Linkages between lake shrinkage/expansion and sublacustrine permafrost distribution determined from remote sensing of interior Alaska, USA

S. M. Jepsen,[1] C. I. Voss,[2] M. A. Walvoord,[1] B. J. Minsley,[3] and J. Rover[4]

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[1] Linkages between permafrost distribution and lake surface-area changes in cold regions have not been previously examined over a large scale because of the paucity of subsurface permafrost information. Here, a first large-scale examination of these linkages is made over a 5150 km^2 area of Yukon Flats, Alaska, USA, by evaluating the relationship between lake surface-area changes during 1979–2009, derived from Landsat satellite data, and sublacustrine groundwater flow-path connectivity inferred from a pioneering, airborne geophysical survey of permafrost. The results suggest that the shallow (few tens of meters) thaw state of permafrost has more influence than deeper permafrost conditions on the evolving water budgets of lakes on a multidecadal time scale. In the region studied, these key shallow aquifers have high hydraulic conductivity and great spatial variability in thaw state, making groundwater flow and associated lake level evolution particularly sensitive to climate change owing to the close proximity of these aquifers to the atmosphere. **Citation:** Jepsen, S. M., C. I. Voss, M. A. Walvoord, B. J. Minsley, and J. Rover (2013), Linkages between lake shrinkage/expansion and sublacustrine permafrost distribution determined from remote sensing of interior Alaska, USA, *Geophys. Res. Lett.*, *40*, doi:10.1002/grl.50187.

1. Introduction

[2] Lakes are important hydrological components of cold regions that influence carbon cycling and climate [*Subin et al.*, 2012; *Abnizova et al.*, 2012; *Tranvik et al.*, 2009], groundwater/surface-water exchange [*Walvoord et al.*, 2012; *Nakanishi and Dorava*, 1994], and habitats for wildlife, migratory arctic shorebirds, and waterfowl [*Prowse and Brown*, 2010]. Lakes of cold regions have undergone marked fluctuations in number and surface area since at least the 1950s [*Rover et al.*, 2012; *Carroll et al.*, 2011; *Yoshikawa and Hinzman*, 2003], possibly because of changes in permafrost and/or climate [*Huang et al.*, 2011; *Labrecque et al.*, 2009; *Plug et al.*, 2008; *Smith et al.*, 2005]. Potential permafrost-related drivers of lake change include deepening of the permafrost table [*Marsh et al.*, 2009; *Zhang et al.*, 2008; *Osterkamp*, 2007], degradation of ice-wedge systems [*Jorgenson et al.*, 2006; *Marsh and Neumann*, 2001; *Brewer et al.*, 1993; *Mackay*, 1992], and thawing of sublacustrine permafrost, which facilitates exchanges between lakewater and groundwater (i.e., taliks) [*Walvoord et al.*, 2012; *Rowland et al.*, 2011; *van Everdingen*, 1990].

[3] Taliks form below lakes that do not freeze completely to their bottoms during winter [*Williams and Smith*, 1989]. These taliks may develop into open taliks, extending completely through permafrost [*van Everdingen*, 1990], given sufficient lake size, lake age, and suitable thermal conditions [*Wellman et al.*, 2013; *Rowland et al.*, 2011]. Under current climate conditions in interior Alaska, an open talik through 90 m of permafrost may develop in anywhere from ~200 to >1000 years, depending on lake size, sediment characteristics, and groundwater flow [*Wellman et al.*, 2013]. A few studies have reported substantial groundwater fluxes through open taliks to and from lakes [*Kane and Slaughter*, 1973, and *Yoshikawa and Hinzman*, 2003, respectively].

[4] Work presented here constitutes an unprecedented assessment of the importance of sublacustrine taliks on lake volume changes over a larger scale and broader spectrum of hydrogeologic conditions than was previously possible. The availability of collocated, remotely sensed observations of shrinking and expanding lakes [*Rover et al.*, 2012] and sublacustrine permafrost distribution mapped from an airborne electromagnetic (AEM) survey [*Minsley et al.*, 2012; *Ball et al.*, 2011] in the Yukon Flats basin of interior Alaska presents an opportunity to examine the association between lake volume evolution and permafrost over a large area. The AEM survey allows for the characterization of permafrost and sublacustrine taliks as an indication of lake connectivity to shallow and deep (subpermafrost) groundwater systems. The objective of this study is to examine the statistical association between sublacustrine taliks (N = 153) in the Yukon Flats of interior Alaska, and surface area trends of lakes (1979–2009) mapped from Landsat satellite data. This examination allows for the identification of sublacustrine thaw states most common to lakes undergoing changes in surface area, and offers insights into the etent of connectivity between lakewater and groundwater. A close association between the occurrence of sublacustrine open taliks and lake surface-area changes would support the hypothesis that changes in lakewater/deep-groundwater exchange through open taliks play an important role in lake size dynamics. Such a relationship is envisioned to potentially result from the formation of new open taliks or regional changes in groundwater flow through existing open taliks. In contrast, a weak association

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[1]National Research Program, U.S. Geological Survey, Denver, Colorado, USA.
[2]National Research Program, U.S. Geological Survey, Menlo Park, California, USA.
[3]Crustal Geophysics and Geochemistry Science Center, U.S. Geological Survey, Denver, Colorado, USA.
[4]Earth Resources Observation and Science (EROS) Center, U.S. Geological Survey, Sioux Falls, South Dakota, USA.

Corresponding author: S. M. Jepsen, Denver Federal Center, Box 25046, MS-403, Denver, CO 80225, USA. (sjepsen@usgs.gov)

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between sublacustrine open taliks and surface-area changes, coupled with a strong association between shallow thaw states (i.e., states exclusive of open taliks) and surface-area changes, would support the hypothesis that changes in lakewater/shallow-groundwater exchange play a more important role in lake size dynamics than changes in deep groundwater exchange through open taliks.

2. Study Area

[5] The 5150 km^2 study area is located in the Yukon Flats, a broad lowland in the Yukon River Basin of interior Alaska, USA, approximately 200 km northeast of Fairbanks (Figure 1a). The study area is low in topographic relief, with elevations (relative to sea level) decreasing westward from ~145 to ~100 m (*Gesch*, 2007). It encompasses ~8500 lakes covering ~10% of the land surface. The basin underlying the study area contains up to ~3 km of mid-Tertiary to early-Quaternary clay, silt and sand, and surficial deposits (up to 50 m thick) of primarily fluvial gravel [*Clark et al.*, 2009; *Williams*, 1962]. The study area overlies the regional transition between discontinuous and continuous permafrost [*Jorgenson et al.*, 2008]. Maximum permafrost thickness is approximately 100 m [*Minsley et al.*, 2012; *Williams*, 1962], and the permafrost-table depth is highly variable (e.g., 0.4−2.5 m near Twelvemile Lake; Figure 1c) [*Jepsen et al.*, 2013]. Permafrost is generally present except in areas around and below water bodies [*Nakanishi and Dorava*, 1994]. Closed spruce-hardwood forests occur along rivers and creeks, and open, low-growing spruce forests occur elsewhere [*Viereck and Little*, 2007]. Climate is continental boreal, with a mean annual air temperature of approximately −6°C, extreme seasonality in mean monthly air temperature (~45°C), and mean annual precipitation of approximately 170 mm [*Nakanishi and Dorava*, 1994].

[6] Shrinking lakes are most prevalent in the southern study area, while most expanding lakes are found north of the Yukon River and near its tributaries (Figure 1b, c). On the basis of this observation, the study area is divided into the following four physiographic units, using creek geomorphology [*USGS*, 2011] and mapped surface geology [*Williams*, 1962] to guide the placement of boundaries: Loess Base, South Flats, Rivers and Creeks, and North Flats (Figure 1c). South Flats contains the smallest lakes, many occupying partially drained lake basins (Figure 2) referred to as "thaw sinks" by *Jorgenson and Osterkamp* [2005].

3. Methods

[7] Lake taliks (totaling 153) are characterized from electrical resistivity cross sections along 392 flight-line km of the AEM survey (Figure 1c). A ~100 m wide swath of ground (i.e., the approximate system footprint in *Ball et al.* [2011]) is sampled along each flight line. Interpretation of

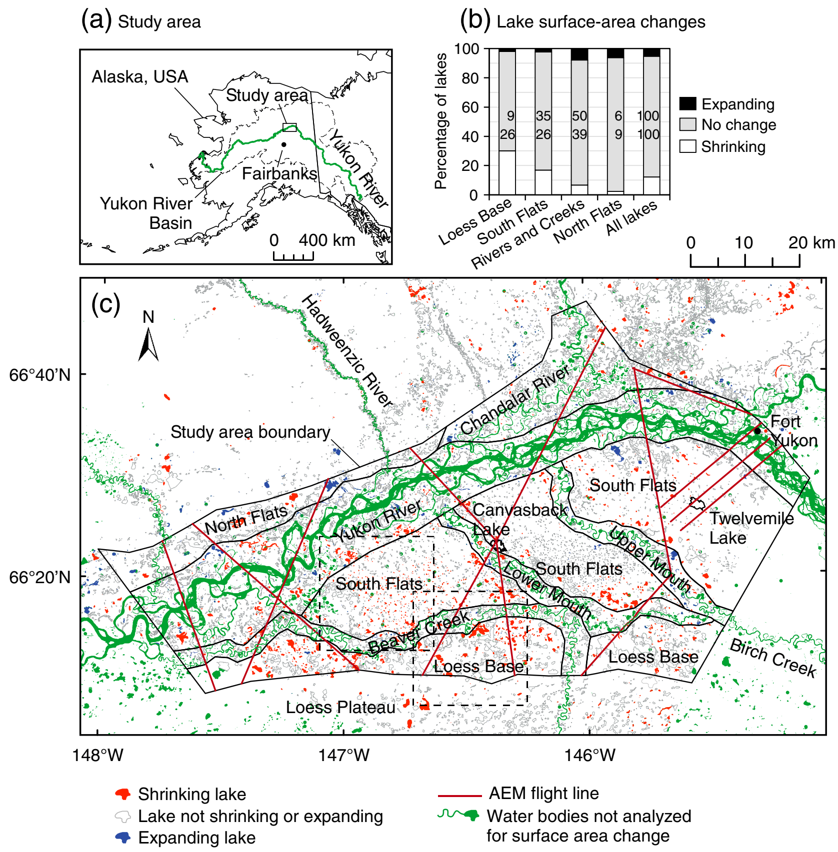

Figure 1. (a, c) Location of study area, Yukon Flats, Alaska, USA, and (b) lake surface-area changes by physiographic unit based on trends from *Rover et al.* [2012]. The upper and lower numbers in the bar charts of Figure 1b are the percentages of total lakes (~8500) and total lake surface area (53.6 × 10^3 ha) in the study area, respectively. "Rivers and Creeks" represents all rivers and creeks grouped together (locations from *USGS* [2012]). Dashed boxes are the extents of Figure 2.

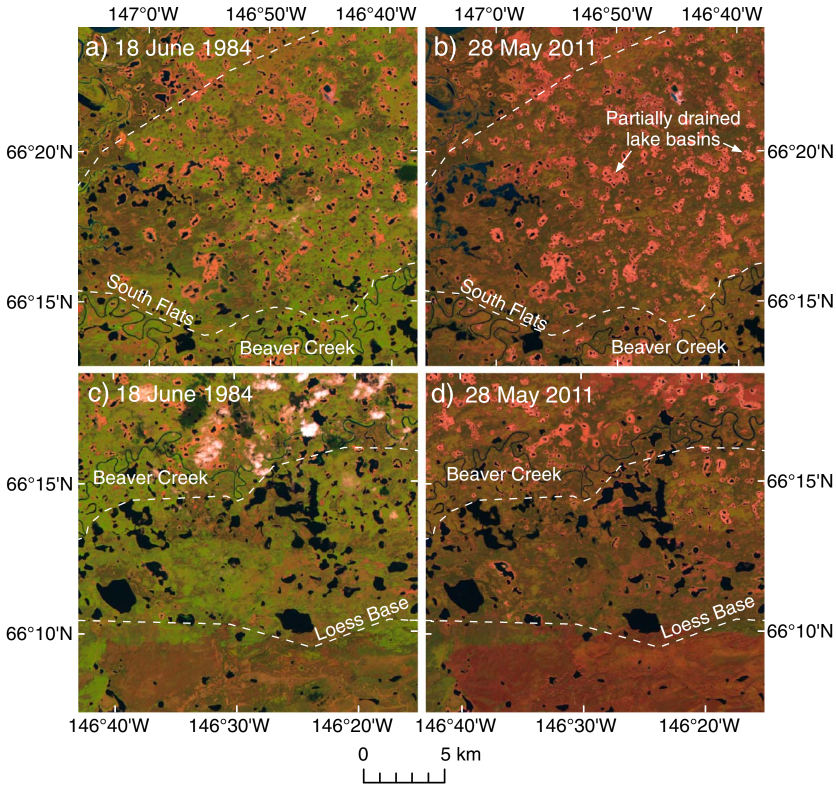

Figure 2. RGB composites (bands 5-4-3) from Landsat 5 showing lakes in the (a, b) South Flats, and (c, d) Loess Base [*USGS*, 2011]. Spatial extents of the images are delineated in Figure 1a.

the resistivity cross sections follows that of *Minsley et al.* [2012]. The resistivity of geologic materials varies with both rock/soil type and thaw state (i.e., frozen versus unfrozen) [*Palacky*, 1987; *Hoekstra et al.*, 1975], potentially resulting in an overlap in resistivity between different materials having contrasting thaw states [*Minsley et al.*, 2012]. To reduce this ambiguity, we incorporate knowledge about the known depositional history of the Yukon Flats [*Clark et al.*, 2009; *Williams*, 1962] to develop a lithologic model and place constraints on the spatial distribution of different materials. The lithologic model consists of two layers: an upper layer of fluvial gravel (~15–50 m thick) and an underlying layer of lacustrine silt. The observed resistivity transition occurring at the interface between frozen gravel and frozen silt, and between frozen silt and unfrozen silt, in a deep borehole in Fort Yukon [*Clark et al.*, 2009] (transitions illustrated along line L-L′ of Figure 3a) are used to constrain our model relating thaw state to resistivity for each lithology (Figure 3, bottom). The interface between fluvial gravel and underlying lacustrine silt, given their depositional environment, is expected to be horizontal at the scale of individual lakes. Therefore, at a given depth, it is reasonable to assume that lateral resistivity transitions across lake basins are related to changes in thaw state, rather than material type. Shallow groundtruth data and a discussion about possible thaw state interpretation errors are provided as auxiliary material.

[8] Sublacustrine silt is considered to be unfrozen if the vertical distance between the gravel-silt contact and interpreted bottom of permafrost, t_f, is less than a threshold value, set to 10 m to account for the uncertainty in interface positions (Figure 3). One of four possible combinations of thaw states for sublacustrine gravel and silt (Type A–D cases, Figure 3) are assigned to each lake. Type A cases are assumed to represent open taliks, and Type D cases are assumed to represent closed taliks with a phase boundary occurring near the gravel-silt contact. In Type B and C cases, the gravel is assumed to be completely or partially frozen.

[9] Determination of shrinking, stable, and expanding lakes is based on the regression analysis by *Rover et al.* [2012] using Landsat satellite data [*USGS*, 2011]. This analysis uses a supervised decision tree classification approach (average model accuracy 98.9%) to map lake surface areas from Landsat radiance data. Linear regression is used to determine if lake surface areas have decreasing trends (“shrinking” lakes), no trends (“stable” lakes), or increasing trends (“expanding” lakes) at the 95% level of statistical significance ($p < 0.05$) for the period of 1979–2009. These surface area trends are calculated from available cloud-free observations during May–September (17–20 observations per lake). Existence of a statistical association between lake surface-area trend and sublacustrine thaw state is determined using contingency tables with chi-square tests of independence (provided as auxiliary material). Lake surface-area trend is considered to be “significantly associated” with sublacustrine thaw state if the null hypothesis, postulating that area trend and thaw state are independent, is rejected at the 95% level of significance ($p < 0.05$).

4. Results and Discussion

[10] The occurrence of open taliks (Type A) is not significantly associated with lake surface-area trend ($p = 0.37$), as illustrated by the similar percentages of surface area trends

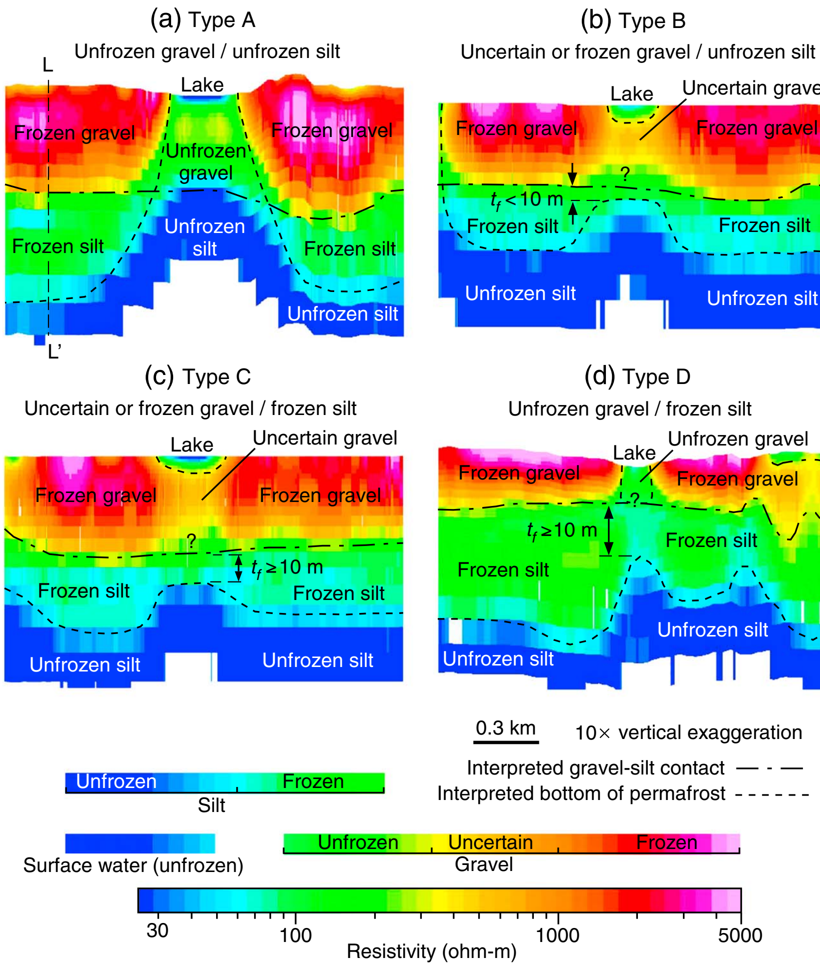

Figure 3. Examples of the four different gravel-silt thaw states (Types A–D) interpreted from electrical resistivity cross sections of the airborne electromagnetic survey [*Minsley et al.*, 2012]. The vertical distance between the gravel-silt contact and the interpreted bottom of permafrost, t_f, is used to determine whether silt is unfrozen ($t_f < 10$ m) or frozen ($t_f \geq 10$ m).

for Type A cases and all lakes (Figure 4a). This suggests that the formation of open taliks is not a primary mechanism of the observed lake surface-area dynamics in the Yukon Flats. The lack of association between open taliks and lake surface-area trends also reduces the likelihood that changes in regional groundwater flow, which influence lakewater/deep-groundwater exchange through sublacustrine open taliks [*Walvoord et al.*, 2012], account for the observed lake dynamics.

[11] In contrast to open taliks, the occurrence of unfrozen sublacustrine gravel is significantly associated with lake surface-area trend (p = 0.04). For example, lakes overlying unfrozen gravel are 2.5 times as likely to be shrinking as lakes not overlying unfrozen gravel (Figure 4b). Lakes overlying unfrozen gravel and frozen silt (Type D cases), most prevalent in the Loess Base (Figure 4c), are particularly susceptible to shrinkage (Figure 4a). These observations suggest that changes in lakewater/groundwater exchange as a potential driver of lake volume evolution result more likely from shallow (few tens of meters), rather than deeper (~50–100 m), thermal changes in permafrost. Shallow thermal changes influencing lakewater/groundwater exchange would likely need to occur in terrestrial areas of watersheds in order to provide lateral groundwater flow-path connectivity to and from sublacustrine aquifers, possibly including deepening of the permafrost table [*Marsh et al.*, 2009; *Osterkamp*, 2007] and growth of supra- and intra-permafrost taliks [*Zhang et al.*, 2008]. Such processes could allow substantial groundwater exchange between watersheds in the study area owing to the high hydraulic conductivity of unfrozen gravel [*Jepsen et al.*, 2013]. In addition, the occurrence of unfrozen gravel is more spatially variable across the landscape than deeper silt, as indicated by the greater standard deviation of unfrozen gravel than deeper unfrozen silt across physiographic units (19% in Figure 4d versus 13% in Figure 4e).

[12] The occurrence of frozen sublacustrine silt is significantly associated with lakes that are expanding (p = 0.05). Lakes overlying frozen silt are 2.7 times as likely to be expanding as lakes overlying unfrozen silt (Figure 4f). Given the low hydraulic conductivity of frozen silt, upwelling of deep groundwater is not likely to be a significant source of recharge to many of these expanding lakes. Rather, enhanced water supply to these lakes may follow shallow flow paths through unfrozen gravel, or overland flow paths from adjacent water bodies [*Woo and Mielko*, 2007]. The presence of frozen silt below many of the expanding lakes may be an indication regarding their age and/or persistence of being filled with water—many of them may be too young to have formed open taliks, or may undergo cycles of filling and drainage thereby

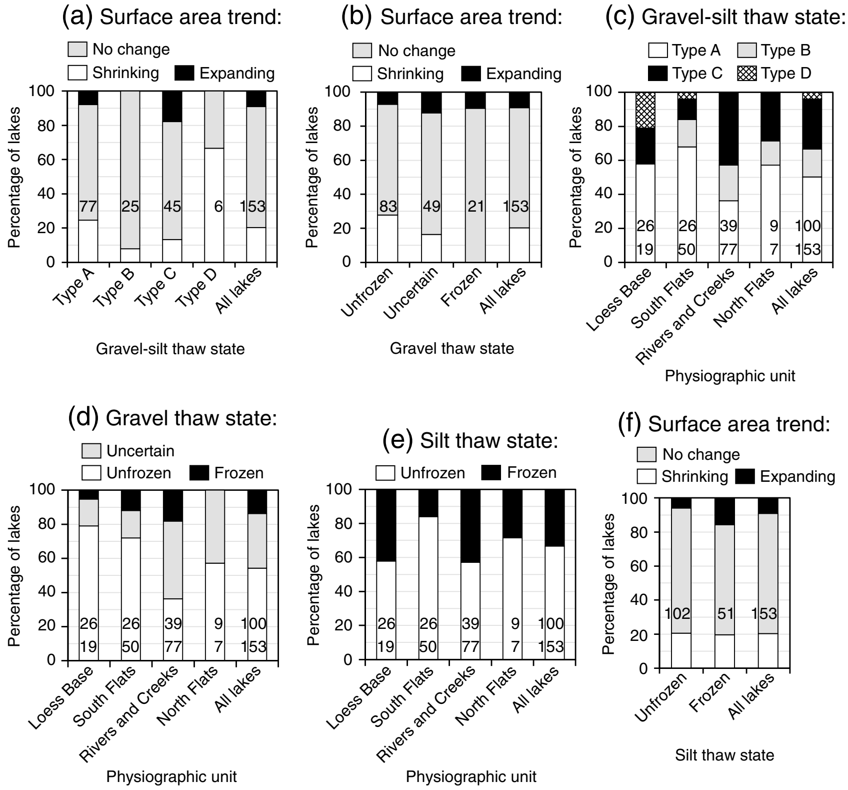

Figure 4. Relationships between (a, b, and f) lake surface-area trends and sublacustrine thaw states and (c–e) sublacustrine thaw states and location. Thaw states in Figure 4a and c are defined in Figure 3. Numbers in bars of Figure 4a, b, and f are the number of lakes sampled by the airborne electromagnetic (AEM) survey. In bars of the remaining panels, the upper and lower numbers are the percentages of total lake surface area from *Rover et al.* [2012] and the number of lakes sampled by the AEM survey, respectively.

allowing their lake bottoms to freeze intermittently. The observed high occurrence of expanding lakes along rivers and creeks (Figure 1b), coupled with the possibility that many of these lakes are young, could be an indication of recent increases in regional groundwater discharge through taliks in low-lying river corridors [*Walvoord et al.*, 2012].

[13] These regional scale results are consistent with previous studies indicating the substantial impact of shallow permafrost thaw on lakewater-groundwater exchange and hence lake water budgets [*Marsh et al.*, 2009; *Jorgenson and Osterkamp*, 2005; *Yoshikawa and Hinzman*, 2003; *Marsh and Neumann*, 2001; *Brewer et al.*, 1993; *Mackay*, 1992]. Reported thaw depths in these studies have been up to a few tens of meters, generally becoming shallower northward where permafrost becomes colder and more continuous. The use of airborne electromagnetics in this study has allowed a deeper and larger-scale inspection of linkages between groundwater flow-path connectivity and changes in lake water budgets than was available in previous ground-based studies.

5. Conclusions

[14] Dynamics of lake water budgets in permafrost regions, which control lake abundance and volume, depend in part on sublacustrine connectivity of lakes with shallow and deep groundwater via taliks. Results of a pioneering, airborne electromagnetic survey over Yukon Flats, interior Alaska, offer an unprecedented means of evaluating relationships between lake surface-area changes, proxies of water budget and lake volume changes, and thaw states of sublacustrine ground in a permafrost region. Lack of a significant association between the occurrence of open taliks and lake surface-area changes ($p = 0.37$) suggests that lake shrinkage and expansion is not occurring as a result of sublacustrine thaw zones breaching the bottom of permafrost, thereby linking lakewater and subpermafrost groundwater. This lack of association also suggests that regional scale changes in groundwater flow and associated lacustrine interactions through open taliks are unlikely to account for the observed lake size dynamics at the multidecadal time scale considered (1979−2009). These results do suggest that if increased groundwater exchange is driving the observed lake shrinkage and expansion, the process likely involves shallow thermal changes in permafrost (upper few tens of meters), such as deepening of the permafrost table and growth of supra- and intra-permafrost taliks. In the region studied, these key shallow aquifers exhibit the highest hydraulic conductivity and greatest spatial variability in unfrozen state. The thermal and hydrological properties of these aquifers will be particularly sensitive to climate change owing to their close proximity to the atmosphere.

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