Abrupt climate changes for Iceland during the last millennium: Evidence from high resolution sea ice reconstructions

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A B S T R A C T

A high resolution account of Icelandic sea ice over the last millennium has been constructed using a novel proxy based on the presence in sediments of a biomarker (IP35) produced by sea ice algae. Comparison with historical sea ice records demonstrates a strong correlation between documented sea ice occurrences and the IP35 proxy. An excellent agreement is also observed between the IP35 record and a diatom-based sea surface temperature reconstruction obtained from the same core and the Crowley and Lowery Northern Hemisphere temperature reconstruction. Using this approach, we provide new historical sea ice data for periods where records are scarce or absent and evidence for abrupt changes to sea ice and/or climate conditions around Iceland during the Little Ice Age.

1. Introduction

Given the current debate regarding climate change on Earth and, in particular, the relative contributions of natural processes and anthropogenic inputs, it is crucial to obtain a clear and detailed account of past climatic variations and the factors controlling these (Jones et al., 2001). Polar sea ice, by its influence on the heat exchanges between the oceans and the atmosphere and its contributions to numerous oceanic processes (e.g. thermo-haline circulation) is a key component of the Earth’s climate system (Thomas and Dieckmann, 2003). Therefore, improving our knowledge of historical sea ice fluctuations at a high spatial and temporal resolution will help to refine future climate change models and improve predictions. Very few documentary records for sea ice exist which pre-date the instrument era and these often include unreliable data (Bergthórsson, 1969; Ogilvie and Jónsson, 2001). Here, we report a detailed analysis of a sediment core (MD99-2275) collected from the North Icelandic Shelf (Fig. 1). This area is under the strong influence of three surface currents (Fig. 1). The warm and high salinity Irminger current is a branch of the North Atlantic drift, travelling along the western and the north western coasts of Iceland, while the East Greenland and the East Icelandic currents bring cold and low salinity polar waters to the region. Any change in the relative strengths of these currents will influence the position of the oceanic Polar Front, and this is likely to be archived in the sediment record (Knudsen et al., 2004).

In this study, we have used the recently established sea ice proxy, IP35 (Belt et al., 2007), which is based on the preservation in marine sediments of a unique chemical fossil produced by sea ice algae (Fig. 2), to obtain an uninterrupted, high resolution (ca. 2–5 yr) record of sea ice occurrences for the last millennium. The very high sedimentation rates associated with the core location, together with well documented occurrences of volcanic tephras (Eiríksson et al., 2004; Knudsen and Eiríksson, 2002; Larsen et al., 2002; Rousse et al., 2006) have enabled us to perform this study at an unprecedented sub-decadal resolution and to make comparisons with historical data documenting past sea ice extending back to the early days of Icelandic colonization (ca. 1080 BP). We demonstrate strong correlations between documented sea ice occurrences and the IP35 proxy (Bergthórsson, 1969; Ogilvie and Jónsson, 2001) and reveal new sea ice data for periods where historical sources are scarce or absent. We have also compared our IP35 data with diatom-based sea surface temperature reconstructions (Jiang et al., 2005; Eiríksson et al., 2006) to confirm that the Icelandic climate was relatively mild, and that little sea ice occurred in the region from 800 to 1300 AD, corresponding to the end of the Warm Mediaeval Period (MWP). In contrast, both reconstructed sea ice and sea surface

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temperatures show that the climatic conditions around northern Iceland worsened during the second part of the millennium with cooler sea surface temperatures and larger amounts of sea ice. More detailed correlations exist throughout the record, and also provide evidence for a succession of abrupt climate changes in Iceland during the latter part of the record, corresponding to the Little Ice Age (LIA, 1300–1900 AD). Finally, our sea ice record also shows strong correlations with hemispheric-scale temperature reconstructions (Crowley, 2000; Mann et al., 1998), indicating that climatic conditions over Iceland were representative for at least the last millennium. This case study demonstrates that \( \text{IP}_{25} \) is a reliable proxy for historical sea ice reconstructions and could become an invaluable tool for high or ultra-high resolution studies of the Earth’s climate system.

2. Methods

2.1. Sediment samples

The core MD99-2275 (66 33.06'N, 17 41.59'W; 410 m water depth) was collected during the R/V Marion Dufresne IMAGES V cruise in 1999. The age model of the entire core was determined using a combination of tephra marker horizons and thirty-five radiocarbon dates (Eiriksson et al., 2004; Knudsen and Eiriksson, 2002; Larsen et al., 2002; Rousse et al., 2006). This age model was further constrained using 6 tephra layers corresponding to the time period examined in the present study according to the method of Sicre et al. (2008).

2.2. \( \text{IP}_{25} \) analysis

The core was sampled continuously at 1 cm intervals (2–5 yr). Freeze-dried sediments were extracted using dichloromethane/methanol (50/50) to yield a total organic extract. Hydrocarbon fractions were obtained from this extract using open column chromatography (\( \text{SiO}_2 \), hexane). An internal standard was added (7-hexynonadecane, 0.1 \( \mu \)g sample\(^{-1} \)) to permit quantification by GC-MS. \( \text{IP}_{25} \) was identified on the basis of comparisons between its GC retention index and mass spectrum.
with an authentic standard (Belt et al., 2007). Relative abundances of IP$_{25}$ were calculated on the basis of the individual GC-MS responses for IP$_{25}$ and the internal standard, together with the mass of sediment analysed for each 1 cm interval.

2.3. Previous studies

2.3.1. Sea ice studies

There are a number of historical sources that document past sea ice occurrence around Iceland back to the early days of colonisation. These sources have been carefully analysed and interpreted enabling qualitative sea ice indices (as indicated by the symbols and descriptors in Fig. 3) to be developed (Koch, 1945; Bergthórsson, 1969). Most recently, Ogilvie (1992) and Ogilvie and Jónsson (2001) examined the reliability of some of the original sources to further refine these indices.

2.3.2. Diatom-based sea surface temperature reconstructions

Recently, Jiang et al. (2005) and Eiriksson et al. (2006) reconstructed past sea surface temperatures around the North Icelandic Shelf using the relative abundances of diatom frustules in sediments

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**Fig. 3.** Relative abundances of IP$_{25}$ found in the core MD99-2275 for the period 800–1050 AD plotted against historical records of Icelandic sea ice interpreted from Ogilvie (1992) and Ogilvie and Jónsson (2001) (bottom scales) and diatom-based reconstructed sea surface temperature (Jiang et al., 2005).

**Fig. 4.** Relative abundances of IP$_{25}$ found in the core MD99-2275 for the period 800–1050 AD plotted against reconstructed Northern Hemisphere annual temperatures (Crowley, 2000).
from the core MD99-2275. In the current study, we have used the
jiang et al. (2005) dataset which is available at: ftp://rock.geosociety.

2.4. Study site

For the current study, we chose a site location close to the north
cost of Iceland since this region is strongly influenced by the
boundaries of the cold and low-salinity waters of the East Icelandic
Current and the warmer and higher salinity waters associated with
the Irminger Current (Eiriksson et al., 2004; Knudsen and Eiriksson,
Larsen et al., 2002; Rousse et al., 2006). As such, analysis of a sediment
core from this region should provide an excellent case study for
interrogating substantial and rapid changes to sea ice cover which,
in turn, may reveal relationships to more global climatic forcing (e.g.
the North Atlantic Oscillation) on relatively short timescales, for which
there is little previous evidence.

3. Results and discussion

Palaeoceanologists continue to emphasise the importance of
data derived from so-called proxy methods for climate reconstruction
and that such data should have both high temporal and spatial
resolution if it is to be valuable for both historical determinations and
future climate prediction models (Mann et al., 1998; Jones et al.,
2001). Such studies routinely rely on a multi-proxy approach since direct
measures of climate conditions are either scarce, absent or unreliable.
For example, a paucity of historical ice sea records has sometimes been
interpreted as an indication of ice free conditions (Ogilvie and Jónsson,
2001) which is potentially misleading since poor records can also be
attributed to abrupt changes to population resulting from famine and
epidemics. In addition, proxy data usually reflects mean annual or multi-
annual temperatures rather than seasonally sensitive phenomena such as
sea ice. Recently, we reported a new proxy for Arctic sea ice, IP25,
which is a mono-ununsaturated highly branched isoprenoid (HBI) alkene
biosynthesised by sea-ice diatoms (Belte et al., 2007; Fig. 2). HBI alkenes
are commonly occurring chemicals found in a wide range of marine
sediments (Rowland and Rosnol, 1990). However, Rowland and co-
workers (2001) showed that the extent of HBI unsaturation reflected the
growth temperature of the diatoms responsible for their production,
with more saturated isomers being formed at low temperatures.
Consistent with these observations, IP25 is a mono-ununsaturated HBI
alkene only found in sea ice and related sediments and is therefore
considered as a specific biomarker of sea ice (Belte et al., 2007).

Fig. 3 shows a continuous record of the relative abundance of IP25
for the top (ca. 300 cm) of the MD99-2275 sediment core. These
results, when compared with climatic data from previous studies
(Ogilvie, 1992; Crowley and Lowery, 2000; Jones et al., 2001; Ogilvie
and Jónsson, 2001; Knudsen et al., 2004; Eiriksson et al., 2006; Jiang
et al., 2005) show a series of excellent correlations (Figs. 3 and 4).
Firstly, averaged centennial-scale abundances of IP25 are entirely
consistent with previous estimations of the Little Ice Age (LIA), the
Medieval Warm Period (MWP) and relative centennial temperatures
(Jones et al., 2001; Ogilvie and Jónsson, 2001). For example, centennial-scale IP25 abundances are highest for the 19th and 17th
centuries (Fig. 3) in-line with the conclusions of Crowley (2000),
Jones et al. (1998, 2001) and Mann et al. (1998) that these were
the coldest centuries of the last millennium in the northern hemisphere.
In contrast, IP25 abundances are substantially reduced during the 18th
and 16th centuries as well as for the first half of the millennium
(Fig. 3) due to lower sea ice occurrences associated with warmer
conditions (Jones et al., 1998, 2001; Mann et al., 1998). At a higher
temporal resolution, 1690–1700 is considered to be the coldest
decade for the 17th century in the northern hemisphere (Jones et al.,
1998; Crowley and Lowery, 2000) including Iceland (Ogilvie and
Jónsson, 2001), and this is reflected by the highest abundance of
the IP25 biomarker in the MD99-2275 sediment core over the past
1000 years (Figs. 3 and 4).

IP25 is also abundant in sediments dated 1776, 1638, 1364, 1331 and
1309 corresponding to decades where large amounts of sea ice have
been reported around Iceland (Ogilvie and Jónsson, 2001). In addition,
these dates correspond to cold decades as shown by both the diatom-
based sea surface temperatures (Fig. 3; Jiang et al., 2005) and the mean
northern hemisphere temperatures (Fig. 4; Crowley and Lowery,
2000). For the 19th century, Ogilvie and Jónsson described a highly
variable climate with a succession of cold and mild decades. IP25
abundances are similarly variable during this period with the highest
abundances of IP25 observed in the more recent sediments, in
agreement with the historical data describing the latter part of the
19th century as the coldest.

The current IP25 data also provide additional sea ice information
for periods where the historical sources are limited or unreliable.
For example, very little data about Icelandic climate is available for
periods corresponding to the earliest days of Iceland colonisation
(ca. 870) to the end of the 13th century and from 1430 to 1560
(Ogilvie and Jónsson, 2001) and it is often assumed that the climate of
Iceland was favourable during these periods. However, the frequent incidence of dramatic reductions in population due to
documented famine and epidemics during these times, which may
themselves be attributed in part to severe climatic conditions, could
equally account for absences in climatic records (Ogilvie and
Jónsson, 2001). The epoch immediately following the first colonisa-
tion period corresponds to the end of the MWP and therefore little
or no sea ice might be predicted for this time. Consistent with this
hypothesis, IP25 abundances are indeed low with mean values for
800–1300 lower than the subsequent 700 years (Fig. 3). This is also
in agreement with diatom-based sea surface temperature recon-
structions and northern hemisphere temperature profiles, both of
which show warmer temperatures during this time (Figs. 3 and 4).
Significantly, however, higher abundances of IP25 are observed for
the few years when severe weather was reported including 1048 and
968 (BerghórsArn, 1969; Ogilvie and Jónsson, 2001; Fig. 3). IP25
abundances are also low between 1400 and 1460 and during the
16th century, consistent with reports of a mild climate (Ogilvie and
Jónsson, 2001) and the diatom-based temperature record (Fig. 3).
However, our data shows dramatic differences for the mid-late 15th
century, where there are abrupt increases in the abundance of IP25
(particularly 1494, 1474 and 1467), reflecting enhanced sea ice
occurrences due to more severe conditions during this period, with
the centennial mean close to that of the preceding 14th century, for
which reliable historical records suggest several severe decades
(Ogilvie and Jónsson, 2001). Thus, despite a paucity of historical
climate records for the 1430–1560 era, we provide compelling
evidence for substantial changes in climate during this time
including a 40–50-year period of extensive sea ice cover. Interest-
ingly, these rapid and dramatic changes in the abundance of IP25
during the mid-late 15th century are also consistent with substantial
oscillations observed in the diatom-based temperature record
(Fig. 3). Additional abrupt and coincident changes in both the IP25
abundances and sea surface temperatures are observed during the
14th, 17th and 18th centuries (e.g. 1364, 1638, 1688 and 1776)
confirming that a number of substantial climate changes occurred
in Iceland during the LIA.

As such, the high resolution and continuous dataset achieved in this
study has enabled several abrupt changes to sea ice conditions to be
determined for which there have been little or no precedent from
previous decadal (or longer timescale) determinations (Fig. 3). Since
debates continue as to what extent epochs such as the LIA and MWP can
be classified in both temporal and spatial terms, our sea ice dataset
illustrates that, for north Iceland (at least), substantial, abrupt and highly
frequent changes to climate conditions are confirmed to have taken
place within the well accepted centennial scale trends derived
previously. Not only will such data enhance the quality of climate prediction models but, for locations where there is the additional impact on past human populations, a more accurate account of climate-induced control over human activity should become achievable.

4. Conclusion

This first application of a novel sea ice proxy has involved a comparison between the abundances of a sea ice derived biomarker found in an Icelandic sediment core with historical sea ice records, diatom-based sea surface temperatures and mean northern hemisphere temperatures. For the last millennium, we demonstrate a significant set of correlations between the abundance of the $IP_{25}$ biomarker and at least one (and often two or all three) of these other climatic measures. As such, we have been able to make cross comparisons with other proxy methods and validate existing historical sea ice records. In addition, the cross correlation approach using $IP_{25}$ abundances and other proxies has yielded new historical sea ice data for periods where records are scarce or absent and, in addition, has provided more convincing evidence for abrupt changes to sea ice and/or climate conditions, especially during the Little Ice Age. $IP_{25}$ will likely provide an invaluable tool for future palaeoclimatic studies for regions where historical data are absent and periods before written records began.

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