

Arctic Landscapes in Transition: Responses to Thawing Permafrost

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Observations indicate that over the past several decades, geomorphic processes in the Arctic have been changing or intensifying. Coastal erosion, which currently supplies most of the sediment and carbon to the Arctic Ocean [Rachold *et al.*, 2000], may have doubled since 1955 [Mars and Houseknecht, 2007]. Further inland, expansion of channel networks [Toniolo *et al.*, 2009] and increased river bank erosion [Costard *et al.*, 2007] have been attributed to warming. Lakes, ponds, and wetlands appear to be more dynamic, growing in some areas, shrinking in others, and changing distribution across lowland regions [e.g., Smith *et al.*, 2005]. On the Arctic coastal plain, recent degradation of frozen ground previously stable for thousands of years suggests 10–30% of lowland and tundra landscapes may be affected by even modest warming [Jorgenson *et al.*, 2006]. In headwater regions, hillslope soil erosion and landslides are increasing [e.g., Gooseff *et al.*, 2009].

These changes result from a system-wide response to changing climate [Hinzman *et al.*, 2005] arising from a region-wide warming and thawing of permafrost (Figure 1). Permafrost is ground that has existed at temperatures below freezing for at least 2 years. Within permafrost lie all forms of ground ice (ice in pores, cavities, and voids, or other openings in soil or rock) as well as massive ice (ice formed as lenses, layers, wedges, and blocky structures). Massive ice leaves large unstable voids in soils when it melts.

Although some level of landscape change is expected in response to natural climate variability, the scale and rapidity of recently observed changes suggest that Arctic landscapes may be particularly sensitive to climate change and capable of rapid geomorphic responses to perturbations. Scientists

require improved understanding of mechanisms and feedbacks driving landscape processes to better predict geomorphic responses to climate change.

Complexities of the Arctic's Thermal Dependence

A dynamic Arctic landscape has the potential to alter human and natural systems across a broad range of scales and processes. Thawing permafrost increases permeability of previously frozen soils and changes the distribution of surface waters across the landscape through increasing or decreasing wetland surface area depending

upon site-specific conditions [Hinzman *et al.*, 2005]. Thermally induced erosion of areas with high ground ice content, including hillslopes and river channels, could restructure Arctic drainage networks, greatly changing runoff volumes and timings. It could also increase sediment and nutrient loading to rivers, affecting fisheries and coastal oceans. Erosion and ground surface subsidence (thermokarst) resulting from permafrost degradation damage roads, pipelines, and infrastructure critically important to Arctic communities and resource extraction. Additionally, thawing and release of large carbon reservoirs currently stored in permafrost may influence global climate [Walter *et al.*, 2007; Schuur *et al.*, 2008].

The thermal dependence of Arctic landscapes is a fundamental attribute that distinguishes the Arctic from temperate systems. Permafrost, including ground ice, controls the distribution and routing of

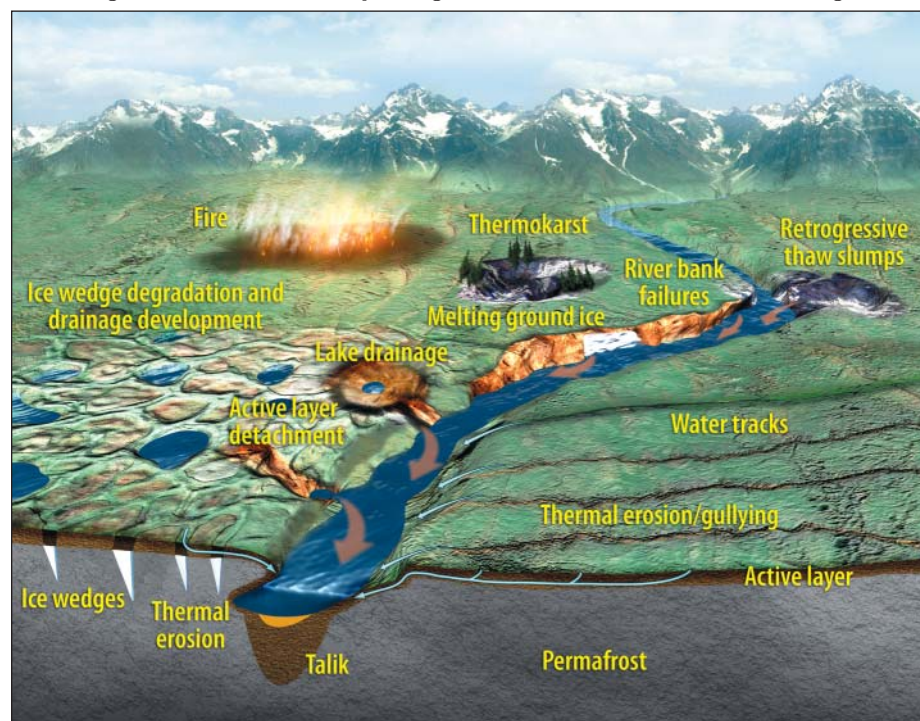


Fig. 1. Conceptual depiction of the Arctic landscape highlighting observed changes in response to thermal alterations of permafrost and melting of ground ice. Aqua-colored arrows depict water fluxes, and tan arrows denote sediment fluxes. Dissolved and solid constituents such as carbon, nutrients, and trace elements will also follow similar pathways. Arrow size does not reflect relative magnitudes. Observations and modeling suggest that the rate and frequency of the processes depicted will increase with rising Arctic temperatures. Thermokarst topography has depressed areas and hummocks formed by melting permafrost. Active layer refers to seasonal thawed ground, and talik is permanently thawed ground.

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water across Arctic landscapes [Quinton and Carey, 2008], exerts a fundamental control on the stability of frozen soils, and induces strong feedbacks on vegetation distributions. Confounding the prediction of landscape response to warming are the facts that permafrost distributions vary in extent from continuous to isolated across the Arctic and sub-Arctic and ground ice distributions are extremely heterogeneous, not readily detected remotely, and difficult to model. Finally, even if a perfect understanding of all landscapes under current conditions existed, transient responses of Arctic landscapes to climate change may be dramatically different in rate and direction than processes found in relatively stable landscapes with and without permafrost.

Significant limitations to predicting landscape responses to warming arise from the fact that most observations of Arctic processes are derived from local- or regional-scale studies of a single landscape component (e.g., lakes, hillslopes, or coastlines) or process (e.g., permafrost temperature change). However, responses in one part of the landscape do not occur in isolation from the rest of the landscape. For example, increased hillslope erosion from thawing soils may increase sediment loading to rivers, causing increased channel mobility that may in turn lead to river erosion, triggering further hillslope instability. Land surface drying in response to permafrost degradation may cause increases in fire; a consequence of fire, however, can be a loss of ground surface insulation and a change in surface albedo that accelerates permafrost thawing. A significant increase in sediment delivery through rivers to deltas could offset the impacts of climate-induced coastal erosion in some areas. As a result, complex feedbacks across systems confound simple determination of drivers and responses.

One Example of Potential Changes: Drainage Network Response to Warming

A seemingly basic question illustrates current limitations in understanding how Arctic terrestrial systems function and how scientists may recognize critical drivers of change: How will Arctic drainage networks respond to thawing permafrost and melting ground ice?

The potential expansion or contraction of channel networks will be a first-order control on local water and energy balances and the routing of water, sediments, nutrients, and carbon from upland to lowland areas and ultimately into oceans. A logical hypothesis, supported by numerical modeling of changes between periglacial and temperate climates in Europe [e.g., Bogaart *et al.*, 2003], is that under permafrost-dominated conditions, channel networks should extend across more of the landscape than under temperate conditions. This arises because the expansion of channelization under permafrost conditions would, in theory, stem from greater surface water runoff due to

limited subsurface storage, which in turn results in greater soil erosion and hence larger channel networks.

Observations of watersheds dominated by permafrost, however, suggest that at the hillslope scale, permafrost-dominated regions are fundamentally different from their temperate counterparts. McNamara *et al.* [1999] observed that in permafrost-dominated environments, drainage areas that would typically support a first-order channel (the smallest, most upslope channels) in temperate systems lacked channels but possessed “water tracks.” Water tracks are linear or curvilinear features where enhanced soil moisture allows water to be preferentially and efficiently routed from hillslopes. Typically, water tracks occupy poorly defined depressions and are not consistently connected to higher-order channels occupying valley bottoms. McNamara *et al.* [1999] hypothesized that despite the dominance of surface runoff processes in transmitting water from hillslopes to channel networks, the inhibiting effect of frozen ground on erosion prevented distinct channel networks from developing on hillslopes.

Numerous observations suggest that increased erosion associated with thawing permafrost and melting ground ice may occur more rapidly than reductions in surface runoff associated with deepening thaw layers. These observations include increased thermal erosion on hillslopes [Gooseff *et al.*, 2009], detachments of seasonally thawed layers following wildfire, gully development within water tracks [Osterkamp *et al.*, 2009], and the expansion of stream channels in response to melting ground ice [Toniolo *et al.*, 2009]. What drives the timing and location of surface erosion is poorly understood, although the distribution of massive and buried ice bodies [Marsh and Neumann, 2001] and extreme hydrological events appear to be important contributors. Also unknown is whether these features represent transient events or if they are permanent changes in the landscape [Gooseff *et al.*, 2009].

Current Efforts to Understand Arctic Landscapes

At present, the ability to predict Arctic landscape response to a changing climate is limited. Numerical and analytical models have been extensively used to predict permafrost thawing and deepening of the seasonally thawed (active) layer in response to warming surface conditions [see Riseborough *et al.*, 2008]. Unfortunately, these models typically are one-dimensional (vertical) and fail to capture the three-dimensional process of water interacting with thermally controlled soil processes. Further, they do not predict dynamic responses to changes in soil moisture, collapse of soil structure, vegetation change, or land surface response to thawing permafrost.

Recent hydrological modeling advances [see Riseborough *et al.*, 2008, and references therein] offer the promise of improved

hydrological predictions in Arctic regions by incorporating active-layer parameterizations to explore seasonal variability and test predicted warming scenarios on runoff generation and routing. These models, however, still lack the ability to evolve the physical structure of watersheds, limiting their dynamical applications. Also promising are recent efforts to consider enhanced melting of massive ground ice by flowing water [Marsh and Neumann, 2001]. Other efforts to estimate the loss of soil volume due to ground ice melting and the resulting failure of lake shores [Plug and West, 2009] are also yielding interesting results. Such efforts offer possible ways that feedbacks associated with lake expansion or drainage can be incorporated into larger models. Nonetheless, they are still focused on isolated components of a vast landscape.

The Need for an Integrated Approach

It will not be possible to fully assess changes to and vulnerabilities of Arctic ecosystems, carbon, water and energy budgets, infrastructure, and societies until scientists first develop the capability to move toward a landscape-scale understanding of Arctic responses to climate change. This requires identification of the drivers for change, the geomorphic responses to these drivers, and the feedbacks between drivers and responses. The data and level of process understanding needed for this advancement vary significantly in both temporal and spatial scales for different disciplines. For example, a stream ecologist may require predictions of hillslope stability within a single watershed over a time frame of decades to assess the impact of increased sediment and nutrient loads on critical subsistence fisheries. Global climate modelers need to be able to scale up such processes to represent changes in the distribution and connectivity of surface water bodies at the continental scale at time spans of centuries to accurately capture how geomorphic changes affect carbon, water, and energy cycles.

At all scales, however, a number of key questions must be answered, which include the following: What are the process interactions between geomorphic, permafrost, ecologic, hydrologic, and geochemical systems? What are and how do scientists identify the thresholds for landscape change in response to climate change? Will transitional processes differ significantly from end state processes? How will changes in land surface characteristics alter the distribution and transport of mass across the landscape?

Further, improved prediction of a dynamic Arctic landscape cannot be achieved without significant advances in observations and process-based studies. Researchers should build on available scientific work at the Long Term Ecological Research (LTER) stations in Alaska and focused field studies conducted in northern Canada, Europe, and Russia. A number of U.S. and internationally based efforts (e.g., Arctic Observing Network (AON),

Sustained AON, the International Polar Year, and the Circumpolar Active Layer Monitoring (CALM) Network) have sought to coordinate research efforts and focus attention on the Arctic.

Within the hydrogeomorphic community, a concerted effort is needed to identify and fund studies that integrate across landscape elements and leverage existing Arctic data and research networks. Given the scale of the questions to be addressed, a particular focus must be placed on identifying existing and developing new remote sensing technologies to detect near-surface and subsurface changes in the Arctic. Of critical importance is the ability to move from point-based measurements to spatially distributed assessments of active-layer dynamics and the distribution of ground ice in the shallow subsurface.

Through such integrated efforts, the role of permafrost thawing within changing Arctic landscapes as global temperatures increase will be better quantified. Armed with such data, Arctic communities will be better able to cope with rapid alterations to their lifestyle, and the global community will be better able to understand how such landscape changes affect carbon budgets.

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