Extreme Sensitivity of Shallow Lakes and Sublake Permafrost to Arctic Climate Change

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The interaction and feedbacks between surface water and permafrost are fundamental processes shaping the surface of continuous permafrost landscapes. Lake-rich regions of Arctic lowlands, such as coastal plains of northern Alaska, Siberia, and Northwest Canada, where shallow thermokarst lakes often cover 20-40% of the land surface are a pronounced example of these permafrost processes. In these same Arctic coastal regions, current rates of near-surface atmospheric warming are extremely high, 0.8 °C / decade for example in Barrow, Alaska, primarily due to reductions in sea ice extent (Wendler et al., 2014). The thermal response of permafrost over recent decades is also rapid, warming approximately 0.6°C / decade for example at Deadhorse, Alaska, yet this permafrost is still very cold, less than -6°C (Romanovsky et al., 2015). The temperature departure created by water in lakes set in permafrost is well recognized and where mean annual bed temperatures (MABT) are above 0 °C, a talik develops (Brewer, 1958). The critical depth of water in lakes where taliks form is generally in excess of maximum ice thickness, which has historically been around 2 m in northern Alaska. Thus, lakes that are shallower than the maximum ice thickness, which are the majority of water bodies in many Arctic coastal lowlands, should maintain sublake permafrost and have a shallow active layer if MABT's are below freezing. Recent analysis, however, suggests a lake ice thinning trend of 0.15 m / decade for lakes on the Barrow Peninsula, such that the maximum ice thickness has shifted to less than 1.5 m since the early 2000's. We hypothesized that the surface areas most sensitive to Arctic climate warming are below lakes with depths that are near or just below this critical maximum ice thickness threshold primarily because of changing winter climate and reduced ice growth. This hypothesis was tested using field observations of MABT, ice thickness, and water depth collected from lakes of varying depths and climatic zones on the coastal plain and foothills of northern Alaska. A model was developed to explain variation in lake MABT by partitioning the controlling processes between ice-covered and open-water periods. As expected, variation in air temperature explained a high amount of variation in bed temperature (72%) and this was improved to 80% by including lake depth in this model. Bed temperature during the much longer ice-covered period, however, was controlled by lake depth relative to regional maximum ice thickness, termed the Effective Depth Ratio (EDR). A piecewise linear regression model of EDR explained 96% of the variation in bed temperature with key EDR breaks identified at 0.75 and 1.9. These breaks may be physically meaningful towards understanding the processes linking lake ice to bed temperatures and sublake permafrost thaw. For example if regional lake ice grows to 1.5 m thick, the first break is at lake depth of 1.1 m, which will freeze by mid-winter and may separate lakes with active-layers from lakes with shallow taliks. The second EDR break for the same ice thickness is at a lake depth of 2.9 m, which may represent the depth where winter thermal stratification becomes notable (greater than 1 °C) and possibly indicative of lakes that have well developed taliks that store and release more heat. We then combined these ice-covered and open-water models to evaluate the sensitivity of MABT to varying lake and climate forcing scenarios and hindcast longer-term patterns of lake bed warming. This analysis showed that MABT in shallow lakes were most sensitive to changes in ice thickness, whereas ice thickness had minimal impact on deeper lakes and variation in summer air temperature had a very small impact on MABT across all lake depths. Using this model, forced with Barrow climate data, suggests that shallow lake beds (1-m depth) have warmed substantially over the last 30 years (0.8 °C / decade) and more importantly now have an MABT that exceeds 0 °C. Deeper lake beds (3-m depth), however, are suggested to be warming at a much slower rate (0.3 °C / decade), compared to both air temperature (0.8 °C/ decade) and permafrost (0.6 °C/ decade). This contrasting sensitivity and responses of lake thermal regimes relative to surrounding permafrost thermal regimes paint a dramatic and dynamic picture of an evolving Arctic land surface as climate change progresses (Fig 1). We suggest that the most rapid areas of permafrost degradation in Arctic coastal lowlands are below shallow lakes and this response is driven primarily by changing winter conditions.

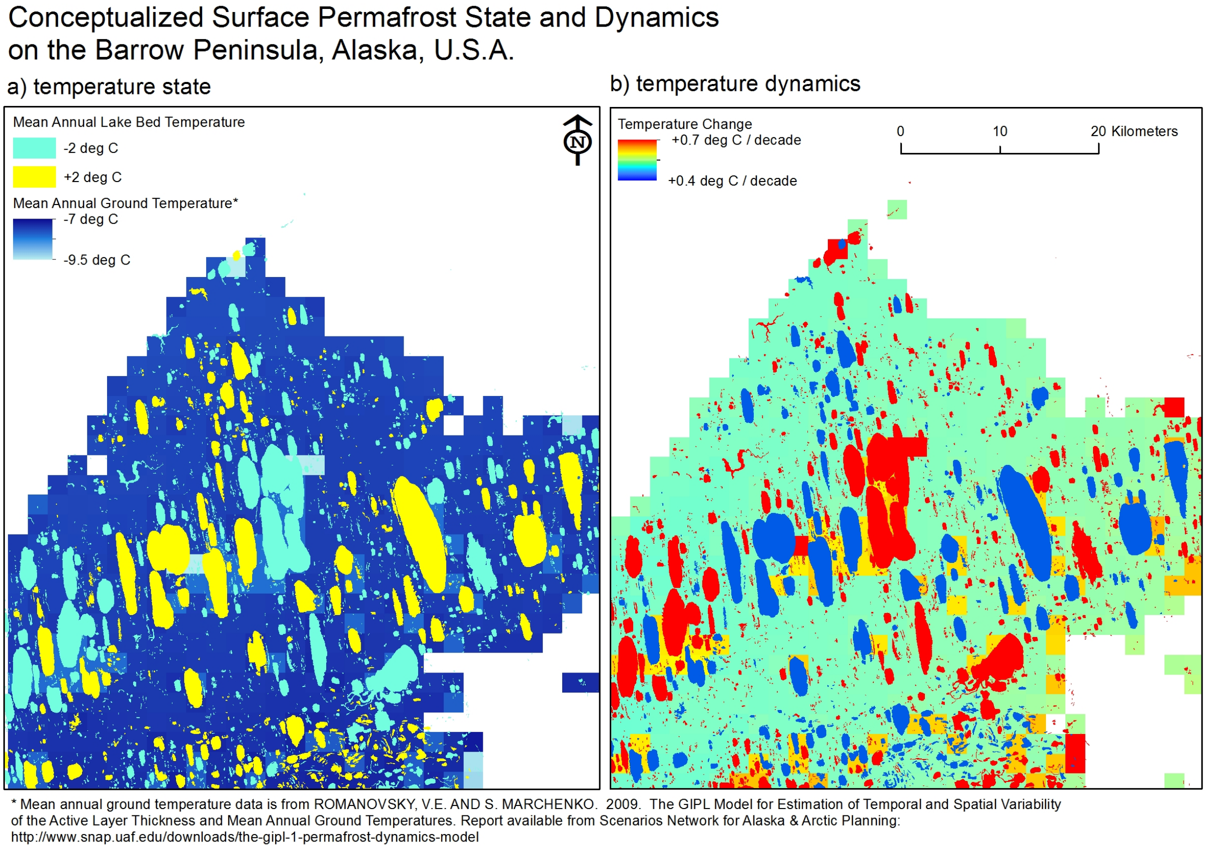

Figure 1: Conceptualized map of surface permafrost state and dynamics on the Barrow Peninsula, Alaska, U.S.A.

References

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