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Tracing sources of freshwater contributions to first-year sea ice in Svalbard fjordss

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ABSTRACT

Salinity, $\delta^{18}O$, and total alkalinity were determined from sea ice cores collected from various fjords (Billefjorden, Tempelfjorden, Raudfjorden, Rijpfjorden, and Palanderbukta) around Spitsbergen and Nordaustlandet, Svalbard between February and April 2013. The data were used to determine whether ice cores could be used to quantitatively evaluate contributions of meteoric water (glacial meltwater, river runoff, and precipitation) to the fjords instead of traditional methods that rely on data collected from the water column where brine introduced during sea ice formation can complicate interpretation. The majority of the cores exhibited only small contributions ($\leq 5\%$) of meteoric water ice compared to that derived from seawater; however, cores collected close to the front of Tunabreen, a tidewater glacier located at the head of Tempelfjorden, contained a significant contribution (36%) of meteoric water ice. The shape of the vertical $\delta^{18}O$ profiles, as well as excess total alkalinities (relative to salinity) from the Tempelfjorden cores suggested that the source of this meteoric water was subglacial meltwater discharged from Tunabreen during fall and/or winter. Although cores were also collected close to the front of Nordenskiöldbreen (a tidewater glacier in Billefjorden), these did not exhibit a large meltwater influence. We speculate that the combination of the 2004 surge and subsequent retreat of Tunabreen, combined with the cyclonic circulation pattern of warm Atlantic waters that intruded into the Isfjorden system in mid-January of 2012 might have played a role in the apparently larger meltwater contribution to Tempelfjorden. Increasing Atlantic water temperatures in the West Spitsbergen Current and larger and/or more frequent intrusion of these waters into Isfjorden reduces winter sea ice growth and can thereby aid in the melt of tidewater glaciers (during summer and winter months). These interactions have important implications on glacier flow and deserve further study.

1. Introduction

Glaciers located both in Greenland and the Canadian Arctic Archipelago have been losing mass at an accelerated rate (Luthcke et al., 2006; Rignot et al., 2008; Velicogna, 2009; Dyurgerov et al., 2010, Gardner et al., 2011). Continued and increasing input of freshwater from glacial melt will impact sea level rise (Gardner et al., 2011), lower saturation states of aragonite and thus increase susceptibility to ocean acidification (Yamamoto-Kawai et al., 2009; Azetsu-Scott et al., 2010), and potentially disrupt deep convection in the North Atlantic (Aagaard and Carmack, 1989; Jungclaus et al., 2006; Myers, 2005; Stouffer et al. 2006). The acceleration of glacial retreat ensures that this freshwater source will play a continually larger role in the freshwater flux and carbonate saturation state of the Arctic and subarctic seas in the near future. As regions where glaciers flow into the ocean, Arctic and subarctic fjords are particularly susceptible to increases in both air and seawater temperatures (Hop et al., 2002; Cottier et al., 2005) that melt ice and thereby influence the carbon cycle through impacts on the saturation state of calcium carbonate (Brown, 2002; Sejr et al., 2011; Rysgaard et al., 2012), primary production (Wiktor, 1999; Zajaczkowski, et al., 2010), and the uptake of atmospheric carbon dioxide (Evans et al., 2014).

The fjords of the Svalbard Archipelago, particularly those in West Spitsbergen, are especially sensitive to change. West Spitsbergen fjords receive waters from both Arctic and Atlantic origins and the dominant influence of either of these water types in the fjords varies significantly on both seasonal and interannual time scales (Cottier et al., 2005; Nilsen et al., 2008). Increases in temperature of the West Spitsbergen Current (Piechura and Walczowski, 2009) and in the extent and frequency of Atlantic

Abbreviations: TA, total alkalinity

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water intrusion into West Spitsbergen fjords (Majewski and Zajaczkowski, 2007) have already been linked to a decline in areal sea ice cover (Zajaczkowski et al., 2010; Cottier et al., 2007; Nilsen et al., 2008) and may also be expected to aid in the basal melting and flow of tidewater glaciers, similar to the glacial fjords of West Greenland that are being exposed to warming seawater temperatures (Rignot et al., 2012). Furthermore, many Svalbard glaciers have been surging, an increase in the elevation gradient that results in a higher ice flux and rapid advance of the glacier front, since the early 1900s (Hagen et al., 2003). Although surge events may be unrelated to climate variability (Lefauconnier and Hagen, 1991), the larger subglacial melt and sediment flux as well as increased iceberg production (in the case of tidewater glaciers) typically associated with surging will increase the input of freshwater and particulates to the fjords. In order to assess the specific impact of increased glacial melt on ocean processes, it is necessary to distinguish this input from other freshwater sources such as river runoff, precipitation, and sea ice meltwater. However, the rejection of brine from the ice matrix into the underlying water column during freezing complicates simple methods of detection using salinity and stable oxygen isotopes (Strain and Tan, 1993).

Meteoric water is water that has undergone distillation and transport in the atmosphere and includes river runoff, direct precipitation on the ocean (i.e., rain or snow), and glacial meltwater. Repeated evaporation and precipitation cycles of the water vapor during transport through the atmosphere result in northern latitude meteoric waters being highly depleted in the heavier isotopes of oxygen (^{18}O) relative to seawater. In contrast, during the formation of sea ice ^{18}O is incorporated into the solid phase to a small extent, with a fractionation factor of $+1.6$–$2.3‰$ (Macdonald et al., 1995; Eicken, 1998). This process ensures that sea-ice meltwater is isotopically heavier than meteoric water and thus $\delta^{18}O$ can be used to distinguish between freshwater inputs from these two sources. Since conservative mixing between a single freshwater source and a seawater endmember results in a linear correlation between salinity and $\delta^{18}O$, a classic method that has been used to determine the predominant source of freshwater (e.g., glacial melt, river runoff, or sea ice melt) to a given region comprises fitting a simple linear regression to a plot of salinity (independent variable) versus $\delta^{18}O$ (dependent variable) and extrapolating this relationship to the intercept ($S=0$) to identify the mean $\delta^{18}O$ value of the freshwater source. Relatively high $\delta^{18}O$ values (e.g., $\delta^{18}O \geq 0‰$) may indicate that sea ice meltwater is the predominant freshwater source whereas more negative values (e.g., $-12 \leq \delta^{18}O \leq -22‰$) suggest local precipitation or river runoff.

High altitude precipitation, such as that atop the ice sheets that form glacial ice, has a typical $\delta^{18}O$ range between $-20‰$ and $-30‰$, and some estimates as low as $-40‰$ have been reported (Dansgaard and Tauber, 1969; Koerner and Russell, 1979; Bedard et al., 1981). Thus, glacial meltwater can be a potential source of highly negative $\delta^{18}O$ values and might be distinguishable from typical Arctic precipitation and river runoff ($-22 \leq \delta^{18}O \leq -14‰$; Cooper et al., 2008). Past studies have exploited such differences in order to infer significant contributions of glacial melt to the coastal ocean (Bedard et al., 1981; Kipphut, 1990). However, sea ice melt/formation processes also affect the freshwater composition such that the salinity–$\delta^{18}O$ relationship need no longer be linear. Specifically, the release of brine during sea ice formation can result in salinity–$\delta^{18}O$ relationships with highly negative intercepts that could be misinterpreted as an influence from glacial melt (Strain and Tan, 1993; Alkire et al., 2010). Therefore, new methods for the identification of glacial meltwater influence in the water column must be explored.

Since the release of brine to the underlying water column during ice formation is the mechanism that results in confusion when interpreting $\delta^{18}O$ measurements in seawater to deduce freshwater sources, it may instead be preferable to focus the study of $\delta^{18}O$ distributions to the overlying sea ice. As such, the complication introduced by the ejection of brine to seawater is removed from the sample medium and $\delta^{18}O$ measurements within the core are more likely to reflect the water type from which the ice was formed (after correction for fractionation). Assuming the sea ice in glacial fjords was formed from waters containing a significant quantity of glacial melt, the $\delta^{18}O$ of the ice should be indicative of such an influence. Prior work has demonstrated the feasibility of such a method to quantify the volume of river water frozen into landfast ice on North American (Macdonald et al., 1995) and Siberian (Eicken et al., 2005) shelves.

In this study, we report salinity, total alkalinity, and stable oxygen isotope ($\delta^{18}O$) distributions in cores of sea ice collected close to glacier outlets from a number of fjords around the Svalbard Archipelago during the delayed ice growth season of winter (February–April) 2013. We test the hypothesis that glacial meltwater extracted from the water column during sea ice formation can be identified and quantified using $\delta^{18}O$ measurements from ice cores such that this approach can be successfully utilized for studying the contribution of glacial meltwater to the total freshwater budgets of Arctic and subarctic seas.

2. Methods

2.1. Sample collection

Samples of seawater and ice were collected as part of three separate expeditions of opportunity to fjords in West Spitsbergen and Nordaustlandet (Fig. 1). The locations, dates of sample collection, and associated vessels are listed in Table 1. During the February cruise aboard *K/V Svalbard*, seawater samples were collected via lowering a single, 10 L Niskin bottle to target depths of 5, 15, 35, 75, and 150 m (5, 15, 25, and 60 m at the shallower Adventfjorden station). The Niskin bottle was then sub-sampled for dissolved oxygen, dissolved inorganic carbon, stable oxygen isotopes ($\delta^{18}O$), total alkalinity, salinity, nutrients, and additional biological parameters on the deck of the ship. Only the relevant $\delta^{18}O$, salinity, and alkalinity results are reported here. Additional seawater samples were collected from the surface along transects entering Billefjorden and Adventfjorden from Isfjorden via lowering a plastic bucket over the side of the ship. Salinity and temperature were also measured at each location using a Saiv *SD204* CTD. Accuracies of salinity and temperature measurements collected with this instrument are reported to be ± 0.02 and ± 0.01 °C, respectively by the manufacturer (http://www.saivas.no/visartikkel.asp?art=2). A comparison of bottle versus CTD salinities indicated the bottle and CTD-derived salinities agreed to within ± 0.04 at all stations except for a subset of bottles collected at Rijpfjorden. At this location, seawater began to freeze within the Niskin bottle during sampling in the open air on the deck of the ship. The bottle salinities exceeded CTD salinities by 0.1, suggesting freezing of $\leq 0.35\%$ of the bottle's contents. Salinity, total alkalinity, and $\delta^{18}O$ measurements from the Rijpfjorden seawater samples were corrected for this small offset.

During the April cruise aboard the *R/V Lance*, CTD profiles were collected in Palanderbukta, a 23-km long and 8-km wide arm of a fjord on the southern side of Whalenbergfjorden on the western side of Nordaustlandet. The profiles were recorded with a SeaBird Electronics SBE19plus V2 SeaCAT Profiler beneath a 47-cm thick sea ice cover at a site (79.63°N, 20.27°E) serving as a temporary ice camp next to the ship. A pump controls the water flow through the temperature and conductivity sensor and records data at a maximum sampling rate of 4 Hz. Accuracies of salinity and