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From documentation to prediction: raising the bar for thermokarst research

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1. Introduction

Rapid warming in the Arctic and the resulting loss of permafrost have caused dramatic changes in Arctic landscapes through thermokarst activity. Thermokarst refers to subsidence of the land surface driven not by chemical dissolution of material but instead by the phase change of ice to water in the subsurface (French 2007). Subsidence arising from this phase change may result from several related processes: 1) the loss of volume due to the phase change of ice to water; 2) the compaction and settling of soil grains no longer supported by ice; 3) compaction of soil matrix due to the loss of pore pressures and water volume resulting from drainage of fluid from the unfrozen soil matrix; and 4) to a much smaller and slower extent, the loss of organic material due to increased microbial degradation under unfrozen conditions. Understanding of the first three of these processes requires quantification of coupled thermal, hydrological, and mechanical processes in the thawing soils and bulk ice. Freeze-thaw processes during annual cycles in the active layer may result in recoverable subsidence as pore water refreezes, resulting in cryosuction and frost heave. Non-recoverable subsidence is typically of greater interest and importance to infrastructure, local hydrology, and biogeochemical feedbacks(Kokelj and Jorgenson 2013). This land surface deformation occurs due to melting of bulk ice, either in ice wedges (large vertically oriented ice

inclusions) or ice lenses (thin, horizontally oriented ice layers), or as previously unfrozen ice-rich soil loses the structural support of ice.

A documented increase of thermokarst has raised many concerns about impacts on local infrastructure and feedbacks on the global carbon cycle through decomposition of newly thawed organic matter. These concerns have led to an increase in research on the controls on and impacts of permafrost thaw and resulting thermokarst activity. A review of the Web of Science reveals that, in the last decade, the number of published papers with the keyword "thermokarst" has gone from approximately 15 to over 50 per year. As the field grows, two new avenues of research – remote sensing and mechanistic modeling – are changing how we understand processes and scale this understanding from field observations to regional assessments. This essay highlights new and exciting research in remote sensing and mechanistic modeling and describes how these fields are creating opportunities for moving beyond documentation to prediction of when, where, and how thermokarst will occur.

2. Advancing predictive understanding of thermokarst

Recent research efforts have documented a greater occurrence of thermokarst features in association with increased air and permafrost temperatures (Jorgenson et al. 2006; Lantz and Kokelj 2008; Kokelj and Jorgenson 2013). There is an abundance of published work on the physical attributes, occurrence, and changes in the occurrence of thermokarst related landforms. In addition to the review by Kokelj and Jorgenson (2013), Grosse et al. (2013) published a review of thermokarst lake research combined with a detailed discussion of causes of lake expansion and drainage. Jorgenson et al. (2010) presented a detailed review of the climatic and ecosystem controls on the thaw of permafrost and associated thermokarst development.

In the authors' opinion, this combined body of work has identified key theories explaining how permafrost loss drives thermokarst and the impacts of thermokarst on infrastructure and

climate feedbacks, and documented these changes and impacts in many ways. To move from documentation to prediction, however, advances on two research fronts are needed. First, prediction through mechanistic understanding of thermokarst requires models that accurately relate climatic drivers to physical processes that control thermokarst development. And second, remote sensing is needed to parameterize and evaluate models and to extrapolate their predictions from local scales, at which theory and mechanistic models are applied, to regional scales at which climate impacts are measured.

3. Understanding the evolution and prediction of thermokarst via physics-based models

Models of thermokarst play a critical role in both understanding the physics behind thermokarst and predicting future thermokarst in a warming climate or disturbed system. In this way, models act as an integrating tool to incorporate field site-scale observations as input, calibration, and evaluation data.

Numerous past efforts have looked to use empirical correlations to predict thermokarst (van Huissteden et al. 2011; Yi et al. 2014; McGuire 2015; Lara et al. 2015); here the focus is on spatially resolved mechanistic models which directly represent physics and thereby causally predict thermokarst and its effects. Such models are based on conservation of mass and energy equations while predicting deformation from melting ground ice (Painter et al. 2012) . In the case of thermokarst, strong coupling terms make the system computationally and algorithmically difficult (Painter et al. 2012). Cryosuction, in which thermal partitioning of ice and liquid in unsaturated soils results in large water fluxes into the freezing zone, can result in significant advected fluxes of energy localized spatially and temporally. Subsidence and frost heave, through poroelastic effects (in the case of distributed ice) and Biot consolidation (in the case of bulk ice), result in an evolving volume for water and ice. The entire system is driven by meteorological forcing. The energy balance is often nonlinear owing to variations in snow distribution, albedo

changes, and large swings in air temperature and incoming radiation present in high-latitude regions. Painter et al. (2012) carefully described a set of model needs for capturing each of these mechanistic processes. While no current model captures all of these processes, many models represent a subset of the needed physics.

Modeling permafrost and active layer evolution, at its core, relies on an energy equation. The simplest models are based on Stefan's equation for propagation of a phase change front, which can enable analytical solutions (Lunardini 1991; Kurylyk et al. 2014). More complex approaches capture diffusion of energy but ignore advective transport of energy (Romanovsky et al. 1997; Hinzman et al. 1998; Ling and Zhang 2003; Zhang et al. 2008). With the exception of thermal erosion by surface water flow, the importance of advected energy is openly debated within the field.

Hydrology has relied extensively on modeling for decades. The most mechanistic of hydrologic models are integrated, distributed models, which include both subsurface and surface flow. Recent work has focused on incorporating energy and phase change necessary for permafrost evolution, active layer change, and thermokarst initiation. Several efforts have focused on thermal evolution in saturated soils – especially talik formation and evolution (McKenzie et al. 2007; Rowland et al. 2011; Grenier et al. 2013). Representations of air/water/ice partitioning in freezing, unsaturated soils have been improving (Painter and Karra 2014), owing to a limited but growing set of laboratory experiments designed to quantify this partitioning (Suzuki 2004; Watanabe and Wake 2009; Wen et al. 2011; Wu et al. 2013). More modelers are looking at unsaturated systems, especially active layer evolution (Dall'Amico et al. 2011; Frampton et al. 2011; Endrizzi et al. 2014; Atchley et al. 2015).

Despite significant advances in the thermal and hydrological systems, coupling these equations to mechanics to fully capture thermokarst is ongoing. Deformation models for the case of partially saturated and frozen soils are limited. Soil subsidence in the absence of ice is more

commonly studied (Fredlund and Hasan, 1979; Schrefler, 2002). Thermal and mechanical models have been combined for simulation of the evolution of thermokarst lakes (Plug and West 2009; Kessler et al. 2012). Models coupling thermal, hydrological, and mechanical (THM) models in saturated soils have proven useful for modeling subsidence (Lewis et al. 2012; Zhang and Michalowski 2015). Older efforts included one-dimensional column models of subsidence in unsaturated soils (Corapcioglu and Panday 1995).

While there is no current model that reasonably represents all physics needed for a mechanistic model of thermokarst in multiple dimensions, newer models are approaching that goal. In the coming decade model advances are expected to greatly improve our ability to understand and predict when, where, and how thermokarst will occur.

4. Detection of thermokarst-driven subsidence with remotely sensing methods

Direct field observations, aerial photographs, and satellite imagery have served as the main tools for quantifying the occurrence of thermokarst. Recently, the availability, spatial resolution, and accuracy of remotely sensed technologies capable of measuring ground surface elevations and changes in these elevations have all increased rapidly. These techniques are beginning to provide datasets at the spatial and temporal resolutions needed to parameterize and test the mechanistic models discussed above, and to upscale model predictions to from site to regional.

Differencing measurements of ground surface elevations collected at multiple time intervals using both interferometric synthetic aperture radar (InSAR) and airborne light detection and ranging (LiDAR) offer significant potential for obtaining spatially distributed datasets on the rate, timing, magnitude, and patterns of thermokarst subsidence. Liu et al. (2010) used InSAR to documented 1-4 cm of seasonal variations in ground surface elevations related to annual freezing and thawing of the active layer across a region of the north slope of Alaska and a similar magnitude of long term subsidence resulting from the melting of ground ice over a decadal time scale. They

hypothesized that the longer term loss of soil volume and lowering of the ground surface may help explain why field measurements have shown little increase in the thaw depth despite documented warming.

Liu et al. (2014) used InSAR to document up to 8 cm of ground subsidence following the 2008 Anaktuvuk River fire on the coastal plain of Alaska and Liu et al. (2015) documented thermokarst resulting from road construction. In the fire study, the authors note that the lack of spatial and vertical constraints on subsurface ice distributions and surface microtopography limited the ability to investigate the causes of variability in subsidence patterns. While a loss of interferometric coherence due to changes in land surface properties limited the ability to accurately assess surface deformation in many locations, the use of L-band PALSAR in the subsequent road study helped to reduce this loss.

An alternative method for quantifying surface deformation across relatively large study areas is using airborne LiDAR data at two different time periods. Along the coast of Alaska, Jones et al. (2013) compared ground surface elevations from LiDAR datasets acquired in 2006 and 2010 to quantify the magnitude and spatial patterns of thermokarst related ground subsidence. Given the uncertainty in the relative accuracy of the datasets, this study was able to identify changes greater than 0.55 m as statistically significant change. Changes of this magnitude were limited to 0.3% of the study area but occurred in close association with ice-bonded coastal, river, and lake bluffs, frost mounds, ice wedges, and thermo-erosional gullies. As repeated acquisition of airborne LiDAR becomes more common across permafrost landscapes, this type of analysis holds great promise for quantifying the rates and patterns of thermokarst development in response to thermal and hydrological drivers.

5. **Conclusions**

To date the majority of published research on thermokarst has been directed at documenting its form, occurrence, and rates of occurrence. The fundamental processes driving thermokarst have long been largely understood. However, the detailed physical couplings between, water, air, soil, and the thermal dynamics governing freeze-thaw and soil mechanics is less understood and not captured in models aimed at predicting the response of frozen soils to warming and thaw. As computational resources increase more sophisticated mechanistic models can be applied; these show great promise as predictive tools. These models will be capable of simulating the response of soil deformation to thawing/freezing cycles and the long-term, non-recoverable response of the land surface to the loss of ice. At the same time, advances in remote sensing of permafrost environments also show promise in providing detailed and spatially extensive estimates in the rates and patterns of subsidence. These datasets provide key constraints to calibrate and evaluate the predictive power of mechanistic models. In the coming decade, these emerging technologies will greatly increase our ability to predict when, where, and how thermokarst will occur in a changing climate.

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