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Invited research article

Ten years of measurements and modeling of soil temperature changes and their effects on permafrost in Northwestern Alaska

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ABSTRACT

Multiple studies demonstrate Northwest Alaska and the Alaskan North Slope are warming. Melting permafrost causes surface destabilization and ecological changes. Here, we use thermistors permanently installed in 1996 in a borehole in northwestern Alaska to study past, present, and future ground and subsurface temperature change, and from this, forecast future permafrost degradation in the region. We measure and model Ground Surface Temperature (GST) warming trends for a 10 year period using equilibrium Temperature-Depth (TD) measurements from borehole T96-012, located near the Red Dog Mine in northwestern Alaska—part of the Arctic ecosystem where a continuous permafrost layer exists. Temperature measurements from 1996 to 2006 indicate the subsurface has clearly warmed at depths shallower than 70 m. Seasonal climate effects are visible in the data to a depth of 30 m based on a visible sinusoidal pattern in the TD plots that correlate with season patterns. Using numerical models constrained by thermal conductivity and temperature measurements at the site, we show that steady warming at depths of ~30 to 70 m is most likely the direct result of longer term (decadal-scale) surface warming. The analysis indicates the GST in the region is warming at ~0.44 ± 0.05 °C/decade, a value consistent with Surface Air Temperature (SAT) warming of ~1.0 ± 0.8 °C/decade observed at Red Dog Mine, but with much lower uncertainty. The high annual variability in the SAT signal produces significant uncertainty in SAT trends. The high annual variability is filtered out of the GST signal by the low thermal diffusivity of the subsurface. Comparison of our results to recent permafrost monitoring studies suggests changes in latitude in the polar regions significantly impacts warming rates. North Slope average GST warming is ~0.9 ± 0.5 °C/decade, double our observations at RDM, but within error. The RDM warming rate is within the warming variation observed in eastern Alaska, 0.36–0.71 °C/decade, which suggests changes in longitude produce a smaller impact but have warming variability likely related to ecosystem, elevation, microclimates, etc. changes. We also forward model future warming by assuming a 1D diffusive heat flow model and incorporating latent heat effects for permafrost melting. Our analysis indicates ~1 to 4 m of loss at the upper permafrost boundary, a ~145 ± 100% increase in the active layer thickness by 2055. If warming continues at a constant rate of ~0.44 ± 0.05 °C/decade, we estimate the 125 m thick zone of permafrost at this site will completely melt by ~2150. Permafrost is expected to melt by ~2200, ~2110, or ~2080, if the rate of warming is altered to 0.25, 0.90, or 2.0 °C/decade, respectively, as an array of different climate models suggest. Since our model assumes no advection of heat (a more efficient heat transport mechanism), and no accelerated warming, our current prediction of complete permafrost loss by 2150 may overestimate the residence time of permafrost in this region of Northwest Alaska.

1. Introduction

Mean Surface Air Temperature (SAT) worldwide has been rising since at least the early 20th century, indicating the Earth surface is warming (Karl and Trenberth, 2003; Hansen et al., 2006; Schmunk, 2013). The role of surface warming on permafrost is a major concern in Alaska and throughout the Arctic because melting permafrost often leads to ground destabilization as well as ecosystem changes (Qingbai et al., 2002; Jorgenson et al., 2008; Osterkamp et al., 2009; U.S. Arctic Commission Permafrost Task Force, 2003). Rates of surface warming and permafrost melting, however, are highly variable in space and time (Lachenbruch and Marshall, 1986; Lachenbruch, 1994; Osterkamp, 2003, 2007). Northwest Alaska represents a vast region (>100.000 km^2) where a significant continuous permafrost layer (up to ~400 m thick) exists, yet only a very limited number of permafrost studies/forecasts exist (Jorgenson et al., 2008). Few studies exist in this region because of limited high quality temperature monitoring boreholes able to assess permafrost conditions.

A key priority for this study is to use newly analyzed borehole temperature and thermal conductivity data for a 125 m deep borehole at the

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Red Dog Mine (RDM) to determine not only past and present warming, but also to use these results to forward model future permafrost degradation in northwest Alaska. RDM is located in the Northwest Arctic Borough, Alaska, (Fig. 1) within the Arctic ecosystem and north of the continuous permafrost line. Well T96-012 is located at the southern end of the RDM area, away from major mining activities, water tributaries, and with minimal vegetation disturbance (AMEC Environment and Infrastructure, 2012), making this an ideal location for permafrost degradation and climate change analysis. In fact, the well was specifically drilled and designed for monitoring permafrost degradation in the region with time. We use geologic logs and core samples provided by the mine to determine thermal properties for T96-012. These data, combined with a decade of quarterly temperature measurements at depth intervals of 4.5–7.5 m are used to assess and model subsurface temperature change and permafrost degradation with time. We use results from this analysis to provide better insight into permafrost evolution in this region that can be used to develop time sensitive strategies for predicting and mitigating changes associated with permafrost melting. This study provides new insight into ground temperature change and its influence on permafrost at the western end of the Brooks Range in northwest Alaska—an area where very few long-term temperature or permafrost studies exist (Lachenbruch and Marshall, 1986; Yoshikawa, 2013; Clow, 2013; Biskaborn et al., 2015). The analysis presented here is, to our knowledge, (1) the first published report of long-term surface and borehole temperature changes inland in northwestern Alaska, (2) the first high-temporal resolution borehole study using permanently installed borehole thermistors, and (3) the first deep borehole (>100 m) decadal scale temperature depth study in northwest Alaska.

2. Previous studies

Ground Surface Temperature (GST) combined with borehole temperature measurements represent a valuable method for understanding and constraining permafrost change in the arctic with time (Lachenbruch and Marshall, 1986; Osterkamp, 2003, 2005, 2007; Smerdon et al., 2004). Consequently, GST combined with subsurface borehole Temperature-Depth (TD) measurements are frequently used to monitor changes in the permafrost (Lachenbruch, 1994; Osterkamp, 2003, 2007). Currently, permafrost monitoring wells exist along a North-South transect in eastern Alaska along the Trans-Alaska Pipeline System (TAPS) and other select sites where high-quality temperature data have been collected since the early 1980′s (Lachenbruch and Marshall, 1986; Osterkamp, 2003, 2007; Romanovsky et al., 2015). Additionally, a recent effort began in 2005 to install permafrost and active layer monitoring sites in every village throughout Alaska. Most new

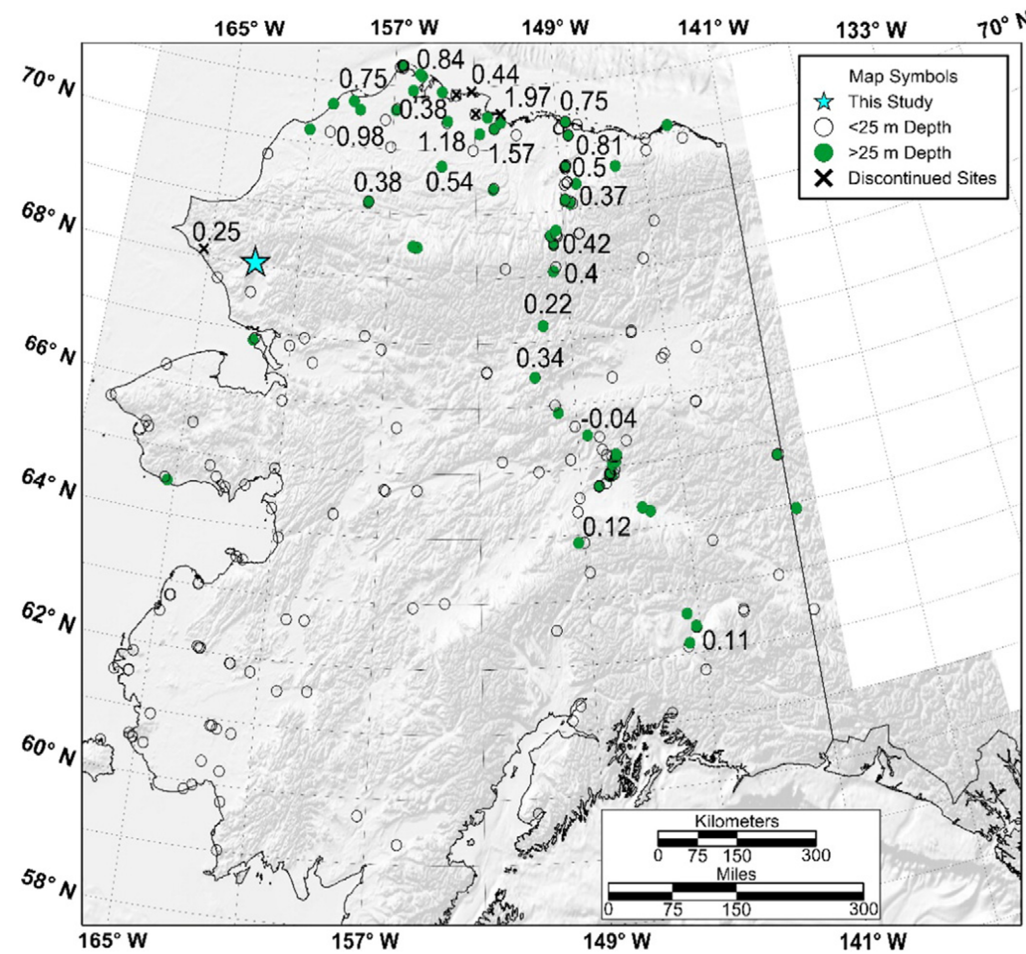

Fig. 1. Sites throughout Alaska that are catalogued within the Global Terrestrial Network for Permafrost (Yoshikawa, 2013; Clow, 2013; Biskaborn et al., 2015). Black X's are sites that are no longer accessible, black open circles are monitoring sites <25 m deep, green filled circles are sites >25 m deep, and the blue star is the location of this study. The nearest active permafrost monitoring sites are Noatak and Kivalina, which are both <6 m deep (Yoshikawa, 2013). The nearest deep well was Cape Thompson, which is no longer accessible (Clow, 2013). Average warming rate estimates, °C/decade, are displayed for sites with published temperature data or warming values. Note that not all monitoring sites have published data for regional comparison.