Quaternary Science Reviews 79 (2013) 168–183

Contents lists available at SciVerse ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

A review of sea ice proxy information from polar ice cores

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ARTICLE INFO

Article history:
Received 21 September 2012
Received in revised form
23 November 2012
Accepted 15 January 2013
Available online 11 February 2013

Keywords:
Sea ice
Ice cores
Sea salt
MSA
Palaeoclimate

ABSTRACT

Sea ice plays an important role in Earth's climate system. The lack of direct indications of past sea ice coverage, however, means that there is limited knowledge of the sensitivity and rate at which sea ice dynamics are involved in amplifying climate changes. As such, there is a need to develop new proxy records for reconstructing past sea ice conditions. Here we review the advances that have been made in using chemical tracers preserved in ice cores to determine past changes in sea ice cover around Antarctica. Ice core records of sea salt concentration show promise for revealing patterns of sea ice extent particularly over glacial–interglacial time scales. In the coldest climates, however, the sea salt signal appears to lose sensitivity and further work is required to determine how this proxy can be developed into a quantitative sea ice indicator. Methane sulphonic acid (MSA) in near-coastal ice cores has been used to reconstruct quantified changes and interannual variability in sea ice extent over shorter time scales spanning the last ~160 years, and has potential to be extended to produce records of Antarctic sea ice changes throughout the Holocene. However the MSA ice core proxy also requires careful site assessment and interpretation alongside other palaeoclimate indicators to ensure reconstructions are not biased by non-sea ice factors, and we summarise some recommended strategies for the further development of sea ice histories from ice core MSA. For both proxies the limited information about the production and transfer of chemical markers from the sea ice zone to the Antarctic ice sheets remains an issue that requires further multidisciplinary study. Despite some exploratory and statistical work, the application of either proxy as an indicator of sea ice change in the Arctic also remains largely unknown. As information about these new ice core proxies builds, so too does the potential to develop a more comprehensive understanding of past changes in sea ice and its role in both long and short-term climate changes.

1. Introduction

Sea ice is a crucial component of the polar climate system. Its presence or absence modifies the albedo of the ocean, as well as the exchange of heat, moisture, momentum, and trace gases such as CO_2, between the atmosphere and ocean. It plays a major role in the production of deep waters in the ocean, and therefore in the entire global ocean circulation system (Dieckmann and Hellmer, 2010). Its strong seasonal cycle provides arguably the most visible sign (to an external observer) of Earth's varying climate, and despite continuing discussion about the exact mechanism, it certainly plays a significant role in the polar amplification of climate change (Serreze and Barry, 2011). In addition to its climatic role, it is of major importance for the biology of the polar oceans (Dieckmann and Hellmer, 2010), for the atmospheric chemistry of the polar lower atmosphere (e.g. Simpson et al., 2007), and for the economy and geopolitics of the Arctic region.

For all these reasons, it is important to be able to predict future changes in sea ice under different future forcing scenarios. Arctic ice extent has been reducing sharply in the last three decades (Comiso, 2012). However, it remains difficult to model sea ice trends: in the CMIP3 models, there were large differences for the Arctic between models, and between models and observations, even for the hemispheric total (Stroeve et al., 2007). While the models contributing to CMIP5 are more consistent with observations (Stroeve et al., 2012), there remains significant uncertainty in predicting future trends.

To improve the models and to gain a better understanding of the links between sea ice and climate, long observational datasets are

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http://dx.doi.org/10.1016/j.quascirev.2013.01.011

required. Unfortunately, satellite observations extend back only to the late 1970s, so before that time, we are reliant on observations that are sporadic in both time and space, and on proxy data. A number of methods have been used to infer past sea ice conditions, either directly or indirectly (Polyak et al., 2010), and here we discuss the role that ice core data may play in that constellation of techniques.

2. The nature of ice core sea ice proxies

The majority of palaeo-data on past sea ice rests on marine sediments, in which the changing occurrence of chemicals or biological organisms associated with sea ice are recorded down the core. Particularly large datasets have been created based on the occurrence of sea ice-related diatoms in the Antarctic (Gersonde et al., 2005), and of dinoflagellate cysts in the Arctic (de Vernal et al., 2005). More recently, additional information has come from measurements of the concentration of the Arctic sea ice biomarker known as IP_{25} (Belt et al., 2007; Belt and Müller, 2013). All of these methods provide an estimate of sea ice properties at the ocean surface above the sediment (assuming little lateral transport) over time. Only by combining data from numerous sites can a spatial picture of the ice extent be established, and such spatial syntheses have until now only been carried out for limited numbers of time slices (notably the last glacial maximum).

Ice cores provide a very different style of proxy record. They contain information about sea ice only if such information is transported in the atmosphere from the surface of the ocean. Any such ice core proxy is therefore necessarily an area-weighted average, recording conditions in an angular sector extending from the coast, and presumably with declining influence as distance from the coast is extended. A single ice core record could therefore give a general impression of the ice conditions in a particular sector of ocean, but without the specific spatial detail provided by marine sediment data. Particularly in the Antarctic, with its approximate radial symmetry (Fig. 1), a first interpretation of such a proxy would be that it indicates the average latitudinal extent of ice within an approximately angular sector of the Southern Ocean that airmasses pass over in the days before reaching the ice core site.

What is then required to create an ice core proxy for sea ice is a chemical that is generated in the sea ice zone and transported aerially to the ice core site. Over some averaging period, ice extent (rather than transport variability or other factors) must be the main determinant of its concentration in, or flux to, ice. While there might be potential to search for very specific sea ice markers (for example, the biomarkers such as IP_{25}), the concentrations transported in the air to the ice core site are expected to be very small. Effort has therefore focused until now on two proxies: the ionic components of sea salt aerosol itself, and the chemical methane sulfonic acid (MSA) that is an oxidation product of dimethylsulfide (DMS), a gas produced biogenically in the ocean.

3. Antarctic ice core sea salt records as a proxy for sea ice

Over most of the globe, sea salt aerosol is generated by bubble bursting and sea spray over open water (de Leeuw et al., 2011). While large particles are deposited rapidly over the ocean, smaller particles are transported over the continents, with the result that the amount of sea salt deposited at an inland site falls off rapidly with distance from the coast over at least the first few hundred km (Guelle et al., 2001).

Sea salt concentration or deposition flux can be measured in ice cores through determination of any of the major component ions of seawater. Sodium (Na) measurements are generally preferred. There is an additional input from crustal dust of all the metals found in sea salt, but this is relatively much more important (requiring a larger and less certain correction) for magnesium, potassium and calcium than it is for sodium. Chloride is subject to fractionation due to the reaction of acids with sea salt to produce HCl, and this can be particularly important and variable at ice core sites with a low snow accumulation rate (Röthlisberger et al., 2003). Na is therefore the most reliable marker for sea salt.

If open water is the main source of sea salt reaching the polar ice caps then we would expect ice core concentrations of sea salt to be (to first order) negatively correlated with the distance to open water, providing the atmospheric circulation strength and pathways remained the same. Expanding the extent of sea ice would push the open water source further from the measurement site, increasing the amount of loss during transport (Minikin et al., 1994; Mulvaney and Wolff, 1994; Benassai et al., 2005; Röthlisberger et al., 2010), and therefore we would expect that the concentration of sea salt should decrease as the amount of sea ice increases.

This concept was indeed applied in some studies in the Canadian Arctic. In particular, a record of sea salt sodium from an ice core from the Penny Ice Cap showed a significant negative correlation with spring sea ice extent in Baffin Bay over the 20th century

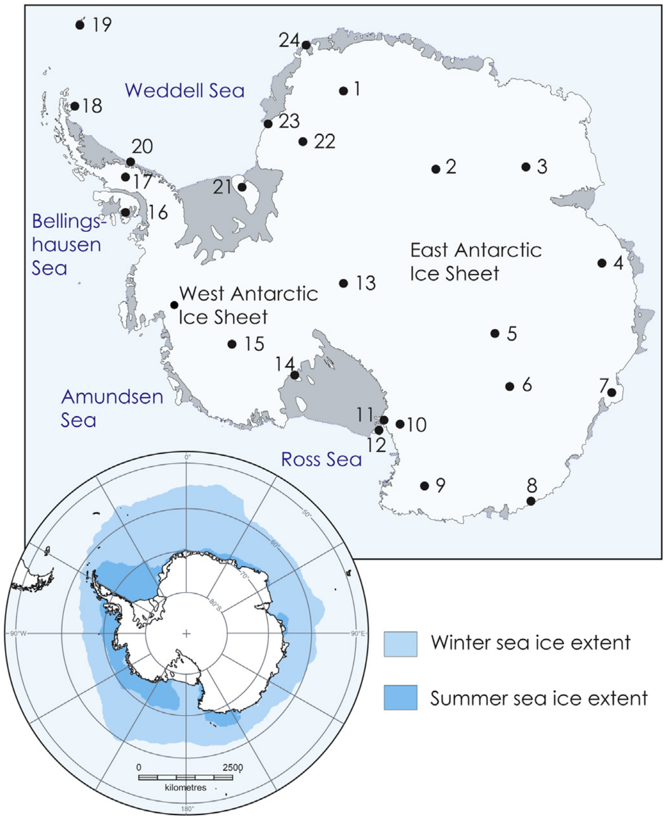

Fig. 1. Map of Antarctica showing the location of ice core data and station observations mentioned in the text. Inset shows present-day mean summer and winter sea ice extent around the Antarctic continent. Site numbers refer to:

Station data: 6. Dome C, 8. Dumont D'Urville, 13. South Pole, 19. South Orkney islands, 23. Halley, 24. Neumayer.

Ice core sea salt records: 1. EDML, 2. Dome Fuji, 5. Vostok, 6. Dome C, 10. Taylor Dome, 14. Siple Dome, 15. West Antarctica (network).

Ice core MSA records: 1. EDML (network), 3. Lambert Glacier, 4. Mount Brown, 5. Vostok, 7. Law Dome, 9. Talos Dome, 11. Newell Glacier, 12. Erebus Saddle, 13. South Pole, 14. Siple Dome, 15. West Antarctica (network) and coastal West Antarctica, 16. Beethoven Peninsula, 17. Dyer Plateau, 18. James Ross Island, 20. Dolleman Island, 21. Berkner Island, 22. Dronning Maud Land.