# Solar forcing of Holocene summer sea-surface temperatures in the northern North Atlantic

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## ABSTRACT

**Mounting evidence from proxy records suggests that variations in solar activity have played a significant role in triggering past climate changes. However, the mechanisms for sun-climate links remain a topic of debate. Here we present a high-resolution summer sea-surface temperature (SST) record covering the past 9300 yr from a site located at the present-day boundary between polar and Atlantic surface-water masses. The record is age constrained via the identification of 15 independently dated tephra markers from terrestrial archives, circumventing marine reservoir age variability problems. Our results indicate a close link between solar activity and SSTs in the northern North Atlantic during the past 4000 yr; they suggest that the climate system in this area is more susceptible to the influence of solar variations during cool periods with less vigorous ocean circulation. Furthermore, the high-resolution SST record indicates that climate in the North Atlantic regions follows solar activity variations on multidecadal to centennial time scales.**

## INTRODUCTION

The Holocene atmospheric circulation above the Greenland Ice Sheet is characterized by centennial- to millennial-scale variability (O'Brien et al., 1995), and similar recurrent climate shifts are also found in deep-sea sediment cores from the North Atlantic (Bond et al., 2001; Mayewski et al., 2004). Denton and Karlén (1973) and Bond et al. (2001) argued that variations in solar activity may have played a significant role in forcing these climate changes. Nevertheless, the relative contributions of the different forcing mechanisms driving these changes are still debated (Carslaw et al., 2002; Rind, 2002; Clemens, 2005; Debret et al., 2009; Sejrup et al., 2010).

The North Icelandic shelf (NIS) is at the present-day boundary between polar and Atlantic surface-water masses defined by the relatively warm saline Irminger Current, and the cold East Greenland and East Icelandic Currents (Fig. 1). Even relatively minor changes in the circulation pattern are likely to be archived in the sedimentary record in this sensitive region (Andrews and Giraudeau, 2003; Andrews et al., 2003; Andersen et al., 2004). A diatom-environmental variable data set is available from the three aforementioned current regimes around Iceland, and the results of a canonical correspondence analysis show that summer sea-surface temperature (SST) has the largest influence on the diatom distribution in the area (Jiang et al., 2001). Consequently, past summer SSTs can potentially be reconstructed from diatom data in the sedimentary record. A significant positive relationship between the diatom-based summer SST reconstruction on the NIS and solar irradiance reconstructed from $^{14}C$ and $^{10}Be$ records has been demonstrated for the past 1200 yr (Jiang et al., 2005). This is in agreement with sediment magnetic data from nearby core MD99–2269 (Fig. 1) that show a series of significant periodicities at ~200, 125, and 88 yr associated with solar variability (Andrews et al., 2003). Here we extend the summer SST record on the NIS to cover the past 9300 yr from core MD99–2275 to test if a positive relationship between summer SSTs on the shelf and reconstructed solar irradiance also can be found further back in time.

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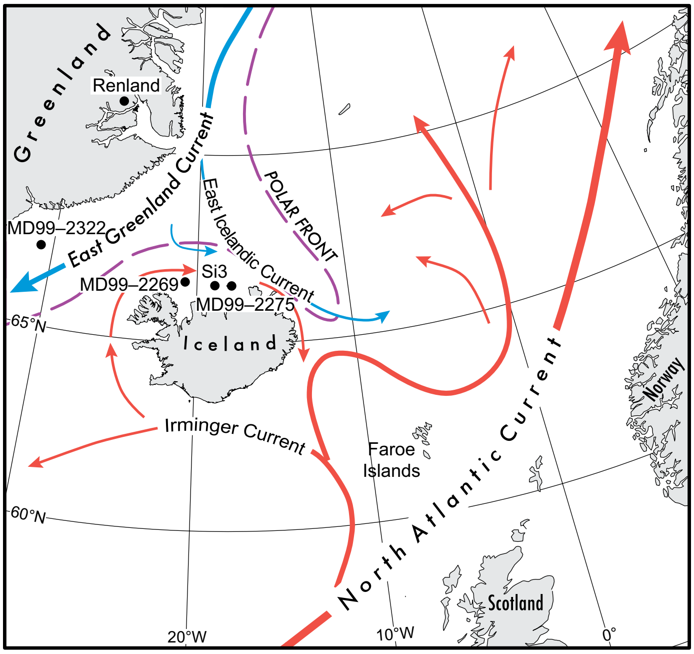


**Figure 1. Locations of core MD99–2275 and the cores referenced in the text, as well as the modern surface circulation in the North Atlantic. Si3—Siglunes 3 hydrographic station.**

## DATA AND METHODS

Samples for diatom analysis were obtained from Calypso piston core (developed onboard the R/V *Marion Dufresne*) MD99–2275 (66°33.10′N, 17°41.99′W; 440 m water depth). A total of 320 diatom samples were extracted from 1-cm-thick slices taken from the uppermost 21 m of the core, with a mean time resolution of <30 yr (Table DR1 in the GSA Data Repository[1]).

Summer SST was reconstructed using a diatom-based transfer function based on a modern data set of diatoms and measured environmental variables (Table DR2) from around Iceland and neighboring areas (Jiang et al., 2001, 2005). Six numerical reconstruction methods (Telford and

[1]GSA Data Repository item 2015073, supplemental information, including Tables DR1–DR4 and Figures DR1–DR3, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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Birks, 2009) were tested (Table DR3). Weighted averaging partial least squares using four components was employed to quantitatively reconstruct summer SSTs by using the C2 program (Juggins, 2007), and the results yielded a root-mean squared error of prediction of 0.94 °C based on the leave-one-out jackknifing. Plots of modern observed summer SSTs versus estimated summer SSTs based on the diatom data from the same surface sample sites exhibit a good linear correlation (Fig. DR1). The reliability of diatom-based summer SST reconstruction was further tested by comparing the reconstructed summer SSTs of the past 100 yr from multicore B05–2006-MC04, from the same location as the studied core MD99–2275, with the instrumental SST data (Ran et al., 2011). The diatom-based reconstructed summer SST shows a distribution pattern similar to that of the instrumental SST data (Fig. DR2). The amplitude of variation in reconstructed summer SSTs is, however, smaller than in the instrumental data, probably because of resuspension and mixing of sediments.

The record was dated using 15 geochemically identified tephra layers and 64 accelerator mass spectrometry $^{14}C$ dates (Table DR4). A tephra-only based age model, supplemented by changes in accumulation rates placed at lithological shifts, was subsequently constructed, circumventing the marine reservoir age variability problem (Fig. 2).

Solar activity estimates are based on the reconstructed $^{14}C$ production rate from the tree-ring based atmospheric $^{14}C$ calibration record (Muscheler et al., 2005; Reimer et al., 2009) and the $^{10}Be$ record from the Greenland Ice Core Project ice core (Vonmoos et al., 2006).

## RESULTS AND DISCUSSION

The maximum range of reconstructed summer SST variability from the NIS during the past 9300 yr is 4.1 °C (5.8–9.9 °C) (Fig. 3; Table DR1). The summer SSTs were generally ~8.2–9.0 °C prior to 8250 cal. $^{14}C$ yr B.P. (calibrated radiocarbon years before 1950), followed by a decline of ~0.8 °C at ca. 8250–8150 cal. yr B.P., coincident with the widespread 8200 cal. yr B.P. cold event (Quillmann et al., 2012). A marked increase in summer SSTs occurred at ca. 8150 cal. yr B.P., reaching the highest values of 8.9–9.9 °C between 8100 and 7000 cal. yr B.P. Our data suggest that the highest summer SSTs during the Holocene Climate Optimum on the NIS were ~2–3 °C higher than the present day, and they are similar to the modern summer SSTs south and southwest of Iceland. Even the cold interval at 8250–8150 cal. yr B.P. exhibits a reconstructed summer SST close to the modern value on the NIS. Between 7000 and 6000 cal. yr B.P., we note stepwise decreasing summer SSTs. Thereafter summer SSTs fluctuated near 8.4 °C until 3000 cal. yr B.P., with cooling intervals at ca. 5700, 5100, 4100, and 3300 cal. yr B.P. A distinct cooling trend began after 3000 cal. yr B.P. with relatively lower SSTs at ca. 2700, 2000, and 1100 cal. yr B.P., and in particular, an absolute minimum occurred at ca. 600 cal. yr B.P., during the Little Ice Age. Spectral analysis indicates the presence of significant periodicities in summer SST centered at 72, 76, 86, 98, 110, and 175 yr, all exceeding the 95% false-alarm level (Fig. DR3).

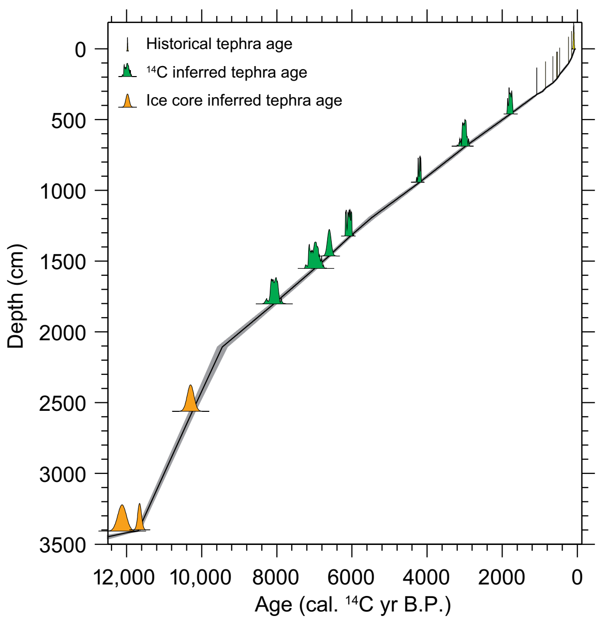


**Figure 2. Calibrated age-depth model for core MD99–2275 based on 15 tephra horizons constructed using depositional models in OxCal 4.1 (https://c14.arch.ox.ac.uk/embed.php?File=oxcal.html), with a k-value of 50 resulting in $A_{model}$ = 70.4%. Lithological boundaries, based on magnetic susceptibility changes, are included in the age model to allow for changes in accumulation rate at lithological shifts.**

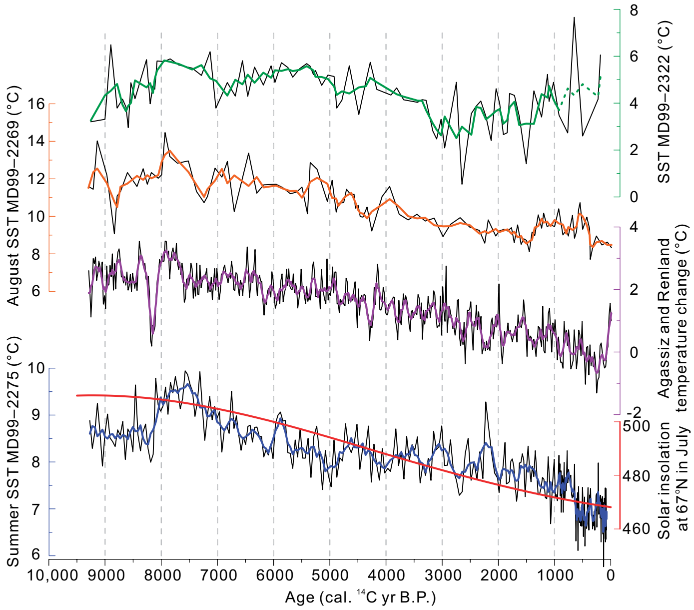


**Figure 3. Comparison of reconstructed summer sea-surface temperatures (SSTs) from core MD99–2275 with August diatom-based SSTs from core MD99–2269 off north Iceland (Andersen et al., 2004); summer SSTs based on planktonic foraminiferal data from core MD99–2232 off southeast Greenland (Jennings et al., 2011); and air temperatures in Greenland derived from the Agassiz and Renland ice core average $\delta^{18}O$ values, corrected for uplift and changes in $\delta^{18}O$ content of the ocean (Vinther et al., 2009). Smoothed records (three point running mean) are denoted by bold lines.**

Two summer SST records from cores (MD99–2269, Andersen et al., 2004; MD99–2322, Jennings et al., 2011) in the area (Fig. 1) show a generally similar pattern (Fig. 3). The concurring decreasing trend in summer SSTs, the centennial- to millennial-scale cold events, and high values at ca. 9000–5200 cal. yr B.P. with a pronounced warming between 8000 and 7000 cal. yr B.P. indicate that the reconstructed SST variations reflect regional paleoceanographic changes. The similarity between our SST record and temperature changes (Fig. 3) observed in the Agassiz ice core (Canadian high arctic) and Renland (Greenland) ice cores (Vinther et al., 2009) further suggests a close coupling between the atmosphere above the Greenland Ice Sheet and the northern North Atlantic realm.

To test whether changes in the summer SSTs on the NIS are linked to solar insolation, we compared our summer SST data with solar insolation values for 67°N at the summer solstice. The long-term trend of summer SSTs appears to follow the local Milankovitch summer forcing (Fig. 3). The major exception is the relatively low summer SSTs versus high summer solar insolation before ca. 8000 cal. yr B.P., probably due to the influence of the melting of the Greenland Ice Sheet and the Laurentide Ice Sheet (Jennings et al., 2011).

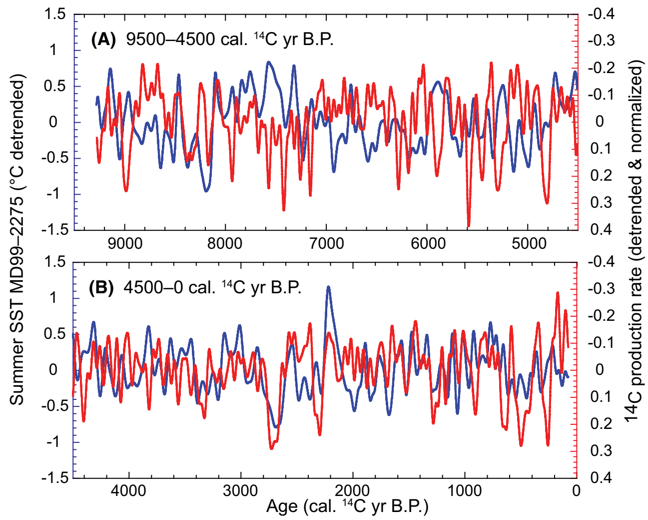


**Figure 4. Comparison of the $^{14}C$ production rate (Muscheler et al., 2005; Reimer et al., 2009) and the reconstructed summer sea-surface temperature (SST) data from core MD99–2275 (50 yr averages). Both records were detrended by removing a 6th order polynomial fitted to the data and low-pass filtered to remove high-frequency variations on time scales shorter than 50 yr.**

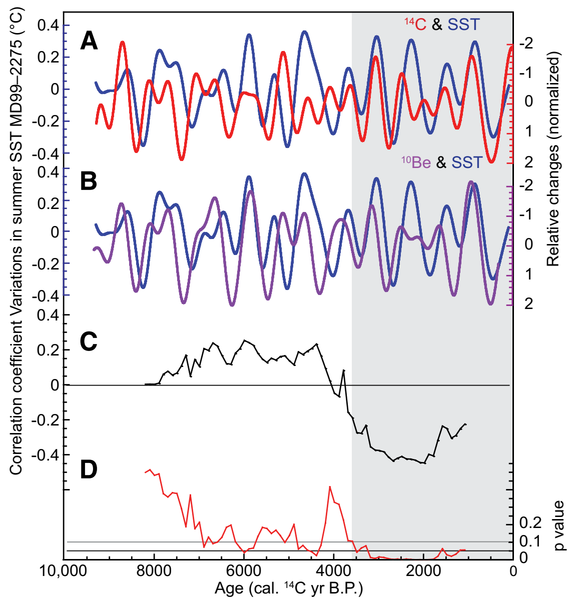


**Figure 5. Comparison of proxy records of solar forcing and reconstructed summer sea-surface temperatures (SSTs) from core MD99–2275. A: Direct comparison of band-pass filtered (1/1800 yr to 1/500 yr) and linearly detrended $^{14}C$ and SST data. B: The same comparison between summer SST and $^{10}Be$ fluxes to Summit, Greenland. C: Running correlation coefficient between $^{14}C$ production rate and SST reconstruction shown in Figure 4 (2000-yr-long windows moved in steps of 100 yr). D: Result of a significance analysis indicating highly significant negative correlations for the past ~4000 yr. The analysis included a random phase test that takes into account the autocorrelations present in the time series (Ebisuzaki, 1997).**

Variable solar activity has been suggested to be an important factor for climate change in the North Atlantic region. The comparison of our reconstructed summer SSTs with a proxy record of solar activity (Fig. 4) strengthens earlier conclusions that solar forcing has been an important component of North Atlantic climate variability during the past 1200 yr (Jiang et al., 2005). This comparison suggests that the sun-climate coupling occurs on multidecadal to centennial time scales (Fig. 4). It is possible that the sun-climate relationship on millennial time scales emerges due to the presence of common shorter term changes in both SST and solar records (Fig. 5), or as a consequence of oceanic feedback processes.

Running correlation coefficients of summer SST versus solar activity records were calculated (Ebisuzaki, 1997). The method calculates the correlation coefficient for selected time windows and includes a random phase test that takes into account the autocorrelations present in the time series. The results indicate a robust negative correlation between the SST and solar activity records over the past 4000 yr at statistically significant levels ($p < 0.05$; Figs. 5C and 5D). However, no statistically significant solar influence on the variability of the reconstructed SST can be seen before ca. 4000 cal. yr B.P. This suggests that a strong link between solar variability and summer SST in this region is limited to the past ~4000 yr. In addition, the presence of highly significant cycles around 90 yr (86, 98 yr) in the SST record (Fig. DR3) suggests a connection to the well-established solar Gleissberg cycle (Peristykh and Damon, 2003), whereas the 110 yr cycle may be associated with the periodicity of 105 yr found in $^{14}C$ records (Damon and Sonnett, 1991). Our results are consistent with a temperature and salinity record south of Iceland, where abrupt multidecadal-to centennial-scale hydrographic variability during the past millennium shows a strong correlation with reconstructed total solar irradiance variability (Moffa-Sánchez et al., 2014).

A slight time lag appears when comparing the longer term changes in solar forcing and climate responses (Figs. 5A and 5B). The apparent instantaneous climate reaction to solar forcing on multidecadal to centennial time scales (Fig. 4), with a delayed response on longer time scales (centennial to millennial time scale), may be caused by a rapid atmospheric response to solar forcing and a delayed ocean circulation response to sustained longer term forcing.

Recent climate model simulations (using the Community Climate System Model version 4.0, CCSM4; www.cesm.ucar.edu/models/ccsm4.0/) show a strong positive correlation between temperature and solar irradiance (Moffa-Sánchez et al., 2014) in the pathway of the North Atlantic Current and particularly in the path of its western branch, the Irminger Current, where our core is located (Fig. 1). The model results indicate that a reduced frequency of Atlantic blocking events during intervals of high solar activity promotes warmer and saltier conditions in the pathway of the Irminger Current due to stronger circulation of the subpolar gyre. This implies that combined atmospheric and ocean circulation effects are important for the sun-climate link observed at our location. Furthermore, using an intermediate complexity model in an ensemble approach, Renssen et al. (2006) showed that the probability of a solar-induced local reduction of the deep-water formation increases when the Arctic is already cold.

The modeling results here may aid understanding of the processes underlying the sun-climate link over the past 4000 yr and the absence of such a strong link between climate variability and solar irradiation prior to 4000 cal. yr B.P. on the NIS. The supposedly weak solar forcing affects ocean circulation depending on hydrographic conditions in the North Atlantic. The rapid melting trend of the Laurentide Ice Sheet and the Greenland Ice Sheet during the early Holocene likely influenced the regional ocean circulation and may have had a dominating impact on the SST compared to variations in total solar irradiance. In contrast, the period 7000–4000 cal. yr B.P. was the least glacially influenced phase of the Holocene, and most alpine areas were either ice free or had reached a stage of glacial minimum. During these warmer than present conditions, the still-strong summer insolation resulted in a vigorous Atlantic Meridional Overturning Circulation (AMOC) and a more northern position of the Intertropical Convergence Zone (Haug et al., 2001; Mayewski et al., 2004). This may have weakened the influence of solar irradiation variability on the North Atlantic (Renssen et al., 2006), but ca. 4000 cal. yr B.P., the general Northern Hemisphere cooling led to a weakening of the AMOC and a southward movement of the Intertropical Convergence Zone (Mayewski et al., 2004), intensifying the Westerlies over the North Atlantic. There is ample evidence for a climatic shift toward cooler and wetter conditions in glacially sensitive regions at that time, such as western North America and the northeast Atlantic regions. The changed conditions resulted in renewed glacial activity in previously glaciated areas, including Iceland (Striberger et al., 2012), and led to conditions where ocean circulation could amplify the solar influence on the climate system in the North Atlantic.

We thus hypothesize that the North Atlantic climate is primarily sensitive to changes in solar activity during cooler periods with a weaker AMOC. The tight coupling between solar variations and SST changes on multidecadal to centennial time scales points to atmospheric processes as the main driver behind the sun-climate link. The absence of a sun-climate link before ca. 4000 cal. yr B.P. is an indication that the overall state of the climate system determines if the climate in a region is susceptible to the limited changes in solar forcing. The high temporal resolution of this study reveals that the sun-climate link occurs on a multidecadal to centennial time scale, and implies that the 1500 yr cycle might be related to oceanic processes (Debret et al., 2009) that, however, could be triggered by solar forcing on shorter time scales.

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**Notes**