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 for lower erosion rates along banks with permafrost, but the correlation between presence of permafrost and erosion rate 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.

Process-based thermal-mechanical numerical modeling of coastal erosion on Tuktoyaktuk Island, NT

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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, which lies to the east of the community sheltering the harbour and shores from the impact of waves, is retreating at a rate of ~2 m/yr and is expected to be breached by 2050. In this study, a process-based thermal-mechanical 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, and thermal abrasion at the cliff toe through the formation of a thermoerosional niche under a storm surge, and to understand 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 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.

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, AK. 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 break up 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.

Intra-ice and intra-sediment cryopeg brine occurrence in permafrost near Utqiaġvik (Barrow)

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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 becomes threats to Arctic coasts, infrastructure, and food security.

Demonstration of the ACE (Arctic Coastal Erosion) model at Drew Point, AK 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, AK, 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 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 both cultural sites and infrastructure that will likely be lost or damaged during this time period.

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 was 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 colour. 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.

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.

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 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.

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 changes.

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 on 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 long-term 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 furthermore the salinity of the remaining unfrozen soil pore-water and likely prevent the complete freezeback of the cryopegs developed in relation to channel migration.

The Influence of Thermal Erosion at River Bed 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 nonsimultaneous 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 river bed deformations in the permafrost areas. The results are compared with data of another researches 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 nonsimultaneous impacts of channel-forming rock melting and a freshet.