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First-year land-fast Antarctic sea ice as an archive of ice shelf meltwater fluxes

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ABSTRACT

Sampling beneath Antarctic ice shelves is sparse; therefore, tracking changes in ocean $\delta^{18}O$ composition adjacent to ice shelves holds promise as an indicator of ice shelf basal melting. Sea ice archives of ice shelf–ocean interaction in particular could be important tools for future observational climate studies. Ocean $\delta^{18}O$ values near the McMurdo Ice Shelf were reconstructed using observational data (sea ice $\delta^{18}O$, snow depth, and ice formation dates) from McMurdo Sound, Antarctica, by combining a recently revised version of an isotope fractionation model with an established thermodynamic sea ice model, resulting in improvements compared to previous approaches. Growth rates from the thermodynamic sea ice model were validated using direct growth rate measurements. That validation and supporting analysis indicated that a change was needed in ocean heat flux assumption from 0 W m^{-2} to around -13 W m^{-2} part way through the sea ice growth season. A well-constrained range ($+1.84$‰ to $+2.21$‰) of effective fractionation coefficients for sea ice was derived, along with a mean of 1.99‰. For the first time, reconstructed ocean $\delta^{18}O$ values were validated using winter-long measurements of Antarctic near-surface water $\delta^{18}O$. Taking uncertainties into account, the reconstructed ocean $\delta^{18}O$ values generally agreed to within ± 0.2‰ with the measured ocean $\delta^{18}O$ mean values. Results indicated an overall decrease in measured ocean $\delta^{18}O$ during the winter, but this was not statistically significant given the uncertainties in the measurements. Although the method works, it currently has limited utility for determining the presence and scale of any step-changes in ocean $\delta^{18}O$ composition associated with present day ice shelf basal melting. This is because the uncertainty of the reconstructed values (± 0.2‰) is of the same magnitude as the expected change. Also, the requirement to parameterise the ocean heat flux is a barrier to the method being an entirely retrospective method (i.e., one requiring only data from the end of the sea ice growth season). In a future Antarctic scenario of increased basal melting of the ice shelves, the method may become more valuable in an Antarctic context. The method developed in this paper will be useful currently in the Arctic, because Arctic waters exhibit much larger fresh water fluxes.

1. Introduction

1.1. Ice shelves in a warming world

Warming of Earth's climate system was stated by the Intergovernmental Panel on Climate Change (2013) to be “unequivocal,” with it “extremely likely” that anthropogenic effects dominated warming since the 1950s (Intergovernmental Panel on Climate Change, 2013). Under the SRES A1B scenario, climate and regional modelling indicate potential for increased melting of Antarctic ice shelves in the future due to ocean warming (Yin et al., 2011) and changes in ocean currents (Hellmer et al., 2012). Basal melt already occurs under Antarctic ice shelves, including deep beneath cold cavity ice shelves such as the Ross Ice Shelf and the Filchner-Ronne Ice Shelf, when High Salinity Shelf Water (HSSW) interacts with the ice to form Ice Shelf Water (ISW) (Jacobs et al., 1985). Detection and attribution of this basal meltwater from ice shelves (e.g., Hattermann et al., 2012) is rare but is important for monitoring ice shelves' response to warming conditions. There are complex and competing feedbacks that have implications for the stability of ice sheets if basal melting of ice shelves increases (Gagliardini et al., 2010).

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1.2. Determining the response of ice shelves to climate change

Identifying the timing and extent of meltwater fluxes from beneath ice shelves is particularly important for determining the response of ice shelves to climate change. However, sampling beneath Antarctic ice shelves is sparse due to logistical and financial challenges. Methods that use observations from surface waters adjacent to ice shelves have been used to obtain information on ice shelf basal melting but are often restricted to summer observations. Sea ice archives of ice shelf–ocean interaction are therefore potentially important tools in future observational climate studies, particularly in conjunction with other observations, or in places where winter observations are difficult logistically.

Monitoring of changes in ISW is an important part of determining existing and future responses of ice shelves to climate change. ISW is seawater with its potential temperature below the surface freezing point temperature (Jacobs et al., 1985). Although the definition of ISW is based strictly on potential temperature, oxygen isotopes are sometimes used as an indicator of glacial input to the water mass. An increase in meltwater flux from beneath ice shelves has been suggested as the cause of lower salinity and more negative ocean δ^{18}O values in the Ross Sea from the 1970s to 2000 (Jacobs et al., 2002). Despite observations indicating that ISW plumes only affect the sea ice at certain locations, those locations may be important archival sites for determining ice shelf–ocean processes. ISW is often thought of as a deep water mass, but there have been observations of ISW reaching the surface (e.g., Fer et al., 2012; Mahoney et al., 2011). ISW rising through the water column can become in situ supercooled due to pressure relief (Foldvik and Kvinge, 1974), and in situ supercooling has been observed as deep as 70 m (Leonard et al., 2011) .

Sea ice that forms from ISW at the surface holds promise as part of the monitoring of ice shelves (Langhorne et al., revised version under review 2015). Incorporated platelet ice is a form of sea ice composed of dendritic crystals with columnar/congelation ice between those crystals. Structural characteristics of incorporated platelet ice indicate that it is associated with the presence of ISW because dendritic crystals are indicative of growth in supercooled sea water. Incorporated platelet ice and related sub-ice platelet layers are observed in some regions in the later parts of the growth season (e.g., Paige, 1966) close to an ice shelf (e.g., Crocker and Wadhams, 1989; Gough et al., 2012a; Gow et al., 1998; Jeffries et al., 1993; Leonard et al., 2006). Although ISW is a necessary precursor for platelet ice formation, incorporated platelet ice does not always appear in cores simultaneously with the appearance of ISW (Gough et al., 2012a; Mahoney et al., 2011). Incorporated platelet ice cannot be distinguished from columnar ice just by the use of isotopes; for example δ^{18}O values of incorporated platelet ice from a McMurdo Sound core were reported by Smith et al. (2012, supplementary material) to be between 1.55‰ to 1.77‰ (±0.02‰), which sits within the range of δ^{18}O values for the columnar ice above it, which was 1.09‰ to 1.88‰ (±0.02‰). Also, as discussed by Smith et al. (2012), measuring the isotopic values of individual platelet crystals is problematic, so such measurements are not reported here.

As a monitoring site for sea ice and ice shelf interaction processes, McMurdo Sound is an ideal location. McMurdo Sound (Fig. 1) is situated north of the McMurdo Ice Shelf. The ocean beneath the McMurdo Ice Shelf is connected to the Ross Ice Shelf cavity through Haskell Strait, with a flow-through of ISW likely originating from beneath the larger adjacent Ross Ice Shelf. Platelet ice observations are common in McMurdo Sound and in the south-western Ross Sea (e.g., Crocker and Wadhams, 1989; Gough et al., 2012a; Gow et al., 1998; Jeffries et al., 1993; Leonard et al., 2006; Smith et al., 1999; Smith et al., 2001). A map indicating platelet ice abundance in McMurdo Sound was produced by Dempsey et al. (2010), and a pan-Antarctic map showing all published observations of platelet ice was produced by Langhorne et al. (revised version under review 2015).

On the eastern side of McMurdo Sound, platelet ice is observed in the late winter (Smith et al., 2001; Smith et al., 2012). Crocker and

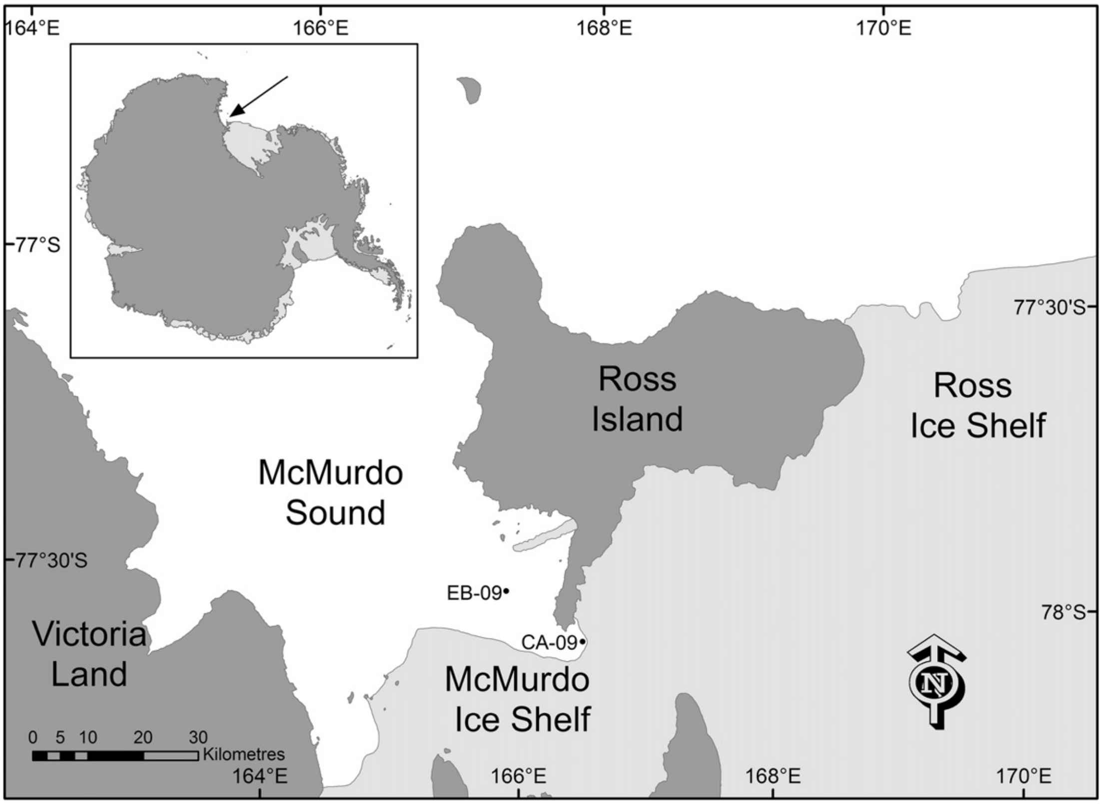

Fig. 1. Locations of sea ice (EB-09) and ocean water samples (EB-09 and CA-09) taken in McMurdo Sound, Antarctica 2009. The insert shows the location of McMurdo Sound (arrow) in relation to Antarctica.