis of 28 interferograms shows minimal seasonal and inter-annual variability for the “The Giant” rock glacier. Part of this time span corresponds to a period of extreme drought in the Andes, which directly influences the availability of water. Hydrochemical data show both the existence of different disconnected water flow pathways inside the rock glacier and the remarkable ionic concentrator effect of this landform.

This study contributes to the knowledge of the material properties of rock glaciers, which represent important reservoirs/water resources and their influence on the distribution of mountain permafrost, hydrology, and dynamics. The presence of large areas of hydrothermal alteration, such as in the Andes, constitutes an additional challenge in the interpretation of cryogenic processes and a key factor in water quality.

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Statistical Prediction Modelling of Rock Glacier Distribution in Norway

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Knowledge about rock glacier activity and distribution is valuable to understand and explore the evolution of permafrost throughout the Holocene. In this study, we updated the existing rock glacier inventories of Norway by interpreting publicly available aerial photos and by acquiring surface velocities from the free public service InSAR Norway (https://insar.ngu.no/). This updated inventory, together with suitable explanatory variables like air temperature, direct solar radiation, topographic roughness, and curvature, was further used to fit a statistical prediction model to rock glacier existence in Norway. The Holocene and late-Pleistocene distribution of intact rock glaciers has subsequently been explored by adjusting the temperature in the model to climatic conditions during the Younger Dryas (YD – ca 12 ka BP; -6 °C), the Holocene thermal maximum (HTM – ca 8 ka BP; +2 °C), and the Little Ice Age (LIA ca 0.2 ka BP; -1 °C). Our model indicates that at present, intact rock glaciers exist at 300 to 400, 600 to 800, and 1300 to 1500 meters above sea level in Finnmark, Troms, and southern Norway, respectively. The adjusted model runs predict that rock glaciers could have existed in 1) low-lying coastal areas in a YD climate, 2) areas at or inside the YD ice sheet margins in an LIA climate, and 3) at high elevation continental areas during the HTM. From these results, we suggest that rock glaciers that were predicted to have existed in the YD were probably also initiated during this time period and remained active a couple of thousand years until they turned relict before or during the Preboreal or the HTM. Rock glaciers attributed to an LIA climate were probably formed after the HTM, and rock glaciers associated with an HTM climate have likely existed continuously since the YD, throughout the HTM, and until today as either active or inactive landforms.

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Operational Monitoring of Rock Glacier Kinematics: Insights from the PERMOS Network

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Rock glaciers are characteristic landforms associated with mountainous periglacial landscape and have been widely used since the mid-20th century as a visual indicator of mountain permafrost. Recently, studies have shown that the velocity of rock glaciers responds sensitively and synchronously to interannual and decennial changes in ground temperatures. An ongoing initiative, led together by GTM-P and the IPA Action Group on Rock Glacier Inventories and Kinematicss, intends to make rock glacier kinematics a new associated parameter within the ECV permafrost. Within the Swiss Permafrost Monitoring Network (PERMOS), rock glaciers have been operationally monitored using terrestrial geodetic surveys for more than twenty years, for the longest time series. Results show a consistent regional evolution for the entire Swiss Alps. Over the past decades, a general increasing trend has been observed with significant interannual variation such as the velocity peak in 2015 and the velocity decrease from 2016 to 2017. This evolution fits well with the in-situ near-surface surface temperature as well as the permafrost temperatures observed in boreholes. In this contribution, we will present the detailed results of the PERMOS monitoring sites and highlight some of the challenges we faced collecting and processing this outstanding dataset.

An Estimation of Past and Present Air Temperature Conditions, Water Equivalent, and Surface Velocity of Rock Glaciers in Cordillera Volcanica, Peru*

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Rock glaciers (RG) are one of the most important geomorphological features in the Peruvian Andes. However, the local characteristics of RG have barely been studied or remain unknown. The aim of this research was to characterize past and present conditions of the RG located in Cordillera Volcanica in southern Peru. For this purpose, an inventory of rock glaciers was carried out and a modern and past regional mean air annual temperature (MAAT) were calculated. We estimate the water equivalent of RG to assess their importance as possible stores of frozen water for past and present conditions using an empirical rule. In addition, the surface velocity of RG was obtained from Landsat 8 imagery. Within the study area, 200 RG were identified (8.25 km2). Of these, 101 were classified as intact and 99 as relict forms. The altitudinal distribution of RG ranges from 4252 to 5554 m a.s.l. where modern MAAT is close to a positive level (0.73°C). In the current conditions, relict RG are located in positive MAAT levels around 1.2°C; however, for the past conditions, relict RG were located in negative MAAT levels around - 5°C. The amount of water stored in intact RG is between 16 and 37 km3. Meanwhile, for past conditions, we estimated that volume stored within rock relict RG was between 18 and 53 km3. (We assume an icerich layer of RG permafrost has between 20-45%.) On the other hand, the average surface velocities of the active RG have been estimated between 2 cm/month and 16 cm/month. The findings of this research contribute to increasing knowledge about RG in the Peruvian Andes. However, further research is needed to understand the importance of RG as stores of frozen water during the past and present conditions.

***For full text, see *Permafrost 2021: Merging Permafrost Science and Cold Regions Engineering*, American Society of Civil Engineers. https://ascelibrary.org/doi/epdf/10.1061/9780784483589**

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Strengths and Limitations of Rock Glacier Inventories

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Rock glaciers have globally been described and monitored for many decades. Recently, attention has increased rapidly in the scientific community as well as within the general public, related to an inferred hydrological resource. In an effort to develop widely accepted guidelines to inventory rock glaciers on a global scale, the IPA Action Group on rock glacier inventories and kinematics recently developed baseline concepts. The development of such a guiding document is extremely valuable. In particular, the distribution of rock glaciers may allow us to estimate the extent of permafrost within a mountainous region. However, it is crucial to communicate and respect limitations of such inventories. Specific caution must be applied when a rock glacier inventory is used to draw conclusions on the state of the cryosphere and hydrological resources. It must be emphasized that rock glaciers are not glaciers, and when inventories include both types of cryoforms or when different inventories are compared with each other, conclusions may be misleading. For example, changes in glacier areas are comparatively easy to monitor. It is also known that those changes are linked to current changes in climate, such as precipitation and air temperatures. However, the rock glacier morphology depends on other parameters, such as local geology, topography, and historic climate. The insulating effect of the active layer and the lack of ice exchange significantly delay the response of a rock glacier to changes in climate. In addition, it is not possible to correlate rock glacier area with its thickness or its ground-ice volume, as both depend on multiple parameters. The outlining of a rock glacier, specifically in the upper section where the exact beginning cannot often be identified, is often confusing, which results in a significant uncertainty in its area, limiting further interpretations. Based on multiple examples, this presentation will provide an overview of the strengths and the limitations of rock glacier inventories and offers suggestions on how to communicate those.

Review of the Inventory and Kinematic Analysis of Aosta Valley (Italy) Rock Glaciers

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ARPA Valle d'Aosta is conducting a general review of the regional rock glacier inventory, begun about ten years ago. The review, based on the analysis of DEMs and more recent and detailed aerial images, allowed us to better delineate the contour of numerous bodies and to detect several others not identified in the first inventory. The mapped rock glaciers are more than a thousand, with planar dimensions ranging from less than 2.000 m2, up to 60.000 m2. About 50% of them are classified as active. A first evaluation about the driving factors controlling the spatial distribution and areal density of the rock glaciers was carried out. Besides aspect and elevation, a significant factor is represented by the fracturing degree of rock masses that supply the talus, frequently in close proximity to tectonic regional features, such as major faults and overthrusts. Furthermore, an analysis on a sample of intact rock glaciers has been performed in order to identify the percentage of active rock glaciers and quantify their surface velocity. This will allow the integration of the inventory with kinematic data. This study is based on the analysis of aerial images covering a temporal range of ten years (flights of 2005, 2012, and 2015). The horizontal ground displacements and the velocity rates of each of the selected rock glacier were computed through manual identification of well recognizable corresponding boulders in the medium-frontal part of each rock glacier. This approach shows good results for significant displacements over the whole time period. For smaller ranges, the uncertainty due to frame resolution, georeferencing, and orthorectification of aerial photograms can be greater than the observed displacement.

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Systematic Monitoring of Rock Glacier Kinematics from Satellite SAR Interferometry: Insights from Case Studies in the European Alps and Disko Island

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Recent observations have shown that rock glaciers located near the lower limit of discontinuous permafrost move downslope with velocities between a few cm/a and several m/a. The majority of the surveyed rock glaciers, irrespective of their size and velocity, respond sensitively and almost synchronously to inter-annual and decennial ground temperature changes. Change in rock glacier motion is thus considered a suitable proxy for short- to medium-term response to environmental change and an indicator of mountain permafrost conditions in general. Satellite radar interferometry (DInSAR) has been efficiently used for the estimation of the rate of motion of rock glaciers. Previous work dealing with rock glaciers at the single-valley or the regional scale has been mainly concerned with the manual delineation of rock glacier outlines and the morphologic or InSAR-based evaluation of their degree of activity. The ESA Copernicus Sentinel-1 constellation, specifically designed for SAR interferometric applications and displacement monitoring, allowed a move from punctual surveys to a more spatially-distributed and systematic monitoring scenario.

In this contribution, we analyze the performance of Sentinel-1 InSAR time-series for the monitoring of the rate of motion of selected active rock glaciers in the Swiss and Italian Alps and over Disko Island (Greenland). The line-of-sight displacement in 6 to 48 days derived from the interferometric pairs is converted to rates of motion along the slope. Reliable displacement information can be derived for the snow-free season and in winter during stable, cold conditions. The typical annual cycle of rock glacier velocities, with higher values in autumn and lower values in spring, with reference to existing in-situ measurements, can be observed with an estimated accuracy on the order of 0.2 m/a. We conclude that Sentinel-1 DInSAR can complement in-situ data collection on rock glacier kinematics and expanding, with a degree of independence, in-situ monitoring networks.

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Multi-Method Approach to Inventorying Rock Glaciers and Features of Interest in Banff and Jasper National Parks, Alberta, Canada

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Rock glaciers are perennially frozen masses of ice and unconsolidated material that creep downslope as a result of cyclic freeze-thaw mechanisms and weight due to gravity. These features are often tongue-shaped, lobate landforms containing longitudinal or transverse flow structures with a surface that consists of poorly sorted, angular rock debris. Although rock glaciers are abundant geomorphological features in the alpine periglacial environments of the Rocky Mountains, their spatial distribution and characteristics are largely unknown. As rock glaciers contain frozen fresh water and can be potential geohazards, inventories are crucial in the assessment of the activity status and distribution of these landforms. This inventory will also provide an estimate of the potential cubic meters of water equivalent storage within the rock glaciers for cryospheric reserves as freshwater depletes. To date, over 800 intact (active/inactive) rock glaciers were successfully identified within the study areas. There were also over 204 features of interest requiring further validation of surface kinematics and morphometric quantification. Grid-based manual inventorying of these features was completed using high-resolution satellite imagery that is readily available through the ESRI World Imagery Base Layer. It was subsequently verified manually with Google Earth Pro. This methodology proved crucial and supports the idea of both multi-temporal and multi-method approaches to the inventorying of rock glaciers and features of interest within the alpine terrains of Canada. Using a digital elevation model of 10m resolution and climate re-analysis products (i.e., ClimateNA, ERA5), geomorphometric and climatic parameters will be extracted for all identified features. This multi-method approach to rock glacier inventorying and classification developed a proof of concept within the study area that verifies the applicability of this method at a regional scale. This work represents the first component of our rock glacier monitoring network within Canada, as there currently are none to date. The inventories completed with this initiative will be shared with the International Permafrost Association's Rock Glacier Inventorying Action Group.

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Accelerating Rock Glacier Threatens Critical Infrastructure

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The Pretty Rocks rock glacier in Denali National Park has the potential to disrupt transportation at the mid-point of the dead-end park road, impact the regional economy, and affect public safety. Approximately 90 m of the full width of the park road crosses the rock glacier. Impacts to the road have been experienced at Pretty Rocks since at least the 1960s and, until recently, only required maintenance every 2-3 years. The park first noticed an increasing impact to the road in 2014. Between 2016 and 2017, the road slumped up to 15 cm/month, creating a slump that steepened the road gradient and limited sight lines for drivers. Road displacement increased to approximately 5 cm/day in 2019, then to almost 9 cm/day by August 2020. Numerous borings and their associated monitoring equipment indicate that most displacement occurs at a discrete failure plane, where there is abundant massive ground ice and temperatures are near thawing. Analysis of nearby climate monitoring sites indicated a step-wise increase in temperature of 2.4°C in mid-2013; this shifted mean annual temperatures to near or above 0°C in the area. Denali maintenance staff and contractors maintained a safe drivable surface during these years by placing up to 4,500 cubic meters of gravel to repair the road. The National Park Service and Federal Highways Administration are developing long-term solutions to the increasing road displacement at Pretty Rocks.

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Reconstruction of Rock Glaciers Dynamics in an Alpine Environment, from Modern to Holocene Timescales

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Rock glaciers are one of the most frequent cryospheric landforms in mid-latitude mountain ranges. Their dynamics strongly influence the evolution of alpine environments over short (years to decades) and long (centuries to millennia) timescales. Being conspicuous expressions of mountain permafrost[1] and important water reserves in the form of ground ice,[2] rock glaciers are seen as increasingly important in the geomorphological and hydrological evolution of mountain systems in the context of climate change and deglaciation.[3, 4] Over longer timescales, rock glaciers transport rock boulders produced by headwall erosion and therefore participate in shaping mountain slopes.[5] Despite their importance, the dynamics of rock glaciers and their evolution over different timescales still need to be better constrained. In this study, we address two main questions: 1) How have the dynamics of rock glaciers changed over time? 2) What is the origin of rock glaciers, and what is their influence on the evolution of alpine environments?

Addressing these two questions requires a quantitative evaluation of the surface velocity field of rock glaciers by relating short and long timescales. Accordingly, we combine methods including remote sensing, geochronology and numerical modelling of rock glacier dynamics[6] and apply this approach to the rock glacier system of the Vallon de la Route in the Combeynot massif (French Alps). Remote sensing employing image correlation document the displacement field of the rock glacier over modern timescales.[7] Over longer periods (103 to 104 years), we use cosmogenic terrestrial nuclides (TCN) dating (10Be in quartz) of rock-boulder surfaces at different positions along the central flow line of the rock glacier, from the headwall to its terminus. The 10Be exposure ages may then be translated into mean surface speeds.

Preleminary results show exposure ages ranging from 1.88 ± 0.14 to 13.10 ± 0.51 ka. They reveal a first order negative correlation between 10Be age and elevation and a positive correlation between 10Be age and horizontal distance to the headwall. These correlations validate the hypothesis that rock boulders fall from the headwall and remain on the glacier surface as they are transported down valley. The further from the headwall (the lower in elevation) the boulder is, the older its surface exposure will be.

The use of numerical modelling of rock glaciers[6] allows us to relate the surface kinematics at different timescales with the overall aim to discuss the age. The origin of rock glaciers and how topo-climatic and geomorphological processes control their evolution in an Alpine environment. While the ages in the upper reaches of the rock glacier can be explained by modern measured speeds, those in the lower reaches are far too old and suggest significant slowing of the rock glacier over the late Holocene.

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Remote Detection of Buried Ice Masses; Transantarctic Mountains, Antarctica

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Glacial ice can yield information on paleoclimate, paleo atmosphere, and ancient organisms. Throughout the Transantarctic Mountain Range (TAM), a minimal number of buried ice masses, which have the potential to be much older than most glaciers, have been discovered. An example of such is found in Ong Valley, Antarctica, covered by a sublimation till that is >1.1 ma years old, consequently making it one of the oldest known ice masses on Earth. In addition to a few known locations, no systematic effort has been made to map such ice masses in Antarctica. We visually analyzed >8,000 high-resolution satellite images covering the TAM from Victoria Land to Pensacola Mountains. The multispectral imagery has sub-meter resolution (0.32-0.5 m), which allowed for permafrost polygon detection. The satellite imagery contains bands 1-3 (Red, Green, Blue) covering a spectrum from 400 to 745nm. On those images we inspected all land areas that were not covered by exposed ice and looked for land areas with polygonal patterned ground, which is known to occur only when regolith either covers ice or the regolith is cemented by ice. (Ice cementation refers to the regolith that contains only interstitial ice, but no massive ice is necessarily present.) Once we discovered the polygonal surface pattern, the corresponding digital elevation model (REMA) was inspected. When a massive ice body is present in a U-shaped glacial valley, it forms a convex shape on the bottom of the otherwise U-shaped valley cross profile. The REMA DEM was used to determine whether the given valley floor had a convex pattern that reveals the presence of buried ice body. Based on these analyses, we identified 28 individual field sites that all fill both the above-mentioned criteria and thus have a strong likelihood of containing a massive buried ice body.

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Rock Glaciers Throughout the French Alps Accelerated and Destabilized Since 1990 as Air Temperatures Increased

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In the past decade, the research community on alpine periglacial landforms reported several cases of increasing rock glacier displacement rates up to abnormally high values. This process is often bonded with the development of surface features typical of landslide processes, as crevasses and cracks. Existing studies of this phenomenon, commonly referred as "destabilization," have been limited to a small number of landforms and short timespans. This study aims to contribute to our understanding of rock glacier destabilization using a regional scale approach over a long period. Our methodological pillar is displacement rates evaluation based on orthophoto comparison. First, we spotted destabilizing landforms by coarsely evaluating displacement rates on all rock glacier in the French Alps since the 1950s using readily available orthoimages provided by the national geographical institute. We then com-

puted a database of orthoimages at high temporal resolution (5-10-year intervals) for all destabilized rock glaciers in the region in the past seven decades, allowing us to evaluate the evolution of their displacement rates in greater detail. Our analysis shows that rock glacier velocities have significantly increased since the 1990s, concurrent with the development of destabilization in 18 landforms that represent 5% of the 337 active rock glaciers. This pattern of activity correlates with rising air temperatures in the region, which suggests that a warming climate may play a role in this process. Surface crevassing shortly precedes the acceleration phase most of the times, although few landforms show "dormant" crevasses for decades before destabilization onsets. Destabilized landforms can reach displacement rates up to 25 m/y, although most common values range around 3-5 m/y. Destabilizing landforms show sliding dynamics, and this process lasts until the destabilized mass is depleted or reaches flat terrain

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Novel Subsurface Measurement Setup to Investigate Heat Transfer Processes Within the Debris Mantle of Rock Glacier Murtèl (Engadine, Eastern Swiss Alps)

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The summertime runoff from melting ground ice stored in debris-covered permafrost landforms is an increasingly important water resource in dry, deglaciating mountain regions. However, annual melt rates in these landforms are hardly known. Lacking quantitative process understanding on how energy flows across the surface debris mantle down to the permafrost table impedes the modelling and prediction of annual permafrost melt water availability.

Evidence from, for example, warming-resilient rock glaciers and crushed rock railroad embankments indicates that air convection within the permeable debris mantle has a cooling effect, thus creating overcooled ground thermal conditions. We investigate heat exchange processes including air circulation and longwave radiation across the openwork debris mantle down to the permafrost table on rock glacier Murtèl. At this Swiss Permafrost Monitoring Network (PERMOS) key site, borehole temperatures down to a depth of 58 m and meteorological conditions have been measured since 1987 and 1997, respectively.

In August 2020, we instrumented natural cavities between the coarse blocks with a variety of sensors such as thermistors, hygrometers, pyrgeometers, sonic anemometers, hot-wire anemometers, and heat flux plates. This unique 'subsurface weather station' measures heat exchange processes within the debris mantle. We complemented the ongoing PERMOS atmospheric measurements by eddy flux, precipitation, and snow temperature measurements. In addition, a visible light and thermal infrared dual camera provides hourly images of snow cover and surface temperatures. To verify the energy balance calculations, we track the water provenance of the outflow in the rock-glacier forefield with electrical conductivity measurements and estimate the discharge from permafrost melt.

The huge amount of collected data will allow us to explicitly model the energy balance within the debris mantle. While our project will provide more reliable ice-rich permafrost runoff forecasts at a yearly resolution, the gained process understanding will also contribute to improved predictions on downwasting rates of debris-covered glaciers and on the delayed response of cold rocky landforms to climate change.

Consensus-Based Rock Glacier Inventorying in the Torngat Mountains, Northern Labrador*

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The Torngat Mountains of northern Labrador are an Arctic cordillera mountain range located at the southern limit of the Canadian Arctic. Fretted coastal relief and cold-maritime climate conditions promote continued existence of small mountain glaciers and widespread periglacial activity. However, apart from brief archaeological investigations and ecological monitoring, there is no baseline information on permafrost in the region. Sparse observations of periglacial landforms in the Torngat Mountains, including rock glaciers and ice-cored moraines, imply permafrost may be widespread, but to date there has been no comprehensive inventory of these features. In this study, we provide preliminary results from the first feature inventory of rock glaciers in the Torngat Mountains National Park and adjacent areas of Nunavik and Nunatsiavut, northeast Canada. Feature inventorying used high-resolution imagery recently made available through ArcGIS Online. A multi-step inventorying approach was used, with initial feature identification performed by eight mappers, and quality-control and feature-grouping completed by an independent review team. A total of 932 unique features (875 after quality-control) were identified in Stage 1, but considerable disagreement existed between mappers. For example, only 100 of the 875 features were identified by four or more mappers in Stage 1. Stage 2 required mappers to independently re-evaluate all 875 unique features identified from Stage 1. The total number of features characterized as rock glaciers by one or more mappers decreased in Stage 2 (n = 760), with 546 features categorized as a rock glacier by four or more mappers. All eight mappers identified the same 167 and 115 features as rock glaciers and non-rock glaciers, respectively. Comparison against an earlier unpublished (coarse) rock glacier inventory showed general agreement but a significant underestimation in the earlier inventory of the number of probable rock glaciers present in the Torngat Mountains ecoregion.

***For full text, see *Permafrost 2021: Merging Permafrost Science and Cold Regions Engineering*, American Society of Civil Engineers. https://ascelibrary.org/doi/epdf/10.1061/9780784483589**

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Rock Glaciers and Contributing Area Parameters in the Front Range of Colorado

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Rock glaciers, a component of the coarse debris system, exist in many different forms which are often dependent upon talus production and topography. Rates of creep/flow also vary considerably, ranging from 1 to more than 100 cm/yr. Here we examine the relationship among contributing area parameters (width, length, area, slope, headwall height, etc.) and rock glacier variables (width, length, area, thickness, slope, creep/flow, and temperature) in the Front Range of Colorado in order to better understand formation factors and kinematics. Rock glacier width had the strongest correlation with contributing area width because of an abundance of lobate rock glaciers (r=0.78). Rock glacier area and contributing area size were also related (r=0.74) and are a function of talus production factors. Mean surface velocity appears to be better correlated with thickness (r=0.58) and length (r=0.62), rather than slope (r=0.33). Mean annual air temperature had a stronger exponential relationship with maximum velocities (r=0.76) compared to mean annual velocity (r=0.60). Front Range rock glacier velocities tend to decrease with warming, whereas a global inventory of rock glaciers indicate greater rates of deformation with warming. Given their relatively slow rates of flow (10-20 cm/yr), Front Range rock glaciers may lack sufficient ice content, experience minimal rates of shear in plastic layers, or experience enhanced sliding via meltwater compared to rock glaciers found in other parts of the world.

Iron Speciation at the Permafrost-Active Layer Boundary

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To understand landscape-scale watershed dynamics in Arctic regimes, it is critical to investigate abiotic and biotic interactions in the transition zone, where the active layer meets the permafrost. Permafrost, which is a considerable component of Arctic soils, contains a unique interface at the transition zone characterized by a sharp redox gradient and a phase change from liquid water to ice. The biogeochemical composition and environmental conditions at this interface influence reactivity (i.e., as permafrost thaws, a higher proportion of interfacial water may be present, disrupting the localized micro-environment). Associated changes in the amount of unfrozen water present will likely affect redox environment, microbial activity and diversity, speciation, water density, conductivity, and soil wettability. Imnavait Creek is a tundra stream on the North Slope of Alaska, where we collected soil and water samples across seasonal thaw and coupled ground penetrating radar (GPR) and electrical resistivity tomography (ERT) to characterize watershed active layer thickness and identify permafrost extent across the stream, respectively. Our work shows the permafrost-active layer interface is a reducing zone highly susceptible to mass flushing of redox active elements (e.g., iron; Fe) if thawed, and this mass flush will likely occur in late fall/early winter. Additionally, we observed high concentrations of Fe in the nearby surface water in late fall/early winter, corresponding to when the soil surface is frozen but the active layer is at its deepest annual depth. As permafrost degradation accelerates, there will be rapid changes to the first 1-2 meters of the soil with potentially significant chemical and biological changes occurring near the permafrost-active layer interface.

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Understanding The Drivers, Dynamics, and Regional Patterns of Terrestrial Ecosystem CO2 Fluxes Across the Arctic-Boreal Zone

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The Arctic-Boreal Zone (ABZ) is experiencing rapid changes with pronounced impacts on the terrestrial carbon cycle due to climate change. Non-growing season carbon emissions have recently been shown to be larger than previously thought. On the other hand, growing season plant productivity and carbon uptake are increasing in areas that are not undergoing major disturbances related to fires, permafrost thaw, and drought. Despite the importance of these ABZ fluxes for global carbon budgets, we lack a comprehensive understanding of their dynamics that would integrate the extent, magnitude, and drivers of these fluxes and their changes in different seasons and regions. Here we aim to fill this knowledge gap by studying the drivers and spatiotemporal patterns of spring, summer, autumn, and winter carbon dioxide (CO2) fluxes and budgets. We use a recently compiled database of monthly ArcticBoreal terrestrial ecosystem CO2 fluxes (ABCflux, n=6309) and upscale fluxes across the ABZ over the past four decades, using machine learning models and a wide array of geospatial data describing, for example, climate, snow, vegetation, soil moisture, and disturbance conditions. We present maps of gross primary productivity, ecosystem respira-

tion, and net ecosystem exchange aggregated over monthly intervals at 1 km spatial resolution from 2000 to 2020 and at 8 km from 1981 to 2017. We use these maps and site-level information to synthesize recent changes in ABZ CO2 fluxes, their sensitivity to various environmental conditions, and what these mean for the CO2 uptake strength of this region in the near future.

* * *

Landscape Connectivity and Dissolved Organic Matter in a Degrading Permafrost Polygonal Landscape

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In Arctic landscapes dominated by ice-wedge polygons, the degradation of these ice wedges leads to dramatic, interconnected changes in both the physical environment and biogeochemical cycling. As ice wedges thaw, poorly drained, low-centered polygons transform into well-drained high-centered polygons, surrounded by connected water-filled troughs that develop above degrading ice wedges. Thermokarst resulting from ice-wedge degradation allows for substantial re-mineralization of preserved organic matter, but it can also cause changes in the lateral transport of dissolved organic carbon (DOC), both in terms of quantity and composition. As yet, it is poorly understood how the connectivity of ice-wedge polygon landscapes contributes to in-situ losses of dissolved organic matter (DOM) and the lateral movement of DOM through a watershed. We sampled surface water along a field-mapped flowpath at a study site with actively degrading ice wedges near Prudhoe Bay, Alaska, in July 2019. Our goal is to understand how DOM is mobilized and transformed, from a mid-point in the sub-watershed to an outlet into a drained lake basin. The flowpath ran through a series of troughs and ponds that formed in thermokarst depressions surrounding high-centered polygons, differentiated by water depth, presence of submerged and emergent vegetation, and width between polygon rims. We measured DOC, chromophoric dissolved organic matter (CDOM), dissolved nitrogen, and temperature at each site. Repeat aerial imagery, high-resolution GPS data, and soil cores from this site show clear signs of icewedge degradation and increased water connectivity over the past fifty years, including the thawing of previously stable ice wedges to form deep ponds within a six-year time period. DOC concentrations were lowest at the outlet and increased going upstream along the flowpath. There was no difference in either DOC concentration or DOM composition between troughs and ponds, indicating the importance of connectivity. The linkages between hydrology, permafrost thaw, and landform change will be key to understanding the altering carbon and nitrogen cycles in a warming Arctic.

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Snow-to-Rain Shifts Regulate Carbon Emissions from Pan-Arctic Permafrost Regions

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The phase of precipitation (i.e., rain or snow) reaching the ground surface is dominantly determined by atmosphere temperature and humidity. The warming atmosphere temperature has caused precipitation to fall more as rainfall than snowfall (i.e., snow-to-rain shifts), leading to decreases in snow fraction of total precipitation. Snow-to-rain shifts directly lead to increases in rainfall fraction and rain-on-snow events, causing significant impacts on terrestrial water storage. The precipitation phase shifts have also decreased snow coverage and snow depth over some permafrost regions in the Northern Hemisphere. With decreased snow depth, the level of snow thermal insulation to the ground is expected to be reduced, which allows more energy to escape from soils to the atmosphere during the cold season, resulting in cooling effects to soil temperature. This cooling effect offsets the warming cold-season air temperature to some extent. Meanwhile, declined snow coverage and snow-season length results in decreased land surface albedo and thus increasing solar radiation absorption and nonlinearly impacts soil temperature, heterotrophic respiration, and carbon emissions. However, due to the opposite effects of decreased snow depth and decreased

snow coverage on soil temperature, the integrated net impact of changes in snow conditions on soil warming is highly uncertain.

Despite the critical role of snow conditions in affecting terrestrial hydrology and ecosystem biogeochemical cycling, the integrated impact of snow-to-rain shifts on permafrost carbon-climate feedback remains unclear. In this study, we used the Energy Exascale Earth System Model (E3SM) land model (ELMv1) to 1) improve understanding of how snow-to-rain shifts impact carbon emissions from pan-Arctic ecosystems via analyzing the sensitivity of ELM-simulated snow water equivalent, active-layer thickness, warm-season net CO2 uptake, and cold-season net CO2 emissions to climate forcing and precipitation-phase partitioning methods (PPMs); 2) evaluate the ELM-simulated SWE and CO2 and CH4 emissions against observationally-constraint datasets; and 3) predict trends of snow-to-rain shifting and cold-season carbon emissions over the pan-Arctic ecosystems under the Representative Concentration Pathway (RCP) 8.5 scenario. Simulations demonstrated good agreements with observation-derived SWE and CO2 emissions over tundra ecosystems. Results also show a larger sensitivity to climate forcing (i.e., CRUJRA, CRUNCEP, and GSWP3) than PPMs. The integrated impacts of snow-to-rain shifts on carbon emissions vary spatially over the permafrost regions. Under RCP 8.5 scenario, the predicted cold-season snowfall fraction will be only around 10% of the total precipitation by the end of the 21st century, strongly modulating permafrost water-carbon-climate interactions and feedback.

* * *

The Vulnerability of Permafrost Carbon to Climate Change: Key Findings from a Decade of Synthesis

Edward Schuur *Permafrost Carbon Network, The Northern Arizona University*

Factors that control terrestrial carbon storage in Arctic and boreal ecosystems are changing. Surface air temperature has risen 2.5 times faster in the Arctic compared to the whole Earth, and permafrost temperatures have been increasing over the last forty years. Disturbance by fire (particularly fire frequency and extreme fire years) is higher now than in the middle of the last century. Soils in the northern circumpolar permafrost zone store 1,460 to 1,600 petagrams of organic carbon (Pg C), almost twice the amount contained in the atmosphere and about an order of magnitude more carbon than contained in plant biomass (55 Pg C), woody debris (16 Pg C), and litter (29 Pg C) in the boreal forest and tundra biome combined. This large permafrost region soil carbon pool has accumulated over hundreds to thousands of years, and there are additional reservoirs in subsea permafrost and regions of deep sediments that are not added to this estimate because of data scarcity. Following the current trajectory of global and Arctic warming, 5% to 15% of the organic soil carbon stored in the northern circumpolar permafrost zone is considered vulnerable to release to the atmosphere by the year 2100. In addition to changing soil organic carbon pools, there is heightened recognition that release rates from inorganic carbon reservoirs in the form of methane hydrates and geologic methane seeps may be increasing due to the opening of new pathways to the atmosphere through degrading permafrost. Many of the abrupt processes that thaw permafrost and release carbon are not represented by Earth System Models but have been described by reduced complexity models. These simplified models project up to 50% additional carbon release by abrupt thaw mechanisms, but they often do not include the response of vegetation that can offset carbon release. An Earth System Model intercomparison project suggested that additional plant carbon uptake, growth, and deposition of new carbon into soil would together completely offset any soil carbon loss this century, and that it would take several centuries before cumulative losses from soils would overwhelm new carbon uptake. Despite these differences, the intercomparison and other studies have indicated that future scenarios with limited human greenhouse gas emissions would reduce changes to high-latitude ecosystems.

Temperature Sensitivity of Permafrost Carbon Release Mediated by Mineral and Microbial Properties

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Temperature sensitivity (Q10) of permafrost carbon (C) release upon thaw is a vital parameter for projecting permafrost C dynamics under climate warming. However, it remains unclear how mineral protection interacts with microbial properties and intrinsic recalcitrance to affect permafrost C fate. Here we sampled permafrost soils across a 1000 km transect on the Tibetan Plateau and conducted two laboratory incubations over 400-day and 28-day durations to explore patterns and drivers of permafrost C release and its temperature response after thaw. We find that mineral protection and microbial properties are two types of crucial predictors of permafrost C dynamics upon thaw. Both high C release and Q10 are associated with weak organo-mineral associations but high microbial abundances and activities, whereas high microbial diversity corresponds to low Q10. The attenuating effects of mineral protection and the dual roles of microbial properties would make the permafrost C-climate feedback more complex than previously thought.

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Representing ph Buffering in Arctic Soils: The Roles of Water, Organic Carbon, and Proton Binding

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Biogeochemical processes that degrade soil organic carbon (SOC) and release CO2 and CH4 are sensitive to soil pH. pH varies with depth and microtopography at Arctic field sites, and pH often changes significantly when these soils are incubated. However, current biogeochemical schemes implemented in Earth System Models (ESMs) do not explicitly account for dynamic pH changes or differences in the buffering capacity of pH among various soils. Process-based representation of pH dynamics via parameterization of soil pH buffering capacity (β) could decrease uncertainty in ESM-simulated CO2 and CH4 fluxes. The objectives of this study are to (1) develop representations for β in carbon-rich Arctic soils using simple soil proxies, including water availability and SOC, and (2) evaluate sensitivity of biogeochemical reaction rates to different β representations. pH titrations were conducted to determine β of 21 Arctic soils (both active layer and permafrost) across three Alaskan sites. A weak relationship for β and %SOC was observed (R2=0.362), whereas gravimetric water content (θg) showed a stronger correlation (R2=0.848). Soil water retention curves developed for a subset of eight soils further supported this trend; higher β was associated with higher water retention during drying (at -1 MPa, R2 = 0.827). One explanation is that higher concentrations of organic ligands involved in proton binding promote water retention. A mechanistic model, the Windermere Humic Aqueous Model (WHAM7), was also used to predict β for each soil. Simulations demonstrated high sensitivity to the fraction of soil organic carbon involved in proton binding (fSOCb), which varied substantially among soils. Empirical correlations with water availability could be an important, simple proxy for β in ESMs. Continued work to understand the relationships between water retention and β could help improve future development of ESMs.

Estimating Greenhouse Gas Production in Thermokarst Lagoons of Bykovsky Peninsula, Siberia

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Thermokarst lagoons, forming when thermokarst lakes are inundated by the sea, are a transition stage where terrestrial permafrost is introduced into the subsea realm. Here permafrost and lacustrine carbon pools are transformed along Arctic coasts. During thaw, previously frozen organic carbon can be converted into the greenhouse gases (GHG) carbon dioxide (CO2) and methane by microorganisms, leading to further climate warming. Especially for transition ecosystems like thermokarst lagoons, it is largely unknown how GHG release is changing and whether thermokarst lagoons are a carbon source or sink.

For getting a first glimpse of the consequences of saltwater inundation, we mimic the inundation of coastal permafrost in an experiment by incubating permafrost and thermokarst samples with artificial sea water under controlled conditions (4°C, dark, anaerobic) for 12 months. We used terrestrial samples from a 2.5 m high Yedoma outcrop, a thermokarst lake core, as well as samples from two neighboring thermokarst lagoons (a nearly closed and a semi-closed) from the Bykovsky Peninsula, Northeast Siberia.

By applying two different scenarios, we aim to estimate (1) future GHG releases from newly formed Arctic lagoons by adding artificial seawater with a constant concentration, and (2) the impact of increasing salinity on GHG production by incubating the samples under freshwater, brackish, and marine conditions.

Here we present (1) total organic carbon and dissolved organic carbon content for deep-drilled sediment cores (~ 30m) and (2) preliminary results on GHG production (methane and CO2) rates measured over 6 months.

First results show that (1) GHG production is higher for inundated terrestrial sediments than for inundated lagoon sediments and (2) increasing salinity is favoring carbon dioxide production while methane production is low.

In conclusion, newly formed thermokarst lagoons, if upscaled to the thermokarst affected shorelines, are likely to produce a significant amount of GHG under our experiment set-up.

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Arctic oilfield infrastructure and ice wedge polygonal terrain, Alpine, Alaska.
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