Estimating talik depth beneath lakes in Arctic Alaska

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ABSTRACT
Water temperature and morphometric data were collected from 28 lakes in Arctic Alaska of various size, geometry, depth and genesis. Using methods pioneered by J. Ross Mackay, calculations of temperature beneath the lake indicate that 20 of these have through taliks. We estimate that over 2100 lakes in the study area have through taliks, suggesting that the continuous permafrost is riddled with taliks that may connect surface lake water with sub-permafrost water.

RÉSUMÉ
Des données de température de l'eau et des données morphométriques ont été recueillies pour 28 lacs de tailles, de géométries, de profondeurs et de genèses variées en Alaska arctique. En utilisant des méthodes mises au point par J. Ross Mackay, le calcul de la température sous le lac indique que 20 d'entre eux sont associés à des taliks traversant. Nous estimons que plus de 2100 lacs dans la zone d'étude ont des taliks traversant, suggérant que le pergélisol continu est criblé de taliks qui peuvent connecter l'eau de surface d'un lac avec l'eau sous le pergélisol.

1 INTRODUCTION

The development of a lake above permafrost introduces a thermal disturbance that causes warming of the frozen ground beneath the lake bed. Generally, if the lake does not freeze to the bed in winter, there is a residual pool of water and a local depression of the permafrost table to form a thaw bulb or talik. Beneath larger and deeper lakes, the thermal perturbation may propagate into the permafrost to create a through talik that extends to the base of the permafrost body. Borehole data and geophysical surveys (e.g., Nolan et al. 2009)) have demonstrated the existence of taliks beneath large lakes and rivers, but these data are expensive to acquire and spatially restricted.

A second approach is to model the effects of the thermal disturbance of the lake (e.g., Ling and Zhang 2003, West and Plug 2008). Adapting a three-dimensional theoretical heat conduction model developed by Arthur Lachenbruch (1957, 1959), J. Ross Mackay estimated the thermal condition beneath lakes to understand pingo formation and dynamics in his classic 1962 paper *Pingos of the Pleistocene Mackenzie Delta Area*. Michael Smith (1976) and Chris Burn (2002), both students of Mackay, subsequently modified and expanded his approach to account for elongated water bodies, and applied these methods using field data (Burn 2002).

The analysis presented here is an extension of the thermal equilibrium approach pioneered by Mackay, Smith and Burn. The requisite morphometric and temperature data have been collected for 28 lakes across a large expanse of Arctic Alaska. The objective is to assess the nature of the talik beneath these lakes given variations in lake size, depth, geometry and average water and ground temperature.

2 STUDY AREA

The North Slope of Arctic Alaska is a region of tundra underlain by continuous permafrost with a thickness of up to 600 m. Elevation gradually declines northward from 1500 m in the foothills of the east-west trending Brooks Range. The area is characterized by thousands of lakes that are oriented in a north-south direction. These lakes are developed on a surface largely composed of frozen unconsolidated sediments sitting above Cretaceous sedimentary bedrock.

The NSF-sponsored Circumarctic Lakes Observation Network (CALON) project is designed to collect and assess basic physical, biological and geochemical information from a representative sample of lakes collected along north-south geomorphic and climatic gradients. The climate generally warms southward across the 2 degrees of latitude, so interior lakes tend to become ice-free earlier in the summer and have a longer ice-free season. Lakes along the Arctic coast become ice-free 2-4 weeks later due to cooler and cloudy maritime conditions. One consequence is an increase in the summer water temperature of interior lakes.

Near the Arctic Ocean, the Outer Coastal Plain is a flat, low relief region with large oriented thermokarst lakes developed in marine silt and sand. This region grades southward into the Inner Coastal Plain; a higher, hillier terrain with aeolian sand at the surface. Lakes here are numerous and oriented, but not as large as those near the coast and tend to be deeper. Further inland and at higher elevations is the silt belt of ice-rich loess deposits (Yedoma), a higher relief terrain with fewer lakes. At the southern part of the study area is the Arctic Foothills at elevations above 120-200 m, which is largely covered by glacial till in which are found kettle lakes.

3 METHODOLOGY

Two north-south transects were used to monitor lakes, and are separated by several hundred kilometers (Figure 1). Ten nodes were established along these transects, with nearby terrestrial meteorological stations deployed at each node to collect regional data. A total of six representative lakes from each node have been monitored since 2012. These lakes were selected to cover a range of lake size, depth and origin.

The meteorological stations collect hourly measurements of air temperature, relative humidity, rainfall, solar radiation, wind speed and direction using Onset Computer sensors.

Lake instrumentation was based on a hierarchical strategy. A rope with an anchor and float was deployed in April through the ice near the center of all lakes. Above the anchor was a water level sensor (Onset U20-001, ±0.2°C) collecting hourly readings of water pressure and temperature, and just below the float was a high-precision sensor (Onset U12-015, ±0.1°C) to measure near-surface water temperature. A 25-cm hole was augured through the ice near the center of each lake. After measuring ice thickness, the sensor string was lowered into the hole, and the float pushed sideways beneath the ice. In spring during breakup, the float remains beneath the moving ice slab, and gradually rises toward the lake surface as the ice melts and thins. Though not foolproof, this strategy partially alleviates the problem of float movement and possible destruction during spring break-up, but the near-surface sensor measurement is only valid for the post-melting period. All floats were retrieved in August, serviced, and redeployed the following April.

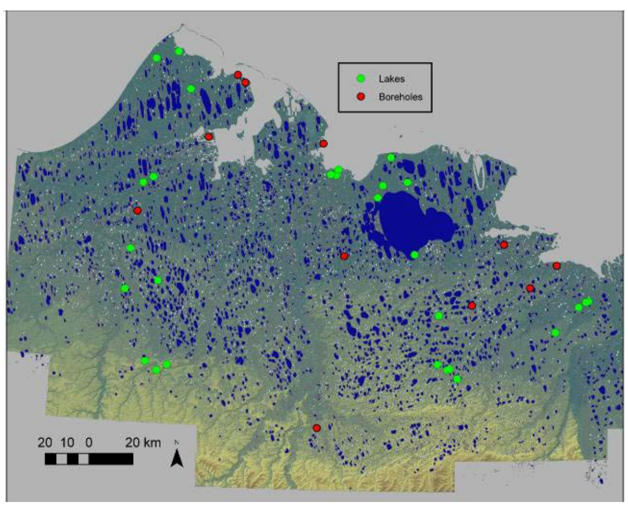

Figure 1. Study area in Arctic Alaska

In half the lakes, more intensive instrumentation was used. Sensor strings with the same configuration were deployed in the lake center in August and left throughout the year. Because the floats became embedded within the ice cover in winter, they tended to drift and move during spring break-up. Often, they would be carried many hundreds of meters, and sometimes ended up near shore or on the littoral terraces. Once retrieved and serviced, the sensor string was returned to the original position near the lake center. Data from these sensor strings are analyzed in this paper as they provide a continuous record for the lake center over the period including late summer, freezeback, winter ice thickening, and meltout. Characteristics of these lakes are given in Table 1 and are shown in Figure 1.

A detailed bathymetric survey was conducted on many of the lakes using a sonar unit. Using a nested sampling scheme, soundings were first made parallel to the shoreline or littoral shelf, then progressively shifted toward the center of the lake (Hinkel et al. 2012). Using this method, many thousands of water depth readings were obtained. The inflatable boat was restricted to use in water depths greater than 0.5 m, so the littoral terraces were avoided. Following data processing, the shoreline was digitized, assigned a depth of 0.0 m, and attached to the spreadsheet of latitude, longitude and depth measurements. In ArcMap, these data were interpolated onto a 5 m grid using a natural neighbour algorithm.

4 BACKGROUND

In deeper lakes, where the ice does not freeze to the lake bed in the central pool, the temperature at the base of the water column and in the lake bed sediments is above zero throughout the year to create a talik. Lachenbruch (1957) presented a three-dimensional theoretical study of heat conduction in permafrost beneath a heated building, which is analogous to a surface thermal disturbance induced by lake formation. Mackay (1962) tailored this approach to estimate the depth of the talik beneath deeper lakes on the Mackenzie delta area (Mackay 1963); in his one-dimensional approach, latent heat effects are neglected since steady-state conditions are assumed, and the thermal properties of the ground have no influence. Building on work by Smith (1976), Burn (2002) applied it to lakes on Richards Island in western Canadian Arctic coast that have a deeper central pool and shallow littoral terrace underlain by permafrost.

Assuming steady-state conditions, the temperature (T) at any depth Z can be estimated as (Mackay 1962):

$$T(Z) = T_g + (Z/I) \qquad [1]$$

where T_g is the mean annual ground surface temperature and I is the local geothermal gradient (m C^{-1}).

The formation of a lake at the ground surface introduces a positive thermal disturbance that is superimposed on the ground thermal profile. If the mean annual water temperature in the central lake pool is above freezing, as is the case for lakes that do not regularly freeze to the bottom in winter, the thermal perturbation beneath the center of a circular lake is estimated by Mackay (1962, eq. 7) as:

$$T(Z) = T_g + (Z/I) + \{(T_l-T_g)*(1-[Z/(Z^2+R^2_l)^{0.5}])\} \qquad [2]$$

where T_g is the mean annual ground temperature of the tundra, T_l is the mean annual lake water temperature, and R_l is the radius of a lake. The thermal impact is maximized beneath the geometric center of the lake. Given enough time, the surface warming can ultimately lead to basal warming of the permafrost body and the upward displacement of the lower permafrost boundary.

Often, lakes are shallower near the shore with bed-fast ice in winter, and many lakes develop a shallow littoral terrace. In either case, the mean annual temperature is warmer than the undisturbed tundra, though not as warm as the lake center. Thus, there is a central inner pool of deep water with radius R_p and temperature T_p, and an annulus of shallow water with bedfast ice in winter. The radius of the lake (R_l) is equal to R_{p+t}, where the subscript “t” refers to the terrace of temperature T_t, such that $T_p > T_t > T_g$. The primary disturbance at depth Z beneath the lake center is the sum of the thermal impact of the unfrozen central pool and that of the surrounding terrace, which introduces an additional term to Eq. 2, as shown in Eq. 3 (Mackay 1962, eq. 8; Smith 1976):

$$T(Z) = T_g + (Z/I) + \{(T_p\text{-}T_g)*(1\text{-}[Z/(Z^2+R^2{}_p)^{0.5}])\} + \{(T_t\text{-}T_g)*(([Z/(Z^2+R^2{}_p)^{0.5}] - [Z/(Z^2+R^2{}_{p+t})^{0.5}]))\} \quad [3]$$

Assuming the lake has been stable for a long duration and the one-dimensional substrate temperature is in equilibrium, Eq. 3 can be used to estimate the temperature at any depth beneath the center of a circular lake with littoral terraces, and to estimate the depth to the top and base of the permafrost layer where T_g = 0ºC.

Lake geometry also has an influence. Many lakes in the study area are elongated and oriented in a north-south direction. For elongated lakes with terraces, Smith (1976, eq. 7) and later Burn (2002) modified the above equations so that T(Z) can be estimated as Eq. 4:

$$T(Z) = T_g + (Z/I) + \{[(T_p\text{-}T_t)/ \pi]*(2\tan^{-1}(H_p /Z))\} + \{[(T_t\text{-}T_g)/ \pi]*(2\tan^{-1}(H_{p+t} /Z))\} \quad [4]$$

Where H_p is the half-width of the deep central pool and H_{p+t} is the half-width of the lake (pool plus terrace). In this approach, the last two terms reflect the thermal impact of the unfrozen pool and terrace, respectively, on the thermal profile. An elongated lake is defined as one where the length exceeds the width by at least a factor of two.

Eqs. 2 through 4 are not single-value functions of depth (Z), and cannot be used to directly determine the upper and lower surfaces of a permafrost body; for this reason, an iterative approach is used. Application of the method depends on obtaining lake morphometrics, the local geothermal gradient (I), and mean annual temperature of the lake water (T_p), littoral terrace (T_t), and unaffected nearby tundra (T_g). Given the simplifying assumptions, measured values can be used to determine the existence of a talik , to estimate the depth of the talik beneath the central lake pool, or to ascertain if a through talik penetrates the permafrost. Data collected from the CALON project are used to assess the thermal state beneath 28 lakes where the necessary data have been collected (Table 1).

The geothermal gradient (I) and ground temperature (T_g) varies across the Arctic North Slope. A total of 13 deep boreholes from the DOI/GTN-P array (Deming et al. 1996; Clow 2014) are found in and around the study area, and are shown in Figure 1. The long-term ground surface temperature for each borehole location was estimated by best-fit extrapolation of the temperature profile to the surface, and is used here as an estimate of T_g. The borehole temperature measurements in the upper 400 m were also used to calculate the borehole-specific geothermal gradient (I), which varied from 21 to 40 m C^{-1}. The geothermal gradient and ground temperature at each lake was estimated by spatially interpolating the borehole data across the study area.

Table 1. CALON lake characteristics; those highlighted in grey do not have a through talik.

Lake	Lat (Dd)	Long (Dd)	Area (ha)	Depth (m)	Tp C
Ikp-002	70.815	-154.424	14.8	0.5	-0.68
Ikp-003	70.793	-154.517	11.2	2.7	1.84
Tes-002	70.789	-153.470	265.3	0.8	-2.34
Tes-003	70.868	-153.773	356.7	0.9	-2.86
Tes-005	70.752	-153.869	34.0	0.6	-3.99
FC-M9925	70.247	-151.478	87.4	0.4	-2.77
Ini-002	70.000	-153.037	1.3	0.8	-1.76
Ini-005	70.018	-153.186	4.9	2.1	3.60
BRW-100	71.242	-156.774	183.8	2.3	2.41
BRW-103	71.123	-156.317	179.8	1.9	2.25
BRW-107	71.274	-156.497	125.0	1.9	1.54
Ikp-001	70.790	-154.450	68.7	2.7	2.20
LMR-400	70.754	-156.720	252.3	1.5	2.53
LMR-402	70.728	-156.843	356.0	1.0	1.92
Tes-001	70.766	-153.562	979.9	2.5	3.23
Tes-006	70.706	-153.924	110.1	2.2	3.07
ATQ-200	70.455	-156.948	271.3	2.5	4.58
ATQ-202	70.288	-156.985	148.8	2.4	4.81
ATQ-207	70.329	-156.592	353.6	3.5	3.90
FC-L9819	70.270	-151.355	100.5	1.8	3.19
FC-L9820	70.267	-151.386	128.5	1.1	0.77
FC-R0066	70.147	-151.765	104.5	2.4	4.10
Ini-001	69.996	-153.070	66.4	4.4	3.50
Ini-003	69.959	-152.951	417.3	2.2	4.50
Ini-006	70.219	-153.172	361.7	4.3	3.91
RDC-300	69.961	-156.546	63.8	6.0	4.18
RDC-308	69.986	-156.424	78.7	2.2	4.38
RDC-311	69.996	-156.689	76.9	7.0	3.65

Although the water temperature on the terraces (T_t) varies annually with water depth, air temperature, and ice duration, it is typically 3-5°C warmer than the surrounding tundra (T_g). For that reason, we conservatively estimate T_t as 3°C warmer than the local T_g.

Twenty eight circular and elongated lakes of varying size have adequate field data to perform the calculations, as shown in Table 1. Eq.3 was applied to the 14 circular lakes and Eq. 4 to the 14 elongated lakes. Lake dimensions were measured on high-resolution satellite imagery or bathymetric maps by establishing a line down the longest axis of the lake, which is typically oriented north-south. The minor axis is perpendicular to the long axis, with axes intersecting in the geometric center of the lake. All measurements of pool and terrace width (R) were made along the minor axis.

5 RESULTS AND DISCUSSION

The results of the analysis estimate that the majority (20) of the 28 lakes may have a through talik (Figure 2). All lakes smaller than 50 ha have no talik or a shallow talik. Three of these lakes (Ini-002, Ikp-002 and Tes-005) have depths of less than 1.0 m and freeze to the bottom in winter, so the mean annual temperature of the central pool is less than 0°C and there is no talik. By contrast, the other two small lakes (Ini-005 and Ikp-003) have depths of 2.1 and 2.7 m, respectively. These small lakes are deep enough to maintain a pool of basal water throughout the winter, and a mean annual water temperature of 2-4 ºC. The calculations suggest that these lakes have a talik, with thawed sediments to a depth of 12-18 m.

Three somewhat larger lakes (FC-9925, Tes-003 and Tes-002) also lack a talik. Although lake area ranges from 87 to 357 ha, lake depth is no greater than 0.9 m and a corresponding mean annual lake bed temperature of about -2.5°C. Bedfast ice in winter prohibits basal permafrost degradation.

To summarize, results suggests that small lakes (<50 ha) or very shallow lakes (<1.0 m) do not have an talik through the permafrost. Permafrost that is warmer than the undisturbed tundra exists beneath the lake, and the base of the permafrost body has been locally displaced upward toward the surface.

All lakes with an area exceeding 66 ha and water deeper than 1.0 m have a through talik irrespective of their morphometry (circular or elongated) or presence of littoral shelves. Using 66 ha as a very conservative estimate of the minimum lake size needed to develop a through talik, we can estimate the number of lakes in the region that would have a through talik. Of the 35,383 lakes in the study area (> 1 ha in size), about 6% (2100) have area greater than 66 ha; these are shown in dark blue in Figure 1. These lakes cover at least 12% of the study area. This suggests that the permafrost is riddled with through taliks, and that the lake water may be hydrologically connected to sub-permafrost groundwater. This approach ignores the critical impact of water depth and thus basal water temperature, and also the effects of lake geometry and radius of the central pool. More importantly, it neglects the spatial patterns noted earlier. Lakes on the Outer Coastal Plain are larger but generally shallower, and more likely to freeze to the bottom in winter. Conversely, lakes on the Inner Coastal Plain and Foothills tend to be deeper; lakes here that are smaller than 66 ha may have a through talik.

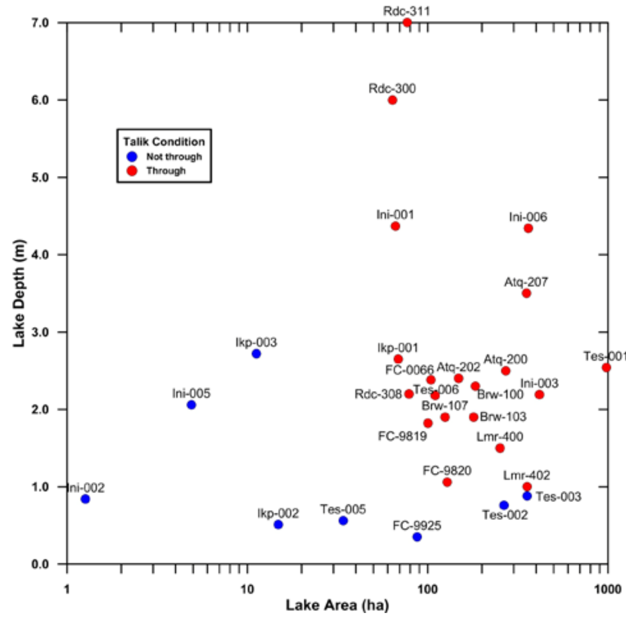

Figure 2. Talik condition based on lake depth and area; note logarithmic scale for area

There are several limitations to this study. First, it is unlikely that lake morphology remains static over the lifetime of a lake. Thermokarst lakes tend to get larger and become more oriented from thermomechanical bank erosion, and littoral shelves can develop and widen over time. Additionally, lake water levels change. Many lakes show evidence of partial drainage, especially in regions of higher relief away from the coast. A reduction in lake size from partial drainage would likely result in a narrowing of the through talik over time as permafrost aggrades laterally, and possibly lead to closure of the vertical thawed zone.

A second assumption is that lake ice thickness has remained constant over time. The water depth limitation of 1.0 m identified in this study is based on contemporary measurements, and all lakes with water depths >0.9 m have mean annual water temperatures greater than zero. However, evidence from Arctic Alaska suggests that regional lake ice thickness has recently declined owing to warmer winters, an extended duration of the ice-free season, and thicker snowcover (Arp et al. 2012). This implies that ice thickness in the recent past was greater, so that the ice-free period would have been shorter and the mean annual water temperature lower. Indeed, studies in Barrow report ice thickness of ~ 2 m in the late 1950s (Brewer 1958). Many of the shallow lakes would have regularly frozen to the lake bed, with consequent impact on T_p and talik development.

Similarly, the permafrost and T_g have been warming such that the current estimates of I, T_g and T_t are not representative of the long-term, steady state condition. The magnitude of recent warming is often cited as 1-2 °C. To test the possible impact of warming, the mean annual ground temperature (T_g), terrace temperature (T_t) and water pool temperature (T_p) were reduced by 1.5 °C, and the temperature field beneath each lake was recalculated using the procedure described above. The overall results were the same; no lake changed category from no or shallow talik to through talik. This suggests that the recent observed warming does not have the potential to open a through talik beneath any lakes. However, for the eight lakes without a through talik, the base of the permafrost was substantially deeper under colder conditions. Further, the 12-18 m thick talik immediately beneath Ikp-003 and Ini-003, both deep and small (<11 ha) lakes, was notably thinner. In other words, recent warming has caused some deepening of the thawed zone beneath these small lakes.

Over the Holocene, as lakes developed, expanded in size and deepened, taliks began to penetrate the permafrost body. Episodic or periodic lake drainage would locally counter this overall trend as permafrost aggraded into the unfrozen zone and eventually closed the talik. Recent warming has likely impacted mean annual lake water temperatures, enhancing permafrost degradation beneath lakes. On a time scale of centuries to millennia, more open taliks would develop, especially where permafrost is thinner. At some point, the continuous permafrost of Arctic Alaska would become discontinuous permafrost.

Imikpuk Lake near Barrow has a radius of 370 m, depth of 2.8 m, and mean annual basal water temperature of 1.8°C. Our calculations suggest that this lake would have a through talik. However, Max Brewer measured a talik thickness of 60 m below Imikpuk Lake in the late 1950s. This disparity might be explained by the model assumption of temperature equilibrium. If we set T_g and T_p 1.5°C cooler to reflect the effects of recent warming so that T_p is 0.3°C, the lake radius is still sufficiently large to have a through talik. Only if the lake radius is reduced to about 250 m would permafrost exist, with the talik 30 m deep. For this reason, the results we present here only reflect the potential condition beneath smaller lakes after the centuries or millennia that would be required for the underlying permafrost to reach equilibrium temperature conditions. The implicit model assumption is that climatic, geomorphic and lacustrine conditions remain static at the surface. This overarching assumption is probably unjustified given the time scales of the processes involved.

6 CONCLUSIONS

The results from this study suggest that through taliks may exist beneath larger lakes in Arctic Alaska. Temperature and morphometryic data were collected from 28 lakes of various size, geometry, and depth. Calculations of temperature beneath the lake indicate that 20 of these have through taliks. Ignoring the effects of lake depth, lake geometry, and the presence of littoral shelves, a proxy of 66 ha is used as the minimum lake size necessary to develop a talik through the permafrost. In this case, over 2100 lakes in the study area have through taliks, suggesting that the continuous permafrost is riddled with taliks that may connect surface lake water with sub-permafrost water.

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