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Analyzing floating and bedfast lake ice regimes across Arctic Alaska using 25 years of space-borne SAR imagery

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A B S T R A C T

Late-winter lake ice regimes are controlled by water depth relative to maximum ice thickness (MIT). When MIT exceeds maximum water depth, lakes freeze to the bottom with bedfast ice (BI) and when MIT is less than maximum water depth lakes have floating ice (FI). Both airborne radar and space-borne synthetic aperture radar (SAR) imagery (Ku-, X-, C-, and L-band) have been used previously to determine whether lakes have a BI or FI regime in a given year, across a number of years, or across large regions. In this study, we use a combination of ERS-1/2, RADARSAT-2, Envisat, and Sentinel-1 SAR imagery for seven lake-rich regions in Arctic Alaska to analyze lake ice regime extents and dynamics over a 25-year period (1992–2016). Our interactive threshold classification method determines a unique statistic-based intensity threshold for each SAR scene, allowing for the comparison of classification results from C-band SAR data acquired with different polarizations and incidence angles. Additionally, our novel method accommodates declining signal strength in aging extended-mission satellite SAR instruments. Comparison of SAR ice regime classifications with extensive field measurements from six years yielded a 93% accuracy. Significant declines in BI regimes were only observed in the Fish Creek area with 3% of lakes exhibiting transitional ice regimes—lakes that switch from BI to FI during this 25-year period. This analysis suggests that the potential conversion from BI to FI regimes is primarily a function of lake depth distributions in addition to regional differences in climate variability. Remote sensing of lake ice regimes with C-band SAR is a useful tool to monitor the associated thermal impacts on permafrost, since lake ice regimes can be used as a proxy for of sub-lake permafrost thaw, considered by the Global Climate Observing System as an Essential Climate Variable (ECV). Continued winter warming and variable snow conditions in the Arctic are expected and our long-term analysis provides a valuable baseline for predicting where potential future lake ice regimes shifts will be most pronounced.

1. Introduction

Shallow lakes are abundant in many regions of the Arctic, primarily due to prior glaciation and degradation of near surface ice-rich permafrost (Duguay et al., 2003; Grosse et al., 2013; Smith et al., 2007). Traditionally, winter lake ice grows 1.5 to 2 m thick at maximum ice thickness (MIT) and shallow lakes with depths less than MIT freeze completely and are called bedfast ice (BI) lakes (Brewer, 1958; Sellmann et al., 1975). Lakes with depths greater than MIT retain some liquid water and are termed floating ice (FI) lakes (Jeffries et al., 1996). Differences between BI and FI regimes in thermokarst lakes (see Appendix 1 for a glossary of abbreviations) are important because lakes with an above freezing (> 0 °C) mean annual bottom temperature will cause sub-lake permafrost degradation (Arp et al., 2016; Brewer, 1958; Burn, 2002). Additionally, BI and FI conditions impact energy and water balance (Arp et al., 2015). In regions where most lakes have BI regimes, lakes with FI provide often limit overwintering fish habitat and winter water supply for ice road construction and municipal uses (Jones et al., 2009). Yet despite this key dichotomy between arctic lakes, relatively little is known about several key features of these lakes: a) the distribution of lakes by ice regime over large regions, b) how regional lake ice regimes vary over time, and c) how they may be changing in response to climate change.

Landscape-scale inventories of lake ice regimes were first made by recognizing that BI lakes consistently become ice-free earlier than adjacent FI lakes due in part to thinner ice (Brewer, 1958) but also due to inability of surface melt-water to drain from ice-cover in BI lakes in comparison to FI lakes (Arp et al., 2015). Sellmann et al. (1975) used

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early summer Landsat imagery across portions of the Arctic Coastal Plain of northern Alaska to distinguish between relatively shallow lakes (BI) and relatively deep lakes (FI). Early uses of side-looking airborne radar (SLAR) showed a marked difference in the radar return from FI (high backscatter) and BI (low backscatter) lakes on Alaska's North Slope (Weeks et al., 1977). This sharp separation between backscatter from BI and FI was attributed to the large difference in dielectric properties between ice and fresh water along with the presence of small tubular bubbles in the ice (Mellor, 1982; Weeks et al., 1978, 1981). Field measurements revealed that while a uniform area of high backscatter indicated FI, low backscatter could indicate BI or the presence of briney water remaining under the ice cover at MIT (Mellor, 1982). Additionally, an ambiguous low radar signal was returned from FI on lakes deeper than ~4 m, which was attributed to the absence of tubular dissolved gas bubbles in ice over deep water (Mellor, 1982).

With the advent of calibrated space-borne synthetic aperture radar (SAR), Jeffries et al. (1994) and Morris et al. (1995) quantified the high and low backscatter intensity (σ^0) from FI and BI lakes, attributing the high σ^0 from FI lakes to the high dielectric contrast at the ice/water interface along with the presence of tubular gas bubbles, and low σ^0 from BI lakes to the low dielectric contrast at the ice/soil interface. They conducted field research at the same locations as the geocoded SAR pixels, establishing C-band SAR with a vertical transmit and receive (VV) single polarization as a useful remote sensing tool for landscape-scale lake regime inventory. Duguay et al. (2002) examined the effect of imaging incidence angle on horizontal transmit and receive (HH) C-band SAR-based ice regime analysis. Jones et al. (2013) successfully used X-band SAR to distinguish between BI and FI lake, river, and beaded stream ice regimes in northern Alaska, while Gunn et al. (2015) used X-band and the even shorter Ku-band on lake ice in Manitoba, Canada. Engram et al. (2013) evaluated L-band single and quadrature polarized backscatter from FI and BI as inferior to C-band VV σ^0 for distinguishing between the two regimes. Investigators have used SAR data to determine winter water availability from FI lakes for use in oil exploration (French et al., 2004; Jeffries et al., 1996; White et al., 2008). Others emphasized lake ice regime information from SAR in the context of climate research (Hall et al., 1994; Morris et al., 1995) and habitat studies (Brown et al., 2010; Jones et al., 2013). Recent investigations using polarimetric C-band SAR data by Atwood et al. (2015) have clarified the specific scattering mechanism that causes high σ^0 from FI. SAR is an established remote sensing tool to determine contrasting lake ice regimes, and a concise summary of various SAR imaging parameters and list of lake ice classification studies appears in Duguay et al. (2015). SAR's ability to image at night and through dry snow to provide landscape-scale lake ice regime classifications makes it a valuable tool for mapping lake ice regimes in the often cloudy and dark Arctic.

Late winter lake ice regimes are known to vary from year to year within and between regions (Arp et al., 2012; Duguay et al., 2002; Jeffries et al., 1994; Surdu et al., 2014). MIT variability can be related to differences in winter temperatures as well as the amount and timing of snowfall (Zhang and Jeffries, 2000). These differences in winter climate along with fluctuations in water level during the open-water period can cause lakes to transition from one ice regime to another in a given year. A shift from BI to FI could indicate thinner lake ice, or it could indicate an increase in lake water balance. A shift from FI to BI could indicate thicker ice, or it could be the result of a decrease in lake water balance (Arp et al., 2012). Deciphering causes of shifting ice regimes or ice regime variability requires consideration of both regional lake depth distributions and changes in climate that affect lake ice and water balance, although lake-specific variation such as partial lake drainage needs to be considered as well (Jones et al., 2009). Thus, analyzing a time series of SAR data at the regional scale is important for better understanding the impact of climate change on BI and FI regimes in arctic lakes.

In addition to examining lake ice regime change as a response to climate change, we can also map lake ice regimes using SAR to indicate the extent of permafrost thaw beneath lakes across the Arctic landscape. Lakes and permafrost have both been identified as Essential Climate Variables (ESVs) by the Global Climate Observing System (Bojinski et al., 2014). Although there are no direct remote sensing methods to detect and measure permafrost (Trofaier et al., 2017), lake ice regimes provide a proxy to the state of the permafrost below thermokarst lakes: liquid water under lake ice at MIT provides a thermal environment above the freezing point all winter, preventing re-freezing of the active layer in sub-lake permafrost, and promoting talik (thaw bulb) development.

Recent studies have broken ground in using SAR to develop landscape-scale inventories of lake ice regimes but have focused on one region for a 20-year timespan (Surdu et al., 2014), or a larger geographic area, such as the North Slope Alaska (Grunblatt and Atwood, 2014) and the pan-Arctic (Bartsch et al., 2017) based on one year. In this study, we analyze 25 years of space-borne C-Band SAR data acquired from multiple platforms covering seven lake-rich study regions in Arctic Alaska. Our study involves 11,571 lakes located in 15,250 km^2 of Arctic tundra landscape. The seven study sites differ in terms of climate and physiography, but are all located in the continuous permafrost zone in Alaska.

Our novel classification methodology allowed us to determine BI and FI across several C-Band SAR platforms to determine regional responses in ice regimes between 1992 and 2016. Our SAR-based classification quantitatively shows the amount of lake-scape area that is affected by variations in ice regimes from year to year, as well as the number and area of lakes that are predominantly BI, FI, or display intermittent ice regimes (INT) that oscillate between regimes, or have transitioned from BI to FI (TRANS-FI) or FI to BI (TRANS-BI) over this 25-year period. Our analysis identifies the composition of lake ice regimes across different lake-rich arctic landscapes and their susceptibility to future change, providing valuable remote sensing information about permafrost and lakes, both of which have been identified as ECVs.

2. Methods

2.1. Study area

To investigate patterns and any trends over the last 25 years that may be occurring in lake ice regimes, we chose seven regions in Alaska: five lake regions in the Arctic Coastal Plain of northern Alaska (ACPnA), one in the North Slope foothills, and one on the northern Seward Peninsula to represent a variety of thermokarst lake types including coastal and inland sites, high and low ice content in permafrost, and a variety of soil types (Fig. 1). Regions were selected based on representation of known lake, physiographic, and climatic variation in Arctic Alaska, but are not watershed based. Regions represent different limnologic landscapes that are all fairly lake-rich, but have different surface geologies that factor into lake depth, snow distribution, and water balance, which in turn affect lake ice regimes. Ground ice content varies between regions, as does surface geology, elevation, and topography.

Several years of measurements from field campaigns and from literature exist for many lakes in the regions near Barrow, Teshekpuk, Fish Creek, Inigok, Umiat and northern Seward Peninsula (Table 1), while lakes in the lower Kuparuk River region are possible subjects of future field investigations. Additionally, very few of the lakes in these areas are accessible by road, which reduces the risk of sampling bias due to easy access. Exact domains of each region were delineated to capture similar lake characteristics and at sizes of comparable magnitude (11,000–35,000 km^2). The percentage of lake-covered area within the regions is variable, ranging from 1% to 26% and the number of lakes per region varies from 123 to 2548 lakes (Table 2).