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Shrinking sea ice, increasing snowfall and thinning lake ice: a complex Arctic linkage explained

Ben W Brock

Department of Geography, Northumbria University, Newcastle upon Tyne, UK

E-mail: Benjamin.brock@northumbria.ac.uk

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Abstract

The dramatic shrinkage of Arctic sea ice is one of the starkest symptoms of global warming, with potentially severe and far-reaching impacts on arctic marine and terrestrial ecology (Post *et al* 2013 *Science* **341** 519–24) and northern hemisphere climate (Screen *et al* 2015 *Environ. Res. Lett.* **10** 084006). In their recent article, Alexeev *et al* (2016 *Environ. Res. Lett.* **11** 074022) highlight another, and unexpected, consequence of Arctic sea ice retreat: the thinning of lake ice in northern Alaska. This is attributed to early winter 'ocean effect' snowfall which insulates lake surfaces and inhibits the formation of deep lake ice. Lake ice thinning has important consequences for Arctic lake hydrology, biology and permafrost degradation.

Lakes and ponds are very significant components of the landscape of the Arctic coastal lowlands of Alaska, western Canada and Siberia, and play an important role in the region's ecology [1] and hydrology [2]. Lakes have a reciprocal relationship with permafrost: their formation is largely governed by patchy near-surface permafrost degradation, while winter freezing to full lake depth, known as a bedfast ice, promotes the preservation of sub-lake permafrost. Observations of a widespread shift from bedfast to floating ice regimes in Arctic lakes over the past two decades [3, 4] are of concern since surface lake ice overlying liquid water in contact with the lake bed leads to localised patches of thawed permafrost, known as taliks [5]. The thinning trend in northern Alaskan lake ice has been linked to warmer, snowier winters [3]. The question addressed by Alexeev *et al* [6] is: *what role might reduced Arctic sea ice cover play in early winter climate and winter lake ice growth in the region?*

North Alaska, like much of the Arctic, has seen temperature and precipitation increases over the last four decades far in excess of global averages, with these trends heightened in the autumn. The decline in Arctic sea ice cover over the same period is well established [7], and has been strongly implicated in regional warming through albedo feedback and evaporation from open water which increases atmospheric moisture [8]. Furthermore, observed increases in Arctic snowfall extremes have been attributed to the increased flux of water vapour to the atmosphere from open sea [9, 10]. Linking these observations, Alexeev *et al* propose that higher temperatures and increased snowfall in early winter, associated with reduced sea ice cover, combine to reduce ice formation on freshwater lakes and ponds. While enough temporal data are apparently available to test this hypothesis, establishing linkages in complex ocean-atmosphere-terrestrial systems based on correlation of time-series is highly problematic.

To overcome this problem, Alexeev *et al* devise a clever modelling experiment, based on the proposition that greater Arctic sea ice cover in autumn should lead to thicker lake ice in early winter, and vice versa. They identify two winters in the available record with contrasting maximum lake ice thickness: 1991/92, which had relatively high sea ice extent; and 2007/08, which had the second lowest sea ice cover on record. In order to link ocean sea ice conditions with atmospheric processes and snowfall over land they use the well-known Weather Research and Forecasting (WRF) regional climate model. After running the model to analyse lake ice growth under the known ocean surface and atmosphere conditions in the 1991/92 and 2007/08 winters, they then rerun the model with the same atmospheric conditions, but with the sea ice cover from the contrasting year: namely 2007/

08 sea ice conditions imposed on the 1991/92 winter and 1991/92 sea ice conditions imposed on the 2007/08 winter. This enables the effect of sea ice cover on land temperature and snowfall conditions to be established independently of variation in atmospheric conditions.

The regular 2007/08 model run, compared with the 2007/08 model run using Artic sea ice cover from 1991/92, shows a twofold 'open ocean' effect. First, with low sea ice cover in 2007/08, there was a significant warming on the Arctic Coastal Plain of up to 5 °C. Second, the amount of snowfall was increased by 10–20 mm water equivalent depth, which amounts to 15%–20% of the snowfall in the regular 2007/08 model run. These results show that open ocean water in proximity to the Alaskan coast led to higher air temperatures and more intense early winter snowfall. Next, the WRF temperature and precipitation outputs from the model runs were applied in a model of lake ice formation, which was validated against lake ice thickness measurements from northern Alaskan lakes. Applying 1991/92 sea ice cover in the 2007/08 model run, which resulted in colder temperatures and less precipitation, increased lake ice thickness by 9% and the area of bedfast ice by an estimated 13%. When 2007/08 sea ice cover was applied in the 1991/92 model run, resulting in higher temperatures and increased snowfall, lake ice thickness decreased by 7% and the area of bedfast ice was estimated to decrease by approximately 9%.

These results clearly demonstrate a causal link between Arctic sea ice extent, atmospheric processes and their impacts on terrestrial freshwater systems. Furthermore, they show that impacts from an open Arctic Ocean in autumn are both direct, through increased air temperature and precipitation, and indirect, though inhibiting bedfast ice formation in lakes leading to localised permafrost degradation and talik formation [5]. Variation in the duration of lake ice cover also affects local energy balance and moisture availability with many uncertain consequences. Not all these changes are negative, as a shift from bedfast to floating ice regimes would provide overwintering fish habitats and could provide winter water supply for domestic and industrial use [11]. Key concerns remain, however, about the magnitude and frequency of 'ocean effect' snow and temperature increases in the future as sea ice cover continues to shrink leading to a potential acceleration of permafrost degradation in Arctic coastal lowlands.

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