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Estimation of snow accumulation over frozen Arctic lakes using repeat ICESat laser altimetry observations – A case study in northern Alaska

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ABSTRACT

The spatial distribution and temporal dynamics of snow in Arctic regions have a direct impact on the regional energy balance and hydrologic cycle. However, our knowledge of snow cover in Arctic regions is very limited due to the sparseness of *in situ* measurements. This study presents a new method to derive snow accumulation information for Arctic regions through tracking the surface elevation changes of numerous frozen arctic lakes measured by Ice, Cloud, and land Elevation satellite (ICESat) repeat altimetry observations. The original ICESat elevation product for continental surface was generated by tracking the centroids of the emitted and the returned laser waveforms. This product contains many biased measurements over frozen arctic lake surfaces due to the scattering effects induced by thin clouds and blowing snow. This study derives an operational approach that produces more reliable altimetry observations by converting the elevation measurements from the centroid scheme to the max-amplitude-peak scheme. Time-variable biases exist between the repeat elevation measurements acquired in different ICESat campaigns. The correction of these inter-campaign biases in this study significantly improves the quantification of the surface elevation change, thus enabling more consistent subsequent snow accumulation estimates. Besides snow fall, lake ice growth also contributes to the surface elevation change. We developed a method to measure and remove this contribution from the total lake surface elevation change, which leads to more accurate estimates of snow accumulation on frozen surfaces of 277 lakes in Arctic regions of northern Alaska. The results were validated using *in situ* snow depth observations from terrestrial stations on the Arctic coastal plain of Alaska. After the correction of the ICESat inter-campaign biases and the removal of contribution by lake surface phase transformation, the snow accumulation derived from the repeat ICESat elevation measurements are highly correlated with *in situ* snow depth observations with a Pearson's correlation coefficient r of 0.88. In comparison with ground-based measurements, the root mean square error (*RMSE*) of our snow accumulation estimates is approximately 5 cm. Our method makes it possible to provide much denser snow accumulation information as compared to the existing *in situ* observations for the Circum-Arctic coastal regions and also the Qinghai-Tibet Plateau where seasonal frozen lakes are abundant.

1. Introduction

Most of the winter precipitation in Arctic regions falls as snow and accumulates on the ground, which is often redistributed by the wind across the landscape throughout the winter. It has a direct impact on the regional environment and ecosystem because of its high reflectivity and low thermal conductivity (Foster et al., 2005; Green et al., 2012; Hall et al., 1991; Liston and Sturm, 2002; Stieglitz et al., 2003). Snow accumulated on lake ice surface acts as an insulating layer effectively reducing the heat transfer between the atmosphere and the underlying ice (Maykut, 1978), and thus influences the magnitude and timing of lake ice growth and decay (Duguay et al., 2003). Snow cover and

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thickness are also important variables determining the fresh water budget of the lakes. During snowmelt in spring, the release of this freshwater pulse comprises a major contribution to the water supply of rivers and lakes in the Arctic (Arp et al., 2015; Dyer, 2008; Kane et al., 2004; Kane et al., 1991; Yang et al., 2003). A general decreasing trend of spring snow depth in Pan-Arctic regions during the past several decades has been reported in several previous studies (Biancamaria et al., 2011; Brown and Robinson, 2011; Callaghan et al., 2011a; Liston and Hiemstra, 2011; Park et al., 2012). The change in snow depth has multiple impacts on the environment, eco-system, and human activities, *i.e.*, the demise or growth of patchy wetlands (Callaghan et al., 2011b), the reproductivity and forage of various animals (Madsen et al., 2007; Turunen et al., 2009), and the recession of boreal forestry (Callaghan et al., 2011b).

However, we have very limited knowledge of snow in Arctic regions due to inadequate measurements. Traditionally, snow depth measurements are collected through *in situ* observations, such as automated weather stations and field surveys. Weather stations are very sparse and only cover very limited areas, owing to the cost and logistical difficulty in setting up and maintaining them in the remote and harsh Arctic environment. In this study, we focus on the Arctic Coastal Plain (ACP) of northern Alaska. In this region, the National Water and Climate Center (NWCC), NOAA National Centers for Environmental Information (NCEI), and Geophysical Institute Permafrost Laboratory (GIPL) operate a number of weather stations which are still providing snow depth observations. The Snow Telemetry (SNOTEL) program of NWCC has three stations at Prudhoe Bay, Sagwon and Imnaviat Creek along the Alaskan oil pipeline corridor, which provides snow depth records starting from 2011 (https://www.wcc.nrcs.usda.gov/snow/index.html). NCEI provides daily snow depth data at four stations, including Utqiagvik (known as Barrow previously) (1901–present), Colville Village (1996–present), Kuparuk (1983 – present), and Alpine (2011–present) (https://www.ncdc.noaa.gov/data-access/land-based-station-data). GIPL offers real-time snow depth data at five stations: Utqiagvik, Deadhorse, Imnaviat, Ivotuk, and West Dock (http://permafrost.gi.alaska.edu/content/data-and-maps). Except for Utqiagvik and Ivotuk, most of these weather stations are distributed in the east part of Alaskan ACP or along the oil pipeline corridor. The U.S. Department of the Interior (DOI) established 16 automatic climate monitoring stations through Global Terrestrial Network for Permafrost (DOI/GTN-P) program for the ACP of northern Alaska (https://pubs.usgs.gov/ds/812/introduction.html). Twelve of them located in the west part of Alaskan ACP. Snow depth measurements were collected by those stations between 1998 and 2011. Overall, *in situ* observations from ground stations are very sparse and mostly distributed along coastal regions.

Dedicated field expeditions focused on snow surveys may cross over a large area, but they are temporally sporadic and conducted only along the expedition routes. In the middle March of 1988, Hall et al. (1991) conducted a three-day *in situ* survey along the route of the Trans-Alaska pipeline between Fairbanks and the Arctic Coast, and snow depths were measured at 16 sites. Nelson et al. (1997) measured snow depths in 1995 for seven locations within the Kuparuk Basin, including Atqasuk, Utqiagvik, Betty Pingo, Happy Valley, Imnavait Creek, Toolik Lake, and West Dock. Walker et al. (1999) collected drift snow depths in winter seasons between 1995 and 2002 in the Toolik snowfence experiment site. Liston and Sturm (2002) made snow depth and density measurements from the headwaters of the Kuparuk basin to the Arctic coast in April of 1994, 1996 and 1997. Sturm and Liston (2003) conducted snow depth surveys at 13 paired lake/tundra locations from Oumalik to Utqiagvik in April 2000 and April 2002. Raynolds et al. (2008) and Walker et al. (2008) collected snow depth information during trips to the Alaskan ACP from 2001 to 2006, and measurements were made at 1 m spacing with 10 × 10 m grids at Happy Valley, Sagwon, Franklin Bluffs, Deadhorse, West Dock, and Howe Island. Apparently, historical snow observations from field surveys are spatially and temporally very limited.

Some efforts have been made to derive the snow depth information using remote sensing technology. For example, a snow radar is a microwave frequency-modulated altimeter implemented in the Operation IceBridge program (https://icebridge.gsfc.nasa.gov/). It operates over a very wide frequency range (2–18 GHz) and can estimate snow depth over ice surfaces by tracking the positions of snow/air and snow/ice interfaces (Brucker and Markus, 2013; Farrell et al., 2012; Galin et al., 2012; Kanagaratnam et al., 2007; Kurtz and Farrell, 2011). The mean difference between the snow depth measurements collected by the snow radar and by a concurrent *in situ* survey along a 2 km transect was 0.8 cm (Farrell et al., 2012; Kurtz et al., 2013). However, most of these data were collected over sea ice or for selected areas in Greenland and Antarctica, and no such data are available for elsewhere. Passive microwave remote sensing systems, such as Special Sensor Microwave/Imager (SSM/I), Scanning Multichannel Microwave Radiometer (SMMR), Advanced Microwave Scanning Radiometer for Earth Observing System (ASMR-E), have also been used to retrieve snow depth and further to estimate Snow Water Equivalent information on land surface based on the difference in brightness temperatures at two channels (*e.g.* 19 and 37 GHz for SMMR, SSM/I and AMSR-E) (Chang et al., 1987; Derksen et al., 2005; Foster et al., 2005; Green et al., 2012; Markus et al., 2006). However, the spatial resolution of passive microwave data is very coarse (*e.g.*, 25 km for SSM/I), and the accuracy of snow depth estimates from passive microwave data is largely affected by the sub-pixel spatial variations of vegetation cover (Derksen et al., 2005; Foster et al., 2005), snow conditions (*e.g.* density and stratigraphy) (Derksen et al., 2012; Markus et al., 2006), surface roughness (Stroeve et al., 2006), and particularly the coverage of thermokarst lakes (Green et al., 2012) that are prevalent features in the circumpolar regions (Duguay et al., 2003).

The Geoscience Laser Altimeter System (GLAS) on board of ICESat became operational in January 2003 (Zwally et al., 2002). It provided surface profile elevation measurements at global scale from 2003 to 2009. With footprint diameter of ~70 m and centimeter-scale precise vertical elevation measurements, ICESat/GLAS provides the possibility of measuring snow depth over relatively flat surfaces through tracking the surface elevation changes in the winter season. Bindschadler et al. (2005) estimated the new snow accumulation in one snowfall event on Antarctic ice sheet using the elevation differences at crossovers of ICESat overpasses before and after the event. Treichler and Kääb (2017) estimated the snow accumulation in a mountainous region at southern Norway using the elevation difference between ICESat and three Digital Elevation Models (DEMs), and the accuracy of the snow depth estimation was subjected to the quality of the reference DEMs and the bias level between ICESat measurements and the reference DEMs.

In this paper, we present a novel method to retrieve snow depth over frozen lake surfaces by tracking surface elevation changes with repeat ICESat/GLAS observations. A repeat satellite track usually does not exactly follow the previous track, and there might be several hundred meters of cross-track shift (*e.g.* 100–500 m for ICESat in northern Alaska). For land surface, the elevation may change significantly over such a short spatial distance, and the direct use of the repeat-track elevation measurements for surface elevation change detection is difficult as the effect of small-scale surface topographic variation between repeat tracks cannot be accurately quantified. In contrast, the frozen lake surfaces in general are spatially homogeneous and virtually invariant within a relatively short distance. Due to the homogeneity of lake surfaces, the repeat track measurements with a certain level of cross-track shift or even measurements from different tracks can be utilized to detect and compute the temporal change in surface elevation as long as the measurement points fall completely within a small- or medium-sized lake or within a certain distance in a large lake. The frequency and density of repeat surface measurements depend on the lake size. More satellite tracks and more measurement points along tracks would be generated over a large lake for a more frequent change