Shifting balance of thermokarst lake ice regimes across the Arctic Coastal Plain of northern Alaska

C. D. Arp,[1] B. M. Jones,[2] Z. Lu,[3] and M. S. Whitman[4]

Received 25 May 2012; revised 20 July 2012; accepted 20 July 2012; published 24 August 2012.

[1] The balance of thermokarst lakes with bedfast- and floating-ice regimes across Arctic lowlands regulates heat storage, permafrost thaw, winter-water supply, and over-wintering aquatic habitat. Using a time-series of late-winter synthetic aperture radar (SAR) imagery to distinguish lake ice regimes in two regions of the Arctic Coastal Plain of northern Alaska from 2003–2011, we found that 18% of the lakes had intermittent ice regimes, varying between bedfast-ice and floating-ice conditions. Comparing this dataset with a radar-based lake classification from 1980 showed that 16% of the bedfast-ice lakes had shifted to floating-ice regimes. A simulated lake ice thinning trend of 1.5 cm/yr since 1978 is believed to be the primary factor driving this form of lake change. The most profound impacts of this regime shift in Arctic lakes may be an increase in the landscape-scale thermal offset created by additional lake heat storage and its role in talik development in otherwise continuous permafrost as well as increases in over-winter aquatic habitat and winter-water supply. **Citation:** Arp, C. D., B. M. Jones, Z. Lu, and M. S. Whitman (2012), Shifting balance of thermokarst lake ice regimes across the Arctic Coastal Plain of northern Alaska, *Geophys. Res. Lett.*, *39*, L16503, doi:10.1029/2012GL052518.

1. Introduction

[2] Thermokarst lakes cover up to 25–40% of lowland Arctic landscapes, including coastal plain regions of Alaska, Siberia, and Canada [*Grosse et al.*, 2012]. The formation and growth of thermokarst lakes is governed by thermal erosion of ice-rich permafrost, and where most lakes are shallow as on the Arctic Coastal Plain of northern Alaska (ACP) [*Sellmann et al.*, 1975], the thickness of lake ice growth is a primary regulator of lake energy balance and permafrost stability [*Ling and Zhang*, 2003; *Arp et al.*, 2011]. Historically, thick ice growth of up to 2 m or more on the ACP caused many shallow lakes to freeze entirely to the bottom (bedfast-ice regime) by late winter or earlier, such that their use as habitat and water supply was restricted to the short, Arctic summer [*Jeffries et al.*, 1996; *Zhang and Jeffries*, 2000]. In lakes exceeding this depth however, a portion of the ice remains floating atop perennially liquid water (floating-ice regime) such that they can provide year-round habitat for fish and other aquatic biota, supply water for municipal and industrial uses [*Brewer*, 1958; *Jones et al.*, 2009], and store large amounts of heat [*Jeffries et al.*, 1999].

[3] Heat transferred from floating-ice lakes creates zones of perennially thawed sediment (taliks) that over time reach depths of 50 m or greater in otherwise continuous permafrost [*Lachenbruch et al.*, 1962]. A shift from a bedfast-ice to a floating-ice regime can initiate talik development [*Ling and Zhang*, 2003] and potentially release large stocks of carbon previously frozen in permafrost in the form of methane [*Walter et al.*, 2007]. Thus, the ice regime of a lake exerts a first-order control on many other physical processes, and the landscape-scale balance of lakes with bedfast-ice and floating-ice regimes plays a key role in ecological, land surface, and climate processes.

[4] *Brewer* [1958] first recognized the important role of these lake ice regimes, classifying thermokarst lakes near Barrow, AK as bedfast-ice at depths <0.9 m and floating-ice at depths >1.8 m. The notable gap of 0.9 m between these ice regime classes likely represent lakes that freeze solid in some years and maintain liquid water in other years. Research using synthetic aperture radar (SAR) imagery to distinguish bedfast-ice from floating-ice lakes, coupled with a numerical ice growth model, indicated a maximum ice thickness ($Z_{ice\text{-}max}$) threshold of 2.2 m separating lake ice regimes [*Jeffries et al.*, 1996]. Simulation of $Z_{ice\text{-}max}$ over a 50 year period for this same region showed a range from 1.3 to 2.5 m, underscoring the potentially dynamic nature of lake ice regimes and the factors responsible for inter-annual variability and regional gradients, particularly snow accumulation and timing [*Zhang and Jeffries*, 2000; *Sturm and Liston*, 2003; *Brown and Duguay*, 2010] and the water level when ice first forms in the early winter [*Jones et al.*, 2009], which is set by spring snowmelt recharge, followed by summer lake level recession that tracks precipitation relative to evaporation [*Bowling et al.*, 2003].

[5] Observed and projected trends in winter warming, increased snowfall, and enhanced hydrologic fluxes for the ACP [*Hinzman et al.*, 2005; *Rawlins et al.*, 2010] indicate that lakes with bedfast-ice regimes could shift towards floating ice conditions in response to thinner ice growth and fuller lake basins [*Arp et al.*, 2011; *Prowse et al.*, 2011]. To evaluate potential shifts across an Arctic lowland landscape with bedfast- and floating-ice regime lakes, we tracked their extent and numbers using Advanced Synthetic Aperture Radar (ASAR) imagery acquired during April from 2003 to

[1]Water and Environmental Research Center, University of Alaska Fairbanks, Fairbanks, Alaska, USA.
[2]Alaska Science Center, U.S. Geological Survey, Anchorage, Alaska, USA.
[3]Cascades Volcano Observatory, U.S. Geological Survey, Vancouver, Washington, USA.
[4]Arctic Field Office, Bureau of Land Management, Fairbanks, Alaska, USA.

Corresponding author: C. D. Arp, Water and Environmental Research Center, University of Alaska Fairbanks, 467 Duckering Bldg., Fairbanks, AK 99709, USA (cdarp@alaska.edu)

0094-8276/12/2012GL052518

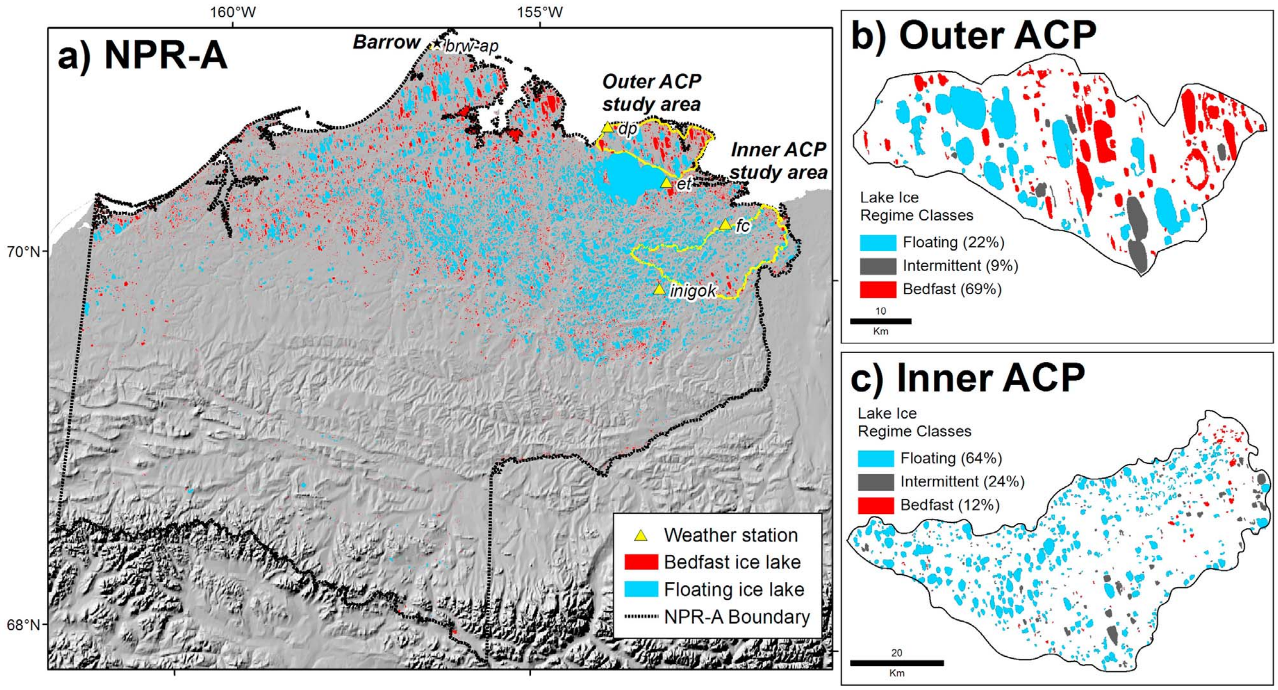

Figure 1. A classification of lakes by ice regimes in the National Petroleum Reserve – Alaska (NPR-A) from side-looking airborne radar (SLAR) imagery in April 1980 [*Mellor*, 1987] showing locations of study areas and climate stations (a). Recent (2003–2011) lake regime classes from mid-April, Advanced Synthetic Aperture Radar (ASAR) imagery in the (b) Outer ACP and (c) Inner ACP study areas.

2011 in two distinct study areas on the ACP. This multi-year ASAR analysis was then compared to a radar-based lake ice classification acquired in April 1980 [*Mellor*, 1987] to quantify any long-term, directional changes. Simulated and observed ice thickness and water balance records were then used to understand the conditions controlling variation in lake ice regimes.

2. Study Area and Methods

[6] We analyzed lakes in two distinct regions of the ACP within the National Petroleum Reserve –Alaska (NPR-A) in northern Alaska (Figure 1). Nearly all water bodies in both regions are considered thermokarst lakes because they expand due to degradation of confining permafrost [*Hopkins*, 1949] and include depressions formed by antecedent conditions (e.g., oxbow and dune-trough depression lakes) [*Grosse et al.*, 2012]. The Outer ACP study area is 1,339 km^2 and located north of Teshekpuk Lake within the Teshekpuk Lake Special Area (TLSA) with many large elliptical thermokarst lakes formed in ice-rich, silty marine sediments. The Inner ACP study area is 2,383 km^2 and bounded by a portion of the Fish Creek watershed with many lakes formed in moderately ice-rich to relatively ice-poor marine sands or in natural depressions (dune-trough and fluvial-borne) [*Jorgenson and Shur*, 2007]. In addition to being representative of typical physiographic characteristics of the inner and outer ACP, these areas were selected based on the presence of permafrost and climate monitoring station observations since 1998 and more recent surveys of lake temperature and late winter snow and lake ice characteristics.

[7] The ASAR scenes were collected for portions of the ACP from 2003 to 2011 during mid-April (Text S1 and Table S1, auxiliary material).[1] ASAR scenes were transformed to sigma naught backscattering coefficient estimates to classify the area of each lake as bedfast-ice or floating-ice. These ASAR classifications of the area of bedfast- and floating-ice per lake were then organized in a GIS database based on a lake polygon vector file derived from a 2010 Landsat TM image. Lakes with bedfast ice in one or more, but not all years of ASAR observations, were classified as having intermittent ice regimes. Ground-truthing of ASAR lake classifications was conducted for a subset of lakes in both study areas from 2007 to 2011. Our ASAR classification of lake ice regimes for both study areas was then compared to a similar classification conducted using Side-Looking Airborne Radar (SLAR) imagery acquired from 7–11 April 1980 [*Mellor*, 1987].

[8] In order to analyze the two primary factors hypothesized to control variation in lake ice regimes for this period, we simulated lake ice thickness (Z_{ice}) for the date of ASAR image acquisition and regional water balance in the year prior to freeze-up as precipitation minus lake evaporation (P-E). Lake ice growth and thickness was simulated on a daily time-step using Stefan's Law [*Leppäranta*, 1983] for congelation ice that accounts for snow-modified heat flux at the ice surface (Text S1, auxiliary material). Model simulations were calibrated to measurements of late winter lake ice growth in both study areas as well as the long-term dataset available from Barrow, AK (Table S2, auxiliary material). Records of

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL052518.

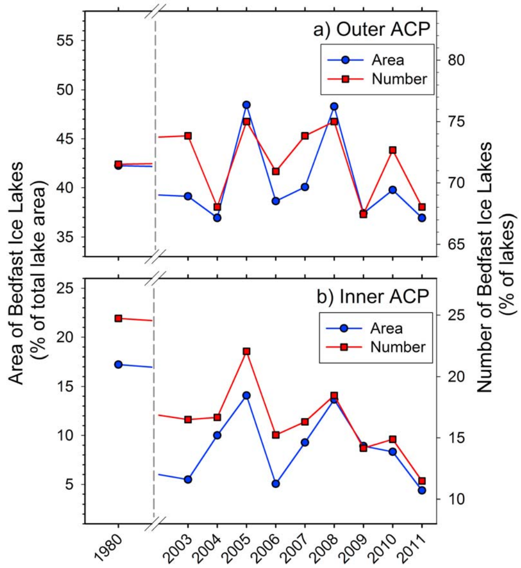

Figure 2. Interannual variability in the area and number of bedfast-ice lakes from 2003–2011 compared to the same lakes classified in 1980 [*Mellor*, 1987] in the (a) Outer ACP and (b) Inner ACP study areas.

precipitation and spring snow-water equivalent (SWE) and simulated lake evaporation utilized the Priestley-Taylor method using data from two stations within each study area and Barrow (Figure 1) (Table S3, auxiliary material). ASAR measured bedfast ice area and number of bedfast ice lakes were statistically compared to estimates of Z_{ice} on the date of acquisition and P-E using multiple regression analysis to evaluate the portion of variability explained by these hypothesized factors.

3. Results and Discussion

3.1. Remote Sensing of Lake Ice Regimes

[9] The *Mellor* [1987] classification of lake ice regimes from the winter of 1980 showed that 26% of the 560 lakes on the Inner ACP had bedfast-ice regimes, compared to the Outer ACP study area, where 74% of the 194 lakes had bedfast-ice regimes. These patterns resulted in 18% of the Inner ACP lake area and 47% of the outer ACP lake area being covered by bedfast-ice lakes. This balance of lake ice regimes across the ACP during one late winter season is similar to gradients observed near Barrow in 1992 when 23% of inner ACP lakes and 77% of outer ACP lakes had bedfast ice regimes [*Jeffries et al.*, 1996]. These ACP gradients primarily relate to lake depth and corresponding sediment grain-size, ground-ice content, and local topography [*Sellmann et al.*, 1975], but also to regional climate particularly winter temperature and snow accumulation patterns that control maximum ice thickness ($Z_{ice\text{-}max}$) [*Mellor*, 1987; *Sturm and Liston*, 2003]. Since $Z_{ice\text{-}max}$ has been shown to exhibit high inter-annual variability on the ACP [*Zhang and Jeffries*, 2000], we expected that a multi-year analysis of the number and extent of lake ice regimes would help reveal the dynamic nature of these lake-rich areas.

[10] Based on an analysis of ice regimes from 2003–2011 using ASAR imagery, we observed a peak in bedfast ice lakes for both study areas in 2005 and a distinct minimum in bedfast ice lakes on the Inner ACP in 2011 (Figure 2 and Figure S1, auxiliary material). However on the Outer ACP nearly equal minimum numbers and extents of bedfast ice lakes were observed in 2004, 2009, and 2011, suggesting some asynchronous behavior in the climatic processes controlling lake ice regimes on the ACP. No significant trends were detected in either the number of lakes with bedfast ice regimes or the extent of bedfast ice during this 9 year period (Figure 2).

[11] Multi-year ASAR analysis allowed us to identify a third class of lake ice regimes on the ACP—those with intermittent or transitional behavior of freezing solid in some years and maintaining liquid water below floating ice in other years (Figure 1). Based on this 9 year period, we identified 159 lakes (25%) on the Inner ACP and 18 lakes (9%) on the Outer ACP with intermittent ice regimes (Figure 1). Lakes of this intermittent ice regime class accounted for 14% and 11% of total lake area in the Inner and Outer ACP, respectively.

[12] Since we were able to distinguish between bedfast- and floating-ice lakes versus those with an intermittent regime from 2003 to 2011, we could then compare this dataset to the April 1980 radar-derived dataset [*Mellor*, 1987] to identify whether any lakes had consistently transitioned to one regime from another. On the Outer ACP most lakes observed and classified during the 2003–2011 period matched the 1980 classification with only three previously bedfast-ice lakes now being classified as floating-ice and two with the opposite transition likely due to partial lake drainage events. A very different result was discovered in the Inner ACP with 39 bedfast-ice lakes or 27% of all bedfast-ice lakes having shifted to floating-ice lakes and also a high proportion, 40%, of the remaining 1980 bedfast-lakes now having floating-ice during at least one year from 2003–2011 (Figure 2). Because only one year was used for the initial lake ice regime classification, it is not possible to know how many previously classified bedfast- or floating-ice lakes were actually intermittent. Still these results suggest the higher number of intermittent ice regime lakes observed during the past decade on the Inner ACP are transitioning to stable floating-ice regimes.

3.2. Controls on Lake Ice Regimes

[13] On a regional basis, $Z_{ice\text{-}max}$ relative to water balance should factor prominently in lake ice regimes. The simulated $Z_{ice\text{-}max}$ record from Barrow shows a variable, but significant decline of 1.5 cm yr^{-1} ($r^2 = 0.48$, $p < 0.01$) from 1978 to 2011 with the thickest ice of 220 cm in 1983 and thinnest ice of 141 cm in 2011 (Figure 3). Ten years of field observations near Barrow were used to calibrate our simulated record with an overall RMSE of 18 cm. This pattern of inter-annual variability in $Z_{ice\text{-}max}$ at Barrow has previously been documented based on a simulated record between 1947 and 1997, with no trend detected and notable decadal-scale variability attributed mainly to the timing and amount of early winter snowfall [*Zhang and Jeffries*, 2000]. The significant thinning trend in our $Z_{ice\text{-}max}$ record spans the most recent 14 years and corresponds well to increases in both early winter (September to December) snowfall and temperature ($r^2 = 0.68$, $p < 0.01$), explaining nearly equal portions of variation, 37% and 31%, respectively, over this 34 year period. Records of early winter snowfall show a steady increase of 1.8 cm yr^{-1} during this period (Figure 3), which can serve to moderate ice growth, though development of snow-ice and patterns of snowfall

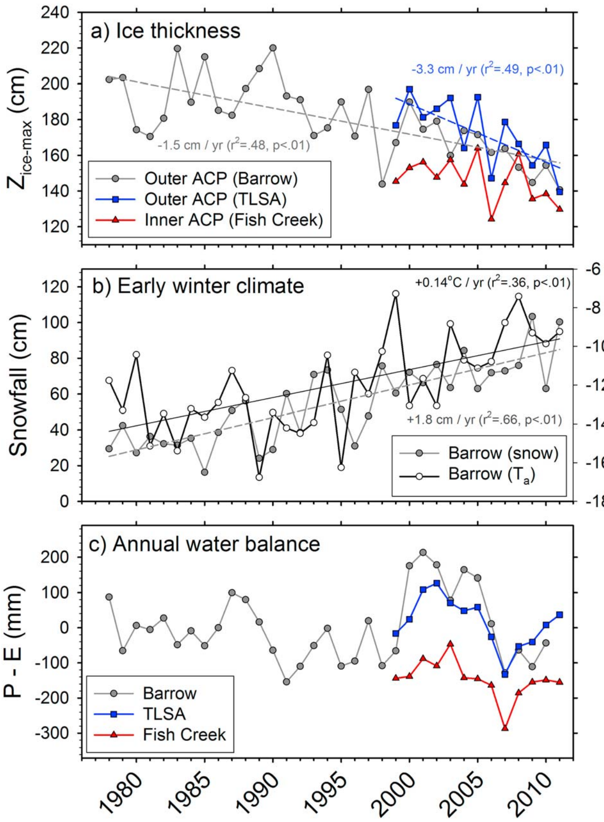

Figure 3. Long-term pattern and trend in the regional processes controlling lake ice regimes, including (a) maximum simulated ice thickness ($Z_{ice\text{-}max}$), (b) early winter (September–December) total snowfall and mean temperature, and (c) lake water balance as the sum of precipitation minus evaporation (P-E).

distribution and accumulation depend greatly on the timing of initial ice formation [*Brown and Duguay*, 2010].

[14] Simulated $Z_{ice\text{-}max}$ for the Outer ACP (TLSA) from 1999 to 2011 showed a stronger decline of 3.3 cm yr^{-1} (r^2 = 0.49, $p < 0.01$) and ranged from 140 cm in 2011 to 197 cm in 2000 (Figure 3). Ice thickness measurements made in a few TLSA lakes in 1976 and 1979 were 232 cm and 202 cm [*Weeks et al.*, 1981], respectively, helping to confirm that there are relatively uniform patterns of very thick ice during the 1970's across the outer ACP as noted in Barrow [*Zhang and Jeffries*, 2000]. For the same 13 year period in the Inner ACP (Fish Creek), there was relatively high inter-annual variability in simulated $Z_{ice\text{-}max}$ ranging from 124 cm in 2006 to 164 cm in 2005 with no trend detected (Figure 3).

[15] Analysis of variation in water balance using records of rainfall and estimates of lake evaporation and spring SWE together as P-E from 1977 to 2010 in Barrow indicate several periods of full lake basins, particularly 1986 to 1989 averaging +49 mm and 2000 to 2006 averaging +137 mm, and lower recent lake water balance from 2007 to 2010 averaging −87 mm (Figure 3). Barrow precipitation records for a portion of this period (1985–2007) were shown to correspond well to inter-annual variability in lake area extent in both study areas in the NPR-A [*Jones et al.*, 2009] and essentially the same P-E records (1977–2008) explained some of the hydrologic variability of several large lakes in the Outer ACP study area, particularly for shallow lakes with bedfast-ice regimes [*Arp et al.*, 2011]. The shorter periods of record for the Inner and Outer ACP showed a very similar pattern of inter-annual variability with the greatest water balance deficit in 2007 and overall drier conditions on the Inner ACP (Figure 3).

[16] We hypothesized that variation in the number and extent of bedfast ice lakes could be predicted by Z_{ice} at the time of ASAR image acquisition and P-E from the preceding year. On the Outer ACP, Z_{ice} explained 41% ($p < 0.01$) of the variation in bedfast-ice area and together with P-E during the previous spring and summer explained 78% ($p < 0.01$) of this variation, while for the number of bedfast ice lakes only Z_{ice} explained significant variation (r^2 = 0.57, $p < 0.01$) (Table S4, auxiliary material). On the Inner ACP, both bedfast ice extent and number of bedfast ice lakes were significantly related only to Z_{ice} (r^2 = 0.62, p = 0.02). One explanation for this difference between regions is that at least 24 of the ASAR monitored lakes in the Inner ACP study area are floodplain lakes or river tapped thermokarst lakes in which the water balance may be controlled by periodic recharge during high snowmelt-driven river peak flows and particularly ice-jam backwater flooding, thus obscuring the relationship to P-E seen in the Outer ACP. Overall however, our analysis suggests a progressive shift in lakes from bedfast-ice to floating-ice regimes resulting primarily from a decrease in winter lake ice growth, particularly on the Inner ACP where lakes should have more stable basins because of lower permafrost ice content [*Jorgenson and Shur*, 2007].

3.3. Implications

[17] The observation that many bedfast-ice lakes have transitioned to floating-ice lakes since 1980 and that many other lakes currently have intermittent-ice regimes indicates both a trend towards shallower lake depths being affected by thinner ice and inherently high inter-annual variability in the threshold separating lake ice regimes. One of the most direct impacts of this threshold governing Arctic lakes is on their thermal regime and the cumulative heat storage in lake sediments. To provide a more quantitative assessment of this relation we plotted mean annual lake-bed temperature (MALT) and its offset with permafrost and air temperatures (Figure 4). Similar to MALT analyses by *Burn* [2002] and *Arp et al.* [2011], this comparison shows a relatively wide, but clear threshold where $Z_{ice\text{-}max}$ equals lake depth that separates bedfast-ice from floating-ice conditions for a given year. The thermal offset to permafrost and air temperature helps standardize these values by year and region, but more importantly highlights the range of impacts that shallow Arctic lakes have on heat storage and flux to the ground and atmosphere [*Jeffries et al.*, 1999; *Riseborough*, 2006]. A regional-scale shift in the balance of lakes from bedfast-ice to floating-ice regimes may have its most profound impact by increasing the number of landscape patches (floating ice-lakes) and total landscape area towards higher thermal offsets of about 9°C with permafrost and 12°C with the lower atmosphere (Figure 4).

[18] *Lachenbruch et al.* [1962] recognized this impact of lakes on otherwise continuous permafrost landscapes as the greatest local departures from the systematic geographical patterns determined by climate factors. Yet incorporation of lakes into models of both deep and shallow permafrost

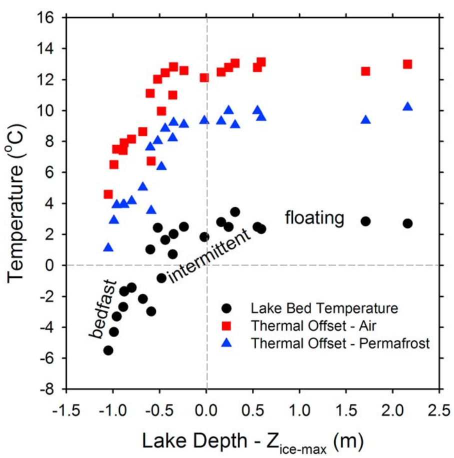

Figure 4. The relation between effective lake depth (depth – maximum ice thickness) and mean annual lake bed temperature (MALT), the thermal offset of MALT with air temperature (3-m height) and the thermal offset of MALT with permafrost (120 cm depth).

dynamics [*Riseborough*, 2006] and atmospheric heat exchange [*Jeffries et al.*, 1999] is still lacking. Prominent studies have documented regional patterns of lake change in permafrost landscapes according to surface-area dynamics [e.g., *Smith et al.*, 2005], however fundamental changes in Arctic lake processes related to ice dynamics may present an equally important, but more subtle landscape-scale response to Arctic climate change [*Arp et al.*, 2011; *Prowse et al.*, 2011]. A landscape-scale shift in the balance of lake ice regimes from bedfast-ice to floating-ice conditions would expand over-winter aquatic habitat and industrial and municipal winter water supply [*Jones et al.*, 2009] and drive a set of positive feedbacks with winter warming and permafrost thaw [*Ling and Zhang*, 2003]. This response of lake ice regimes to changing climate appears to be happening unevenly across the ACP landscape of northern Alaska. Given the uncertainty in Arctic climate projections for winter snowfall that drives both ice growth and lake water balance [*Brown and Duguay*, 2010], coupled with potentially greater uncertainty in the Arctic hydrologic cycle [*Rawlins et al.*, 2010], recognition of lake ice regimes and their dynamic landscape-scale balance is needed in assessments and models of Arctic climate change responses and feedbacks.

[19] **Acknowledgments.** We thank S. Walker, M. Lilly, F. Urban, R. Beck, G. Grosse, and B. Gaglioti for contributions to this research in the field, with data collection, and logistical support. Two anonymous reviewers and June Thormodsgard provided useful comments on this manuscript. Funding of this work was provided primarily by the Bureau of Land Management, the U.S. Fish and Wildlife's Arctic Landscape Conservation Cooperative, and the U.S. Geological Survey - Alaska Science Center, Geographic Analysis and Monitoring Program, and the Land Remote Sensing Program. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

[20] The Editor thanks Chris Burn and an anonymous reviewer for their assistance in evaluating this paper.

References

Arp, C. D., B. M. Jones, F. E. Urban, and G. Grosse (2011), Hydrogeomorphic processes of thermokarst lakes with grounded-ice and floating-ice regimes on the Arctic Coastal Plain, Alaska, *Hydrol. Processes*, *25*(15), 2422–2438.

Bowling, L. C., D. L. Kane, R. E. Gieck, L. D. Hinzman, and D. P. Lettenmaier (2003), The role of surface storage in a low-gradient Arctic watershed, *Water Resour. Research*, *39*(4), 1087, doi:1010.1029/2002WR0010466.

Brewer, M. C. (1958), The thermal regime of an arctic lake, *Eos Trans. AGU*, *39*, 278.

Brown, L. C., and C. R. Duguay (2010), The response and role of ice cover in lake-climate interactions, *Prog. Phys. Geogr.*, *34*(5), 671–704, doi:10.1177/0309133310375653.

Burn, C. R. (2002), Tundra lakes and permafrost, Richards Island, western Arctic coast, Canada, *Can. J. Earth Sci.*, *39*, 1281–1298, doi:10.1139/e02-035.

Grosse, G., B. Jones, and C. Arp (2012), Thermokarst lake, drainage, and drained basins, in *Treatise on Geomorphology*, edited by J. Shroder, R. Giardino, and J. Harbor, pp. 1–29, Academic, San Diego, Calif.

Hinzman, L., et al. (2005), Evidence and implications of recent climate change in northern Alaska and other arctic regions, *Clim. Change*, *72*, 251–298, doi:10.1007/s10584-005-5352-2.

Hopkins, D. M. (1949), Thaw lakes and thaw sinks in the Imuruk Lake area, Seward Peninsula, Alaska, *J. Geol.*, *57*, 119–131, doi:10.1086/625591.

Jeffries, M. O., K. Morris, and G. E. Liston (1996), A method to determine lake depth and water availability on the north slope of Alaska with spaceborne imaging radar and numerical ice growth modelling, *Arctic*, *49*(4), 367–374.

Jeffries, M. O., T. Zhang, K. Frey, and N. Kozlenko (1999), Estimating late-winter heat flow to the atmosphere from the lake-dominated Alaskan North Slope, *J. Glaciol.*, *45*(150), 315–324, doi:10.3189/002214399793377095.

Jones, B. M., C. D. Arp, K. M. Hinkel, R. A. Beck, J. A. Schmutz, and B. Winston (2009), Arctic lake physical processes and regimes with implications for winter water availability and management in the National Petroleum Reserve Alaska, *Environ. Manage. N. Y.*, *43*, 1071–1084, doi:10.1007/s00267-008-9241-0.

Jorgenson, M. T., and Y. Shur (2007), Evolution of lakes and basins in northern Alaska and discussion of the thaw lake cycle, *J. Geophys. Res.*, *112*, F02S17, doi:10.1029/2006JF000531.

Lachenbruch, A. H., M. C. Brewer, G. W. Greene, and B. V. Marshall (1962), Temperatures in permafrost, in *Temperature, Its Measurement and Control in Science and Industry*, pp. 791–803, Reinhold, New York.

Leppäranta, M. (1983), A growth model for black ice, snow ice and snow thickness in subarctic basins, *Nord. Hydrol.*, *14*(2), 59–70.

Ling, F., and T. Zhang (2003), Numerical simulation of permafrost thermal regime and talik development under shallow thaw lakes on the Alaskan Arctic Coastal Plain, *J. Geophys. Res.*, *108*(D16), 4511, doi:10.1029/2002JD003014.

Mellor, J. C. (1987), A statistical analysis and summary of radar-interpreted Arctic lake depths: An addendum to 12 map products, *Tech. Rep. 11*, 33 pp., Bur. of Land Manage. Alaska, Anchorage.

Prowse, T., et al. (2011), Effects of changes in Arctic lake and river ice, *Ambio*, *40*, 63–74, doi:10.1007/s13280-011-0217-6.

Rawlins, M. A., et al. (2010), Analysis of the Arctic system for freshwater cycle intensification: Observations and expectations, *J. Clim.*, *23*, 5715–5737, doi:10.1175/2010JCLI3421.1.

Riseborough, D. W. (2006), Discussion of C.R. Burn's 'Lake-bottom thermal regimes, western Arctic Coast, Canada,' *Permafrost Periglacial Processes*, *17*, 87–89, doi:10.1002/ppp.534.

Sellmann, P. V., J. Brown, R. I. Lewellen, H. McKim, and C. Merry (1975), The classification and geomorphic implications of thaw lakes on the Arctic coastal plain, Alaska, report, 24 pp., U.S. Army Cold Reg. Res. and Eng. Lab., Hanover, N. H.

Smith, L. C., Y. Sheng, G. M. MacDonald, and L. D. Hinzman (2005), Disappearing Arctic lakes, *Science*, *308*, 1429, doi:10.1126/science.1108142.

Sturm, M., and G. E. Liston (2003), The snow cover on lakes of the Arctic Coastal Plain of Alaska, U.S.A, *J. Glaciol.*, *49*(166), 370–380, doi:10.3189/172756503781830539.

Walter, K. M., L. C. Smith, and F. S. Chapin (2007), Methane bubbling from northern lakes: present and future contributions to the global methane budget, *Philos. Trans. R. Soc. A*, *365*, 1657–1676, doi:10.1098/rsta.2007.2036.

Weeks, W. F., A. J. Gow, and R. J. Schertler (1981), Ground-truth observations of ice-covered North Slope lakes imaged by radar, report, 18 pp., U.S. Army Cold Reg. Res. and Eng. Lab., Hanover, N. H.

Zhang, T., and M. O. Jeffries (2000), Modeling interdecadal variations of lake-ice thickness and sensitivity to climatic change in northernmost Alaska, *Ann. Glaciol.*, *31*, 339–347, doi:10.3189/172756400781819905.