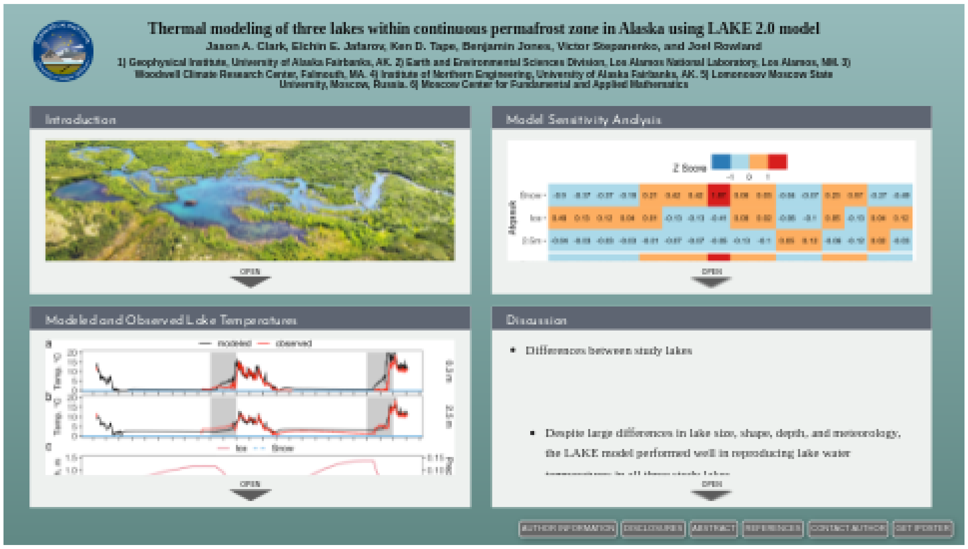
Thermal modeling of three lakes within continuous permafrost zone in Alaska using LAKE 2.0 model



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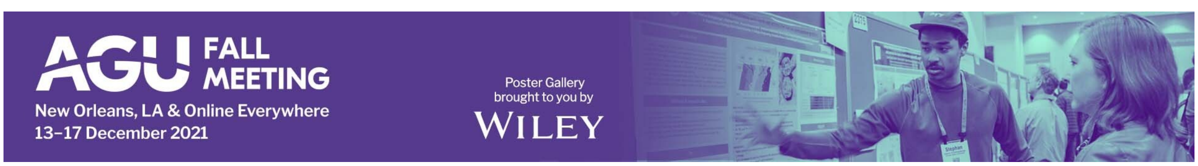

INTRODUCTION

Figure 1. Example lake in permafrost landscape (J. Clark 2021).

Forty percent of Arctic lowlands are covered by lakes (Grosse et al., 2013) (https://www.zotero.org/google-docs/?eAx9r4). Lakes in the Arctic are important reservoirs of heat that affect permafrost thaw and carbon and methane emissions (Abnizova et al., 2012; Rowland et al., 2011) (https://www.zotero.org/google-docs/?5UgIwb). Lake water temperatures regulate heat fluxes, biogeochemical activity, and are influenced by meteorological conditions and the surface radiative balance. Surface water bodies play an important role in the formation of taliks, subsequent surface-groundwater interactions, and advective heat flow degrading permafrost (Jorgenson et al., 2006; Jorgenson and Shur, 2007; Rowland et al., 2011) (https://www.zotero.org/google-docs/?gJH09U). Understanding and modeling water temperatures in permafrost landscapes is critical to be able to predict future talik development, permafrost thaw, and greenhouse gas releases.

In this study, we use the 1-D LAKE model, which has been in active development since 2011, presenting a compromise between explicit resolution of key physical processes and computational efficiency (Stepanenko et al., 2016b, 2011) (https://www.zotero.org/google-docs/?eWtGXy). An advantage of the model in context of climate-lake-permafrost interaction studies, is that it explicitly simulates phase transitions in underlying ground at different depth zones of bottom sediments (Stepanenko et al., 2016b) (https://www.zotero.org/google-docs/?I7UTrF). Moreover, 1D models serve as an optimal solution tool to perform multiple runs for large numbers of water bodies under different scenarios of climate change (Grant et al., 2021) (https://www.zotero.org/google-docs/?vnEqED).

Here we validate the LAKE model thermodynamics using water temperature observations from three Arctic lakes in Alaska: FoxDen, Atqasuk, and Toolik. All three lakes are located within the continuous permafrost zone in the northern part of Alaska (Jorgenson et al., 2008; Obu et al., 2019) (https://www.zotero.org/google-docs/?X75ing). The lakes represent three different climate regimes spanning the continuous permafrost zone, ranging from -6 to -12 °C mean annual air temperatures (MAAT). The morphometry (shape) of the lakes varies from small and shallow (FoxDen) to big and deep (Toolik). Validating lake water temperatures among diverse climatological conditions and lake morphometries allows us to quantify the robustness of the LAKE model. This is a crucial step toward applying the LAKE model to examine the impact of water bodies on Arctic permafrost.

Methods

LAKE model setup

The simulation conducted in the present study spans 2, 4, and 4 years at three study lake sites (Atqasuk, Fox Den, and Toolik) respectively, with a 1 hour time step (1 day for Fox Den) for the input and output data. In the set-up stage, specific features of the study lakes were prescribed, namely the depth of the lake, area of lake surface, morphometry of the lake bottom, the vertical water grid resolution (1m), the vertical soil grid resolution (1m) and depth (10m), and soil type (silty loam). The lake bottom morphometry is expressed via the dependence of the horizontal cross section area on the depth (Iakunin et al., 2020) (https://www.zotero.org/google-docs/?doEaL8). The LAKE 2.0 model was initialized with water column temperature data measured at each site. Atmospheric forcing input data were taken from local meteorological stations (Toolik, Atqasuk), remote meteorological stations (Fox Den) and remotely sensed satellite data (Fox Den, Atqasuk).

Study site: Atqasuk

Atqasuk lake 201 (70.452497, -156.951984) is located on the North Slope of Alaska, approximately 90 km south of Utqiagvik, AK. It is a large lake (2,732,050 m^2) with a maximum depth of 2.54 m surrounded by sedge, moss, dwarf-shrub wetland tundra (Walker et al., 2005) (https://www.zotero.org/google-docs/?TmjNx0). The area is classified as continuous permafrost, but the presence and depth of permafrost under the lake is not confirmed (Jorgenson et al., 2008; Obu et al., 2019) (https://www.zotero.org/google-docs/?rdMEuG). Meteorological data was measured locally at the lake except for frozen season precipitation. Mean annual air temperature was -8.98 °C. Validation water temperatures were measured hourly at 30 cm and 250 cm for 2013 to 2015 (Hinkel et al., 2012) (https://www.zotero.org/google-docs/?YEpYz3). The simulation period was 2013-08-12 to 2015-08-10.

Study site: Fox Den

Fox Den (66.55877, -164.45670) is located on the Northwest portion of the Seward Peninsula in Western Alaska. It is a small lake (17,861 m^2) approximately 2 km from the Chukchi Sea coast, located in a drained lake basin with a maximum depth of 1.6 m, and surrounded by tussock sedge, dwarf-shrub, moss tundra (Walker et al., 2005) (https://www.zotero.org/google-docs/?B4slxl). The area is classified as continuous permafrost, but the presence and depth of permafrost under the lake is not confirmed (Jorgenson et al. 2008; Obu et al. 2019). Meteorological data was not available locally at Fox Den. Instead, meteorological data from the National Weather Service station at Kotzebue, AK

(~90km ENE) was used and short and longwave radiation was obtained from NASA CERES (Rutan et al., 2015; Wielicki et al., 1998) (https://www.zotero.org/google-docs/?Wxb0KV). Mean annual air temperature at Kotzebue was -5.37 °C for 2009 to 2013. Validation water temperatures were measured hourly at 1.5 m for 2009-2013 (Jones et al., 2021) (https://www.zotero.org/google-docs/?Xfh0XR). The simulation period was 2009-06-10 to 2013-06-10.

Study site: Toolik

Toolik Lake (68.63150, -149.60740) is located on the North Slope of Alaska. It is a large and deep lake (1,492,898 m2) with a maximum depth of 26.5m surrounded by non-tussock sedge, dwarf-shrub, moss tundra and prostrate dwarf-shrub, herb tundra (Walker et al., 2005) (https://www.zotero.org/google-docs/?YCUmdC). The lake has a seasonal inlet and outlet. The area is classified as continuous permafrost, but the presence and depth of permafrost under the lake is not confirmed (Jorgenson et al. 2008; Obu et al. 2019). Meteorological data is collected at the nearby Toolik Field Station (~30m W) (Edgar et al., 2018) (https://www.zotero.org/google-docs/?xlb3OI) and includes atmospheric pressure [mb], all season precipitation [mm], snow depth [m], air temperature [°C], wind speed [m s^{-1}], wind direction [degrees], and short and longwave radiation [W m^{-1}]. Mean annual air temperature at Toolik was -7.36 °C. The simulation period was 2013-05-17 to 2016-09-18.

MODELED AND OBSERVED LAKE TEMPERATURES

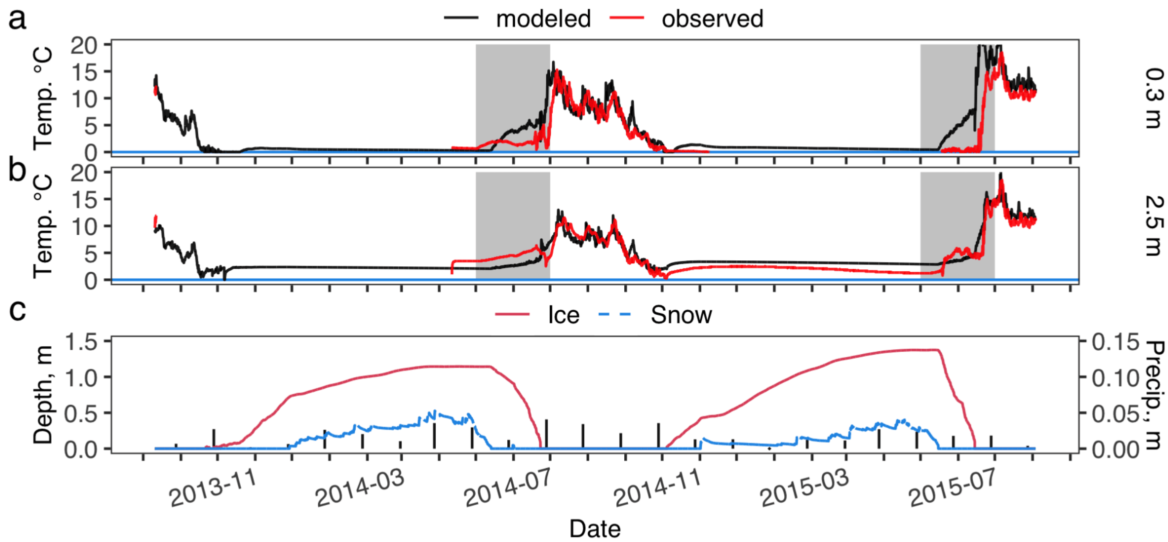

Figure 2. Atqasuk modeled and observed lake water temperature at 0.3 m (a) and 2.5 m (b) and modeled lake ice depth, lake snow depth and measured monthly precipitation (vertical black bars) (c). Grey shading indicates periods of uncertainty in temperature sensor depth.

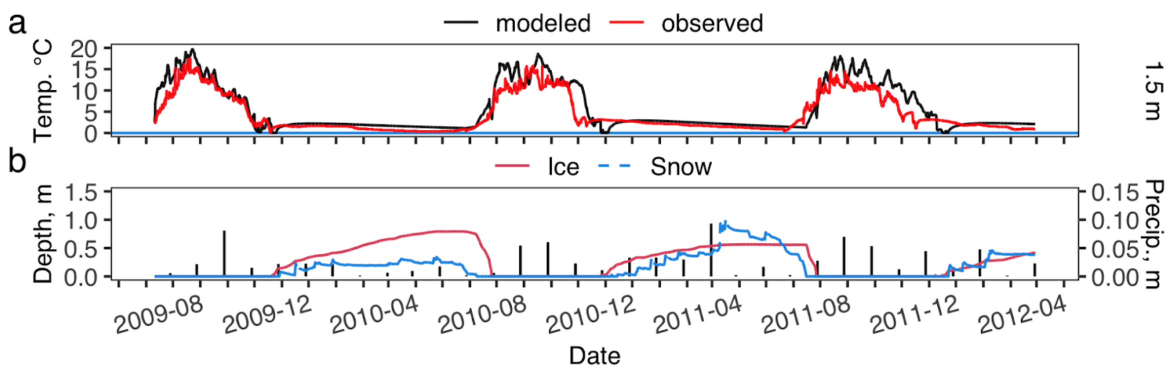

Figure 3. Fox Den modeled and observed water temperature at 1.5 m (a) and modeled lake ice depth, modeled lake snow depth and measured monthly precipitation (vertical black bars) (b).

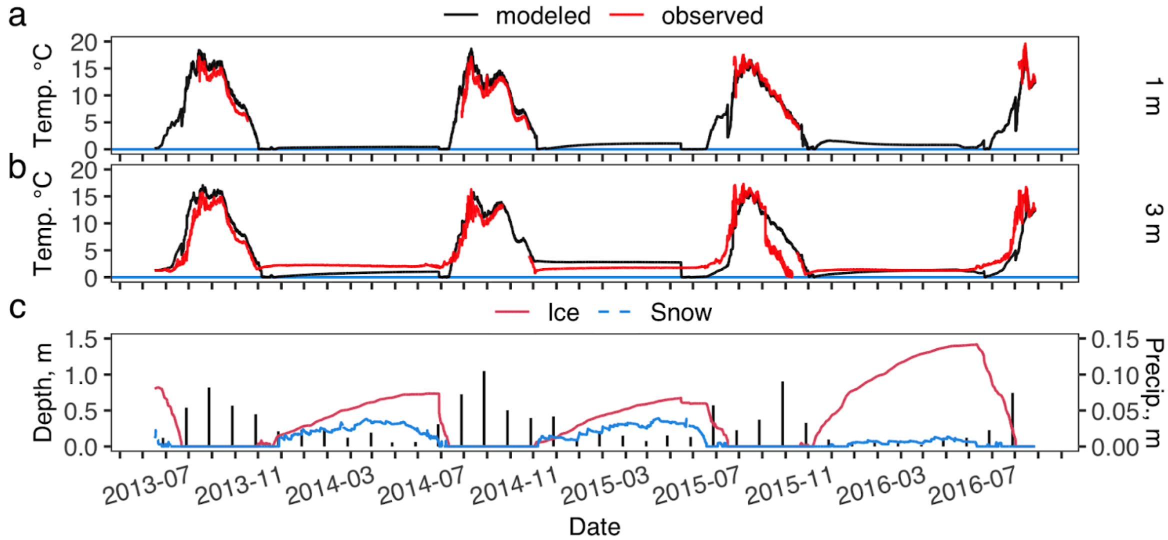

Figure 4. Toolik modeled and observed lake water temperature at 1 m (a) and 3 m (b) and modeled lake ice depth, lake snow depth and measured monthly precipitation (vertical black bars) (c). Missing observed data in (a) and (b) is due to seasonal placement and removal of the temperature sensors, see Methods for details.

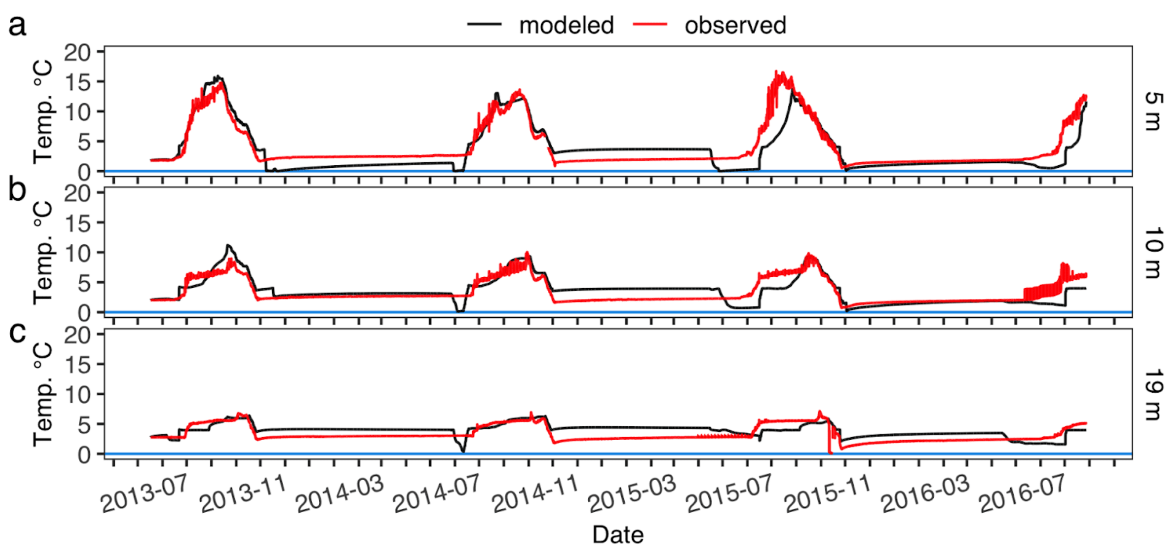

Figure 5. Toolik modeled and observed lake water temperature at 5 m (a), 10 m (b) and 19 m (c).

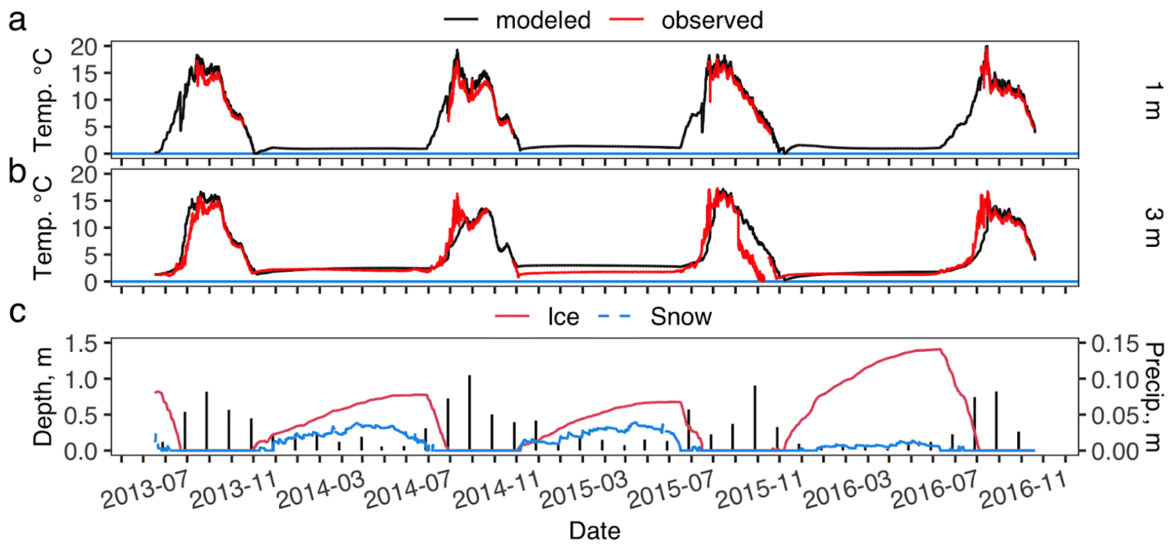

Figure 6. Toolik modeled with no inflow and observed lake water temperature at 1 m (a) and 3 m (b) and modeled lake ice depth, lake snow depth and measured monthly precipitation (vertical black bars) (c). Missing observed data in (a) and (b) is due to seasonal placement and removal of the temperature sensors, see Methods for details.

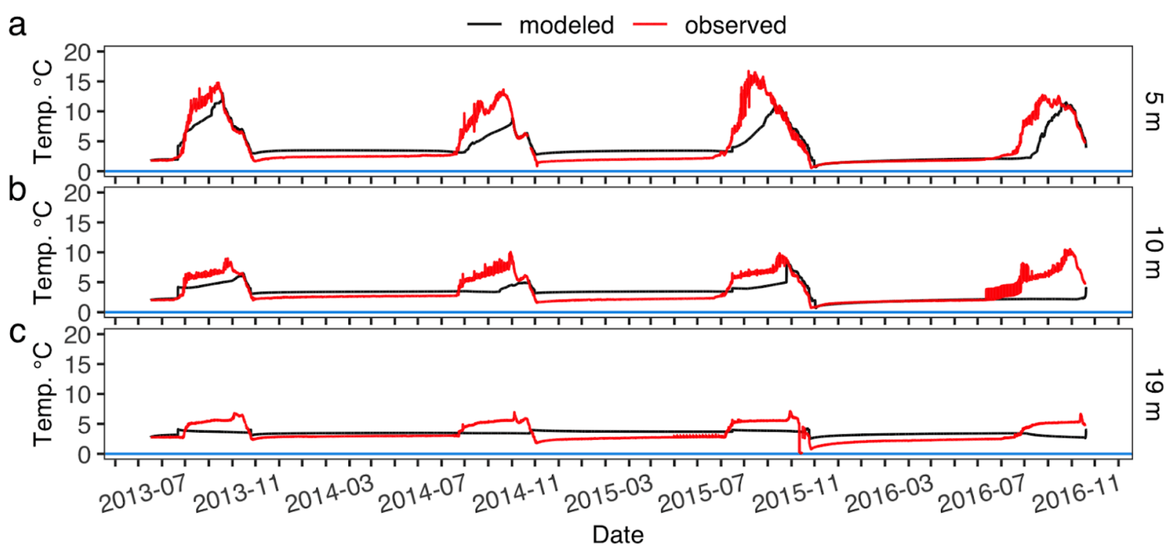

Figure 7. Toolik modeled with no inflow and observed lake water temperature at 5 m (a), 10 m (b) and 19 m (c).

MODEL SENSITIVITY ANALYSIS

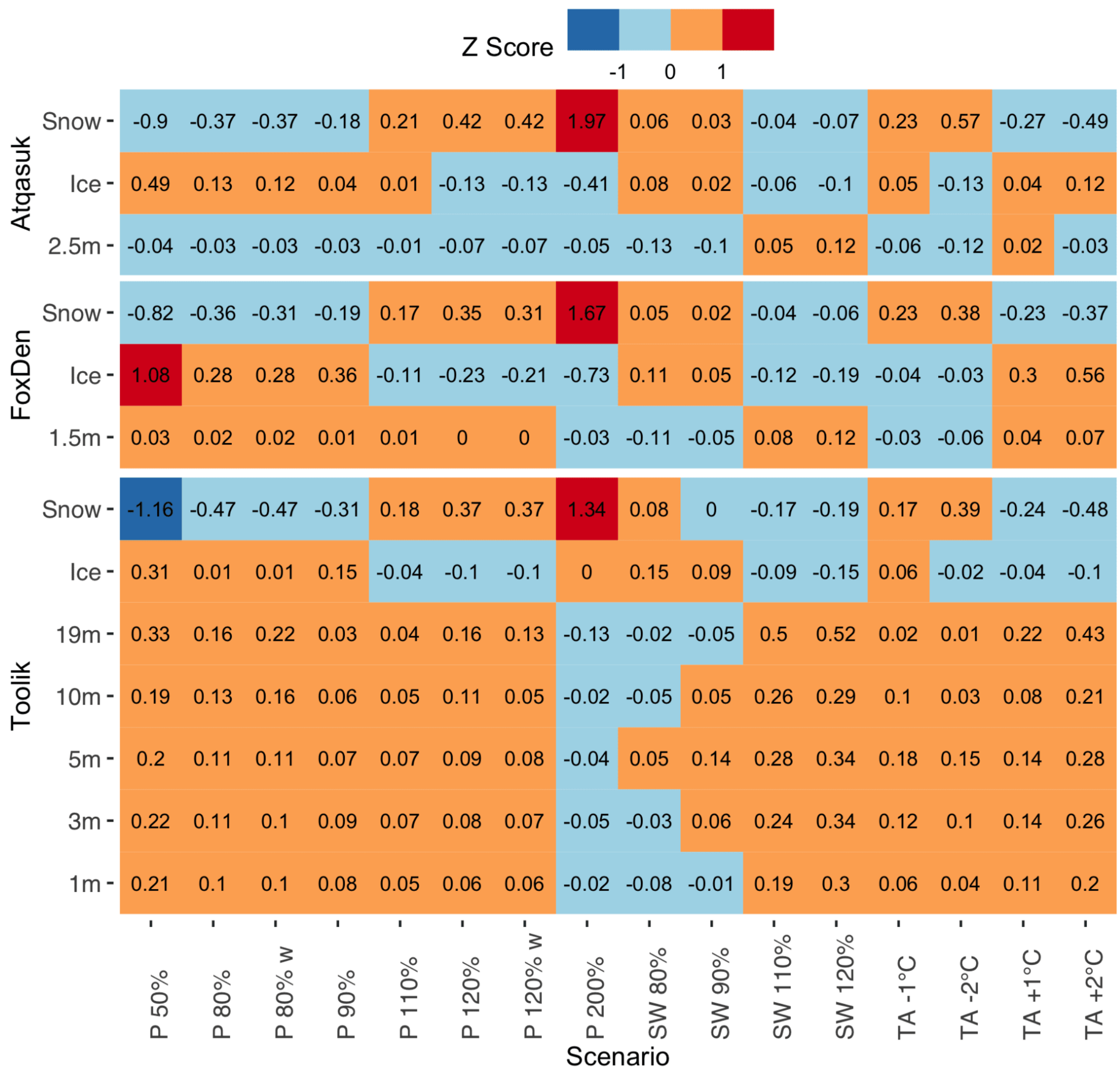

Figure 8. Model sensitivity matrix showing mean Z-score for each scenario compared to the baseline model scenario for each response variable.

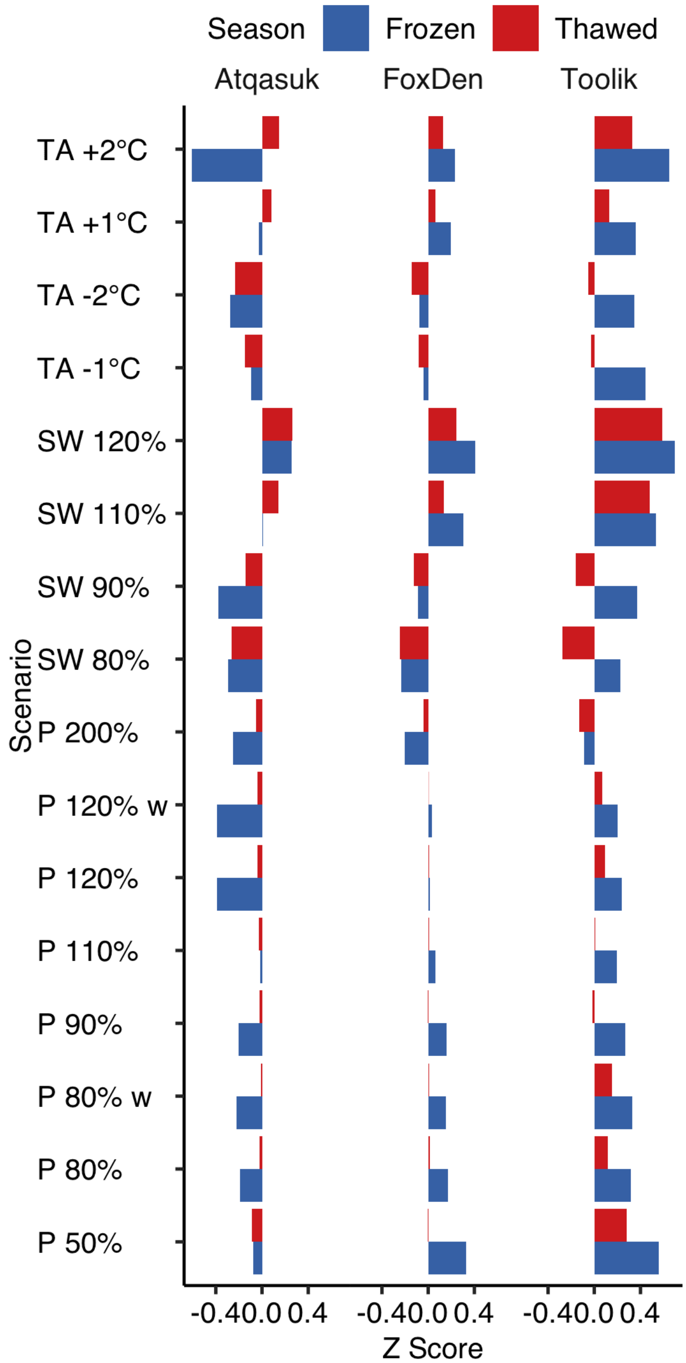

Figure 9. Model water temperature response (mean z-score, all water depths) across the three lakes, 16 scenarios, and two seasons (frozen and thawed, based on ice presence) as compared to the baseline scenario. Blue bars are the frozen season, red bars are the thawed season.

DISCUSSION

Differences between study lakes

- Despite large differences in lake size, shape, depth, and meteorology, the LAKE model performed well in reproducing lake water temperatures in all three study lakes.
- Initially we attempted to model Toolik Lake without including inflow and outflow but we were unable to achieve good matches with measured lake temperatures.
    - Incorporating inflow and outflow into the Toolik simulations greatly improved the model fit to the observed temperature data.
- The "dips" of water temperature in LAKE model results for Toolik lake down to depths of 10 m prior to ice-off can be explained by convective instability under the ice where this instability can be caused by the under-ice penetration of solar radiation creating unstable stratification (a well-known phenomenon, see e.g. Bouffard and Wüest, 2019) (https://www.zotero.org/google-docs/?qDllJS). However, the model significantly overestimated the magnitude of the process, which indicates likely numerical instabilities to be addressed in future studies.
- There was minimal mismatch between modeled lake water temperatures and measured lake water temperatures for all three lakes. The errors in modeled lake temperatures can be partially attributed to the quality of the meteorological data used to drive the LAKE2.0 model, particularly for frozen season precipitation. Furthermore, all meteorological data used in this study was collected from terrestrial stations, not from the lake surfaces, further adding to potential modeled lake temperature error.

Conclusion

- Sublake permafrost and talik development below shallow lakes are topics of interest as the Arctic continues to experience unprecedented warming. Empirical studies have already shown that shallow lakes have warmed substantially over the last 30 years and may have already begun talik development (e.g. Arp et al., 2016) (https://www.zotero.org/google-docs/?DsMvrM). LAKE 2.0 can be a valuable tool to explore the thermal effects of new and developing arctic lakes on underlying permafrost.

Data and script availability

- Weather data and model infiles for simulations in this study have been archived and are publicly available (Jafarov et al., 2021) (https://www.zotero.org/google-docs/?6QHwtR). Observed water temperature data has been published and archived for Atqasuk (Hinkel et al., 2012) (https://www.zotero.org/google-docs/?RsBJWf), Fox Den (Jones et al., 2021) (https://www.zotero.org/google-docs/?L2EP4j), and Toolik Lake (Clark and Jafarov, 2021; MacIntyre and Cortes, 2017) (https://www.zotero.org/google-docs/?ACNu62). Pre-processing scripts were developed to combine data sources, convert units, and format meteorological data for input into the LAKE model. Post-processing scripts were developed to compare LAKE modeled water temperature to observed water temperature and to calculate model error. All processing scripts have been archived and are publicly available (Clark and Jafarov, 2021) (https://www.zotero.org/google-docs/?G6zKS5).

DISCLOSURES

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AUTHOR INFORMATION

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ABSTRACT

Lakes in the Arctic are important reservoirs of heat with much lower albedo and larger absorption of solar radiation than surrounding tundra vegetation. Under climate warming scenarios, we expect Arctic lakes to further accelerate thawing underlying permafrost. Previous studies of Arctic lakes have focused on ice cover and thickness, the ice decay process, catchment hydrology, lake water balance, and eddy covariance measurements, but little work has been done in the Arctic to model lake heat balance. We applied the LAKE model to simulate water temperatures in three Arctic lakes in Northern Alaska over several years. The LAKE model is a one-dimensional that explicitly solves vertical profiles of water state variables on a grid. We used a combination of meteorological data from local and remote weather stations, as well as data derived from remote sensing, to drive the model. We validated simulated water temperatures with data of observed lake temperatures at several depths. Our validation of the LAKE model completes a necessary step toward modeling changes in Arctic lake ice regimes, lake heat balance, and thermal interactions with permafrost. Our results showed that winter precipitation and lake ice plays an important role in forming water temperatures over the winter period. Our findings suggest that reduction in the lake ice thickness and ice time period could lead to more heat storage by lakes and further warming of the Arctic.

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