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Solar forcing as an important trigger for West Greenland sea-ice variability over the last millennium

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A B S T R A C T

Arctic sea ice represents an important component of the climate system, and the present reduction of sea ice in the Arctic is of major concern. Despite its importance, little is known about past changes in sea-ice cover and the underlying forcing mechanisms. Here, we use diatom assemblages from a marine sediment core collected from the West Greenland shelf to reconstruct changes in sea-ice cover over the last millennium. The proxy-based reconstruction demonstrates a generally strong link between changes in sea-ice cover and solar variability during the last millennium. Weaker (or stronger) solar forcing may result in the increase (or decrease) in sea-ice cover west of Greenland. In addition, model simulations show that variations in solar activity not only affect local sea-ice formation, but also control the sea-ice transport from the Arctic Ocean through a sea-ice–ocean–atmosphere feedback mechanism. The role of solar forcing, however, appears to have been more ambiguous during an interval around AD 1500, after the transition from the Medieval Climate Anomaly to the Little Ice Age, likely to be driven by a range of factors.

1. Introduction

Sea ice is a key component of Earth's climate system, since it is an effective insulator between the oceans and the atmosphere, restricting the exchange of heat, mass, momentum and chemical constituents (Divine and Dick, 2006). In addition, it is essential for the powerful ‘ice-albedo’ feedback mechanism that amplifies climate variability at high latitudes (Forster et al., 2007). The ongoing severe reduction of Arctic sea ice is largely ascribed to anthropogenic effects, but the current rate of sea-ice reduction is much faster than predicted by models, with rates exceeding the expected effect from temperature change (IPCC, 2013). The factors controlling sea-ice variability are poorly understood, and the provision of sea-ice reconstructions extending back in time beyond the instrumental and satellite era is therefore critical (Massé et al., 2008; Müller et al., 2009; Stein et al., 2012; Belt and Müller, 2013; Collins et al., 2013; de Vernal et al., 2013; Weckström et al., 2013).

One factor, hitherto not thoroughly tested, is the role of the Sun in influencing the distribution of sea ice. Several studies indicate that multidecadal- to centennial-scale climate change during the last millennium was dominated by solar variability (Shindell et al., 1999; Rind, 2002; Gray et al., 2010). Solar activity has been shown to influence key components of the climate system, such as temperature, winds, precipitation, ocean circulation and iceberg transport (e.g. Verschuren et al., 2000; Bond et al., 2001; Hodell et al., 2001; Andrews et al., 2003; Jiang et al., 2005; Sejrup et al., 2010; Martin-Puertas et al., 2012; Knudsen et al., 2014; Moffa-Sánchez et al., 2014a; Jiang et al., 2015). However, only a few studies

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have investigated the link between variations in sea-ice proxies from the North Atlantic and solar variability on multidecadal to centennial time scales (e.g. Müller et al., 2012; Sha et al., 2014).

The central West Greenland shelf region is characterised by extensive sea-ice cover in the north and by almost sea-ice free waters in the south (Fig. 1) and is thus an ideal region for the study of short- and long-term sea-ice variability. The north-flowing West Greenland Current (WGC), which dominates the surface waters of the area, consists of two components. The upper part is dominated by Polar Water (T < 1 °C; S < 34 PSU) derived from the East Greenland Current (EGC) carrying a steady stream of multi-year ice along the East Greenland coast throughout the year, while the lower part of the WGC primarily consists of Atlantic-sourced water originating from the Irminger Current (IC) (T~4.5 °C; S > 34.95 PSU) (Buch, 2002) (Fig. 1). During winter and spring, the Baffin Current conveys large amounts of sea ice from Baffin Bay to Davis Strait and the Labrador Sea. At this time of year, sea ice normally covers most of Davis Strait north of 65°N. South of 65–67°N, the eastern Labrador Sea is mostly ice free, although sea ice may occur briefly during spring or late winter, as well as during early summer, if multi-year ice, originating from the Arctic Ocean, drifts into the area (Hansen et al., 2004).

Diatoms are marine siliceous algae which have been used successfully for reconstructing past sea-ice conditions (Crosta et al., 1998; Gersonde and Zielinski, 2000; Justwan and Koç Karpuz, 2008; Allen et al., 2011; Collins et al., 2012; Sha et al., 2014). It has further been demonstrated that diatom records from the study region can be used for quantitative reconstruction of April sea-ice variability (see Materials and methods and Supplementary material) (Sha et al., 2014). Here, we reconstruct changes in April sea-ice concentration (SIC) over the last millennium based on high-resolution diatom data from marine sediment core GA306-GC4 (see Materials and methods) (Sha et al., 2012), located off West Greenland, in order to study the sea-ice variability of the last millennium and to test for possible links to solar forcing. The site is located in the boundary zone between a northerly area dominated by sea ice in spring and a southerly area with a predominant absence of spring sea-ice cover (Fig. 1).

2. Materials and methods

2.1. Coring

Gravity core GA306-GC4 (66°44′41″N, 53°56′25″W; 502-cm long) and box core GA306-BC4 (35-cm long) were retrieved from the same location in a water depth of 445 m, in the Holsteinsborg Dyb basin off Kangerlussuaq, West Greenland, during the *Galathea 3 Expedition*, Leg 3, 25 August to 8 September 2006 (Fig. 1). Diatom samples were extracted from 1-cm thick slices taken at 5-cm intervals from core GA306-GC4, yielding a mean time resolution of ca. 10 years. The results of the diatom analyses from GA306-BC4 have previously been presented by Sha et al. (2014) and are given in the Supplementary material (Fig. S4), and the diatom assemblage data from GA306-GC4 have been published by Sha et al. (2012).

2.2. Chronology

The age–depth model for gravity core GA306-GC4 was constructed on the basis of a total of 11 ^{14}C ages of marine mollusc shells (10 from GA306-GC4 and one from GA306-BC4; see Table S1) (Erbs-Hansen et al., 2013). The samples were measured for radiocarbon content at the AMS ^{14}C Dating Centre, Aarhus University, Denmark. All of the ^{14}C dates were calibrated using the Marine09 calibration dataset (Reimer et al., 2009) with a ΔR of 140 ± 30 years (Erbs-Hansen et al., 2013), and the ^{14}C-based chronologies were constructed using the depositional model in the OxCal 4.1 software

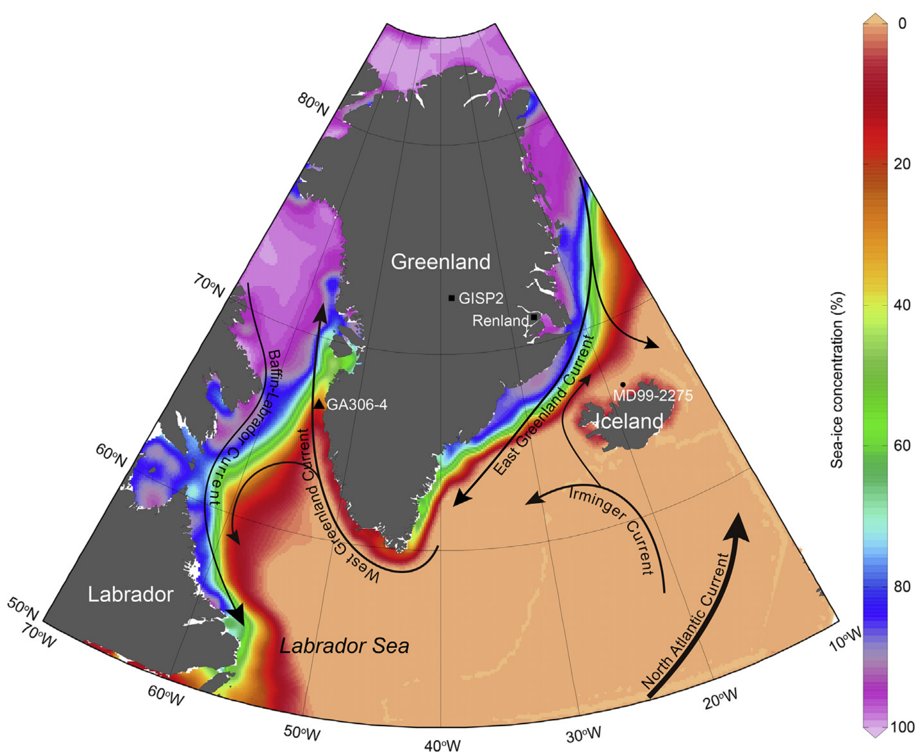

Fig. 1. Location of marine sediment cores GA306-4 (GA306-GC4 and GA306-BC4), and the other records referenced in the text, together with the modern surface circulation of the North Atlantic. The satellite April sea-ice concentration from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data (GSFC product, NSIDC-0051) for the period AD 1979–2010 is also indicated.