Evidence for solar forcing of sea-surface temperature on the North Icelandic Shelf during the late Holocene

Hui Jiang* Laboratory of Geographic Information Science, East China Normal University, 200062 Shanghai, People's Republic of China, and Department of Earth Sciences, University of Aarhus, C.F. Møllers Allé 120, DK-8000 Århus C, Denmark

Jón Eiríksson Earth Science Institute, University of Iceland, Askja, IS-101-Reykjavík, Iceland

Michael Schulz Department of Geosciences, University of Bremen, Klagenfurter Strasse, D-28334 Bremen, Germany

Karen-Luise Knudsen, **Marit-Solveig Seidenkrantz** Department of Earth Sciences, University of Aarhus, C.F. Møllers Allé 120, DK-8000 Århus C, Denmark

ABSTRACT

Diatom proxies from the modern position of the oceanographic Polar Front north of Iceland record variability in sea-surface temperatures (SSTs) during the past 2 k.y. The sedimentary record is dated with tephrochronology, alleviating marine ^{14}C reservoir age uncertainties. Comparison of changes in SSTs on the North Icelandic Shelf with variations in the atmospheric circulation above Greenland, North American Atlantic coastal SSTs, and mean temperature anomalies for the Northern Hemisphere suggests synchronous North Atlantic–wide fluctuations, which would seem to imply a common forcing factor. A positive and significant correlation between our SST record from the North Icelandic Shelf and reconstructed solar irradiance, together with modeling results, supports the hypothesis that solar forcing is an important constituent of natural climate variability in the northern North Atlantic region.

Keywords: sea-surface temperature, solar forcing, diatoms, North Icelandic Shelf, Little Ice Age.

INTRODUCTION

On centennial to millennial time scales, climate variability thought to be linked to solar forcing has been observed in, among others, proxies of sea ice and/or iceberg flux measured in deep-sea sediment cores from the North Atlantic Ocean, ^{10}Be flux recorded from Greenland ice cores, ^{14}C data from Holocene tree rings, and glacial records in the Alaskan area. The past millennial-scale cycle is broadly correlated with the Little Ice Age and the Medieval Warm Period. The Little Ice Age has a well-documented correlation with the Spörer and Maunder solar minima, which may have been partly or even entirely linked to changes in solar irradiance (Lean, 2002).

Iceland is in the North Atlantic storm-track path and 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 Current and the East Icelandic Current (Fig. 1). The Polar Front has swept across the northern North Atlantic Ocean during past regional climatic events. Even relatively minor changes in the circulation pattern are likely to be archived in the sedimentary record in this sensitive boundary region. We present a high-resolution sea-surface temperature (SST) record for the past 2 k.y. based on diatom data from the North Icelandic Shelf. This record shows significant correlation with solar activity at multidecadal to centennial time scales.

DATA AND METHODS

A modern extended data set of diatoms and environmental variables (see Table DR1[1]) from around Iceland and neighboring areas was established for quantitative reconstruction of paleoceanographic conditions on the North Icelandic Shelf. The data set covers the areas influenced by surface-water masses derived from the East Greenland Current, the East Iceland Current, and the Irminger Current, and takes into account different physical characteristics and adequate environmental gradients for the deduction of quantitative relationships between diatom species and environmental variables. Nine measured environmental variables were used (Jiang et al., 2001), and forward selection of environmental variables and associated Monte Carlo permutation tests (99 permutations) show that the diatom distribution in the area is strongly correlated with summer and winter SSTs that capture 41% of the total variance. We extracted 102 diatom samples from 1-cm-thick slices taken at 5 cm intervals (2.5 cm at the top) from the uppermost 5 m of core MD992275 (Fig. 1). The SST record was dated by 7 tephra layers and 19 accelerator mass spectrometer ^{14}C dates (Table DR2; see footnote 1), and a tephra-based age model was used (Larsen et al., 2002). The tephrochronologic approach minimizes chronological errors in the North Icelandic Shelf data and makes it possible to correlate marine and terrestrial records. The resulting sampling resolution ranges from 6 to 30 yr, with a mean of 20 yr.

Six numerical reconstruction methods (Juggins and ter Braak, 1992) were tested for the extended modern diatom vs. SST data set. The best performances are weighted-average partial least squares (WA-PLS) using six components for the summer SSTs and WA-PLS using five components for the winter SSTs, as inferred from root-mean-square error of prediction (RMSEP) based on the leave-one-out jackknifing [$RMSEP_{(Jack)}$] test. The $RMSEP_{(Jack)}$ for the summer SSTs and

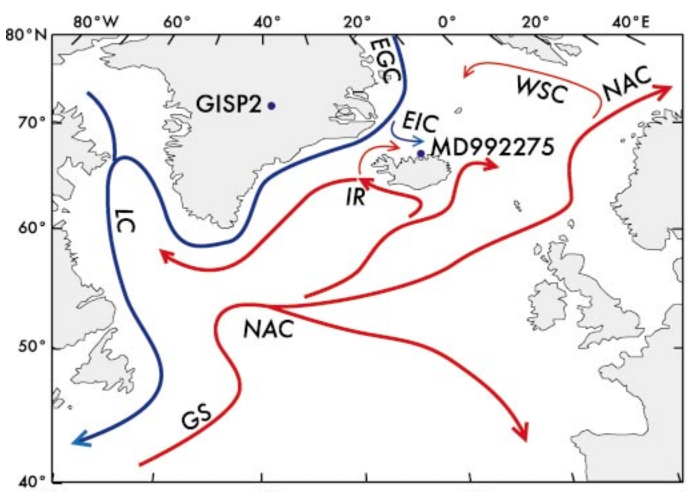

Figure 1. Modern surface current system in northern North Atlantic Ocean and locations of core MD992275 (66°33′N, 17°42′W) and Greenland Ice Sheet Project 2 (GISP2) ice core. GS—Gulf Stream; NAC—North Atlantic Current; IR—Irminger Current; EIC—East Icelandic Current; EGC—East Greenland Current; WSC—West Spitsbergen Current; LC—Labrador Current.

*E-mail: hjiang@geo.ecnu.edu.cn.

[1]GSA Data Repository item 2005010, Table DR1, Table DR2, Table DR3, and Appendix 1, detailed information about locations of the surface sediment samples and associated modern sea-surface temperature data, tephra layers, and ^{14}C dates, reconstructed sea-surface temperature data from core MD992275, and global atmosphere-ocean model ECBILT-CLIO, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

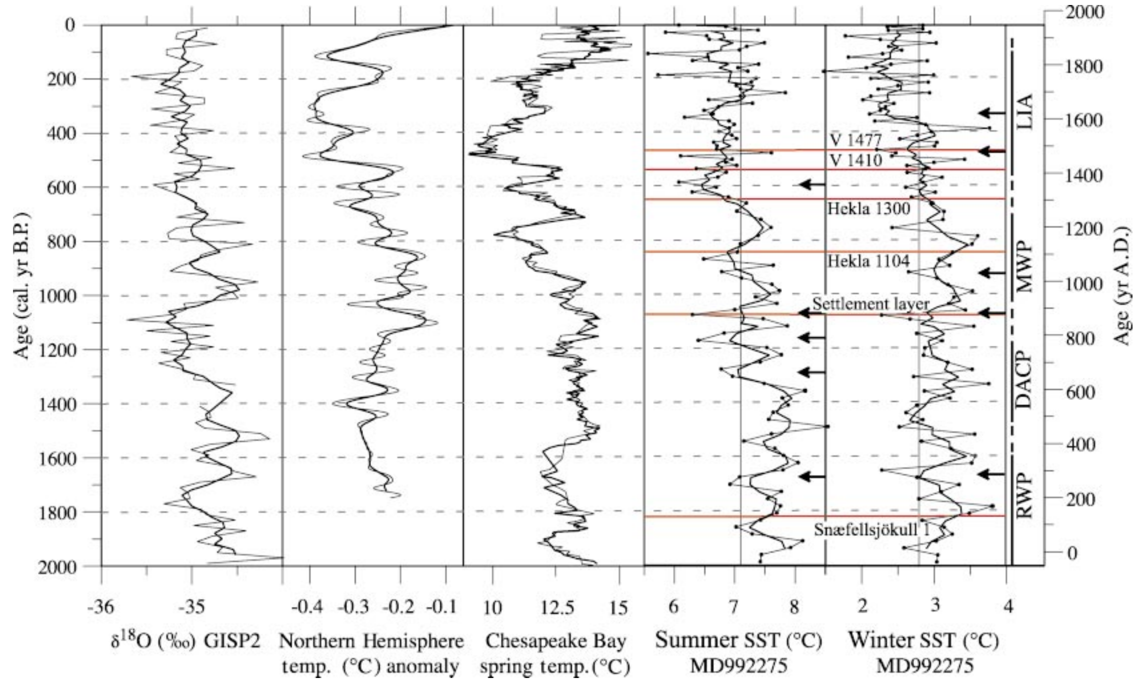

Figure 2. Reconstructed summer and winter sea-surface temperatures (SSTs) off North Iceland plotted along with $\delta^{18}O$ data from Greenland Ice Sheet Project 2 (GISP2) ice core, Northern Hemisphere temperature-anomaly record, and Chesapeake Bay SST reconstruction (for references see Table 1). Smoothed records (50 yr running mean) are denoted by bold lines. Ages are in calendar years (historical tephra dates) before 1950 and in calibrated radiocarbon years (cal. yr B.P.). Approximate timing of documentary history in northwest Europe is also shown. RWP—Roman Warm Period; DACP—Dark Age Cold Period; MWP—Medieval Warm Period; LIA—Little Ice Age. Six tephra marker horizons are indicated (V—Veidivötn volcanic system). Hekla 3 (2980 cal. yr B.P.) tephra is used to determine ages for lowest part of record. Mean values of summer SSTs and winter SSTs (7.1 and 2.8 °C) are indicated. Short, cold intervals based on at least two data points are marked by arrows. For LIA, we have marked only most rapid temperature decreases, one in summer SSTs and two in winter SSTs.

the winter SSTs are 0.98 and 0.91 °C. High accumulation rates (2.5 mm/yr), a reliable chronology, and quantitative reconstruction of climatic parameters thus allow us to discuss climate changes within the past 2 k.y.

CHANGES IN SEA-SURFACE TEMPERATURES AND THEIR REGIONAL SIGNIFICANCE

The maximum ranges of reconstructed North Icelandic Shelf SSTs during the past 2 k.y. are 3 °C (5.5–8.5 °C) for summer and 2.3 °C (1.5–3.8 °C) for winter (Fig. 2) (Table DR3; see footnote 1). The winter SSTs stayed generally above the mean value of 2.8 °C until A.D. 1300, being close to the mean until A.D. 1600 when winter SSTs dropped to values that were generally below the mean. The amplitude of severe cold peaks was progressively reduced after ca. A.D. 1750. The summer reconstruction indicates that summer SSTs remained preferentially above the mean of 7.1 °C prior to ca. A.D. 700. Afterward, summer SSTs varied around the mean until ca. A.D. 1300, when a transition to sustained colder summer SSTs occurred. Summer SSTs were below the mean during the period A.D. 1300–1650 and became highly variable afterward.

Both summer SSTs and winter SSTs had their absolute minima during the latest stage of the Little Ice Age, whereas the early part of the Little Ice Age remained relatively warm. Furthermore, our data suggest that the initial Little Ice Age cooling was largely restricted to summer and only after A.D. 1600 did winter SSTs drop markedly. Some short cold intervals at multidecadal to centennial time scales occurred with cooling by >1.0 °C relative to the neighboring warm intervals (Fig. 2).

To assess the regional significance of the North Icelandic Shelf SST records, we turn to other reconstructed temperature variations from the North Atlantic realm, covering the past 2 k.y. at interdecadal (or higher) resolution. These records include annual mean temperature anomalies for the Northern Hemisphere (Mann and Jones, 2003), oxygen isotope ratios from the central Greenland GISP2 (Greenland Ice Sheet Project 2) ice core (Stuiver et al., 1995; which reflect temperature variations to a first order), and reconstructed spring SSTs from Chesapeake Bay off eastern North America (Cronin et al., 2003) (Fig. 2). Because our prime interest is variability at longer time scales, we smoothed all temperature proxy records by using a 50 yr running-mean filter. All three records show relatively high temperatures during the Roman Warm Period and the Medieval Warm Period and colder temperatures during the Little Ice Age.

To quantify the degree of covariation between the three records and our SST data, we calculated their linear correlation (Table 1). With the exception of winter SSTs and the Chesapeake Bay data, all correlations are significantly different from zero at a 95% level of significance. Moreover, all significant correlations are positive, indicating consistent tendencies in temperature variations at time scales longer than 50 yr throughout the North Atlantic region. These results suggest synchronous North Atlantic–wide fluctuations, which would seem to imply a common forcing factor.

TABLE 1. CORRELATION COEFFICIENTS (PEARSON'S *R*)

	Summer SSTs	Winter SSTs
GISP2 $\delta^{18}O$	0.61 (0.47; 0.72)	0.51 (0.39; 0.61)
Northern Hemisphere temperature	0.28 (0.10; 0.41)	0.48 (0.31; 0.62)
Chesapeake Bay	0.29 (0.14; 0.45)	0.09 (−0.08; 0.25)
Solar irradiance	0.54 (0.30; 0.71)	0.68 (0.50; 0.79)

Note: Correlation coefficients are between (1) temperature proxy records from North Atlantic region and solar irradiance and (2) reconstructed summer and winter sea-surface temperatures (SSTs) from the North Icelandic Shelf. Values in parentheses denote bias-corrected 95% bootstrap confidence intervals. References: Greenland Ice Sheet Project 2 (GISP2) $\delta^{18}O$—Stuiver et al. (1995); Northern Hemisphere temperature—Mann and Jones (2003); Chesapeake Bay—Cronin et al. (2003); and solar irradiance—Bard et al. (2000). All time series were smoothed with a 50 yr running-mean filter prior to estimating the correlations.

LINKING SST VARIATIONS WITH SOLAR FORCING

A Sun vs. climate relationship has long been surmised on the basis of an increasing number of proxy data from terrestrial and marine archives, recording climate changes that may be linked to variations in solar insolation. To test whether the North Icelandic Shelf SST changes were linked to solar forcing, we compared our SST records with high-

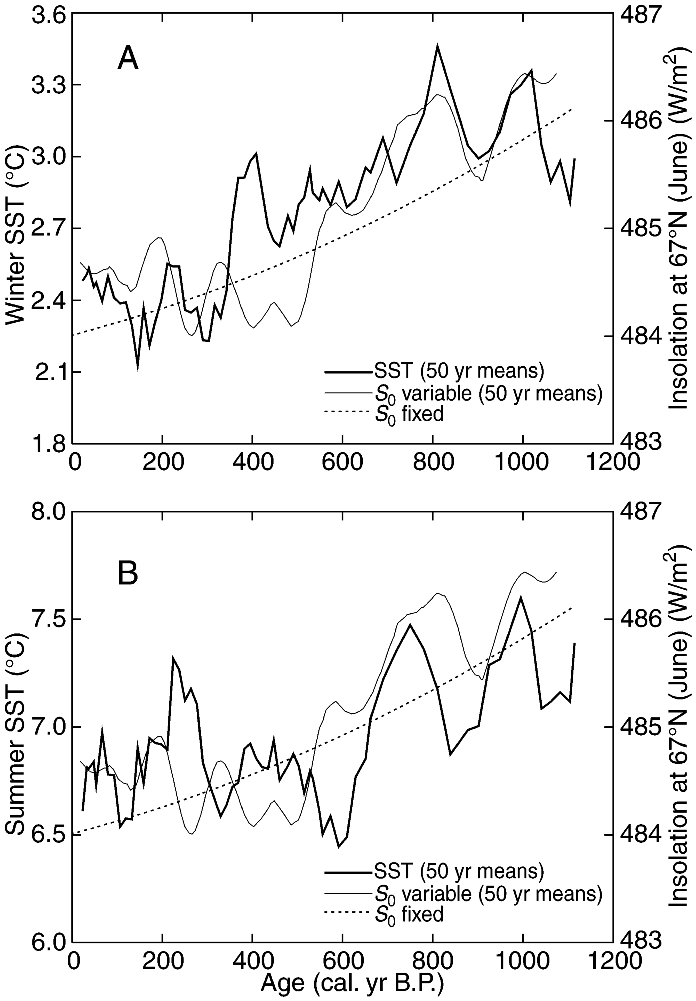

Figure 3. Relationship between solar insolation and sea-surface temperatures (SSTs). A: Winter SSTs (bold line) are smoothed (50 yr running mean) to facilitate comparison with lower-resolution insolation series. Insolation values for 67°N at summer solstice are shown for variable (thin line) and fixed (dashed line) solar irradiance (S_0). Latter curve depicts contribution of Earth's orbital variations to total solar forcing. B: As in A but for summer SSTs.

latitude solar insolation data. We used the solar irradiance reconstruction for the past 1200 yr (Bard et al., 2000), which is based on ^{14}C and ^{10}Be records and which we scaled to match the reconstructed irradiance during the Maunder Minimum (Lean et al., 1995). In addition to variations in solar irradiance, changes in Earth's orbit must be taken into account. Accordingly, daily insolation values for 67°N at summer solstice (after Berger, 1978) were calculated by using the irradiance values (Bard et al., 2000) as input. The summer and winter SST records were smoothed with a 50 yr running-mean filter to account for the lower resolution of the reconstructed irradiance data (Bard et al., 2000) and to restrict the analysis to interdecadal and longer time scales.

Visual comparison of both summer SST and winter SST curves with insolation (Fig. 3) indicates a good match between the potential forcing and the climatic response. Not only is the long-term trend of the forcing visible in the SST records, but features of the multidecadal to centennial time-scale variability are also seen. The correlations between the SSTs and irradiance are positive and significant at the 95% level (Table 1). Accordingly, solar forcing explains ~30%–45% of the SST variance at time scales longer than 50 yr. The correlation between solar forcing and winter SSTs appears to be slightly higher than for summer SSTs (Table 1), although this difference is not significant at the 95% level. This finding is also in agreement with a larger mismatch between solar forcing and the winter SSTs than for the summer SSTs during the Little Ice Age (Fig. 3). Finally, we calculated the sensitivity of the SSTs with respect to solar forcing by estimating the regression slope, and the sensitivity is on the order of 0.2–0.3 °C/(W·m^{-2}) for summer and winter. Although the sign and magnitude of this value agree well with the sensitivity obtained in a coupled ocean-atmosphere model (Cubasch et al., 1997), the value disagrees with an empirical estimate for the period A.D. 1650–1850, which indicates a weak negative correlation between solar insolation and the SSTs north of Iceland (Waple et al., 2002). This discrepancy may be due to unknown internal forcings or feedbacks within the climate system or to the proxy database used by Waple et al. (2002), as it contains no data from the vicinity of Iceland (see Fig. 1A in Mann et al., 1998). Analysis of long-term instrumental SST data shows a positive correlation with solar irradiance around Iceland (Lohmann et al., 2004).

Various concepts have been proposed to understand the possible response of the climate system to direct and indirect solar forcings (Rind, 2002). The SST variations on the North Icelandic Shelf reflect changes in the interaction between the Arctic and the North Atlantic Oceans. To test the sensitivity of climatic conditions around Iceland to solar forcing, we use the global atmosphere-ocean model ECBILT-CLIO, version 3 (Appendix 1; see footnote 1). This coupled model derives from the atmosphere model ECBILT (Opsteegh et al., 1998) and the ocean and sea-ice model CLIO (Goosse and Fichefet, 1999). The atmospheric component solves the quasi-geostrophic equations with T21 resolution (~5.6°) for three layers. The primitive-equation, free-surface ocean component has a horizontal resolution of 3° and 20 levels in the vertical. It is coupled to a thermodynamic-dynamic sea-ice model with viscous-plastic rheology. There is no local flux correction in ECBILT-CLIO. However, precipitation over the Atlantic and Arctic basins is reduced by 8.5% and 25%, respectively, and homogeneously redistributed over the North Pacific. Beside a 5000 yr control run, simulating the present-day climate, we conducted two experiments in which the solar constant (1365 W·m^{-2}) was increased or decreased by 2 W·m^{-2}. All other boundary conditions were the same as in the control run. For these sensitivity experiments, the model was integrated another 1000 yr to reach a new equilibrium, starting from the control run's final state as initial condition. All model results presented here are averages determined from the past 250 yr of each experiment.

Modeled surface temperatures north of Iceland increase (or decrease) during summer and winter for stronger (or weaker) solar forcing (Fig. 4). The model experiments thus support a positive correlation between surface temperature and solar forcing, as indicated by our analysis of paleoclimatic data. Moreover, the temperature response in the model to changes in solar forcing is stronger in winter than in summer. This result is in accordance with our finding that the correlation between solar forcing and our SST values is slightly larger for winter than for summer (Table 1). Finally, the model predicts a wind anomaly north of Iceland for stronger solar forcing during winter. This anomalous wind would tend to weaken the East Icelandic Current (Fig. 1) and therefore contribute to the warming seen in the SSTs.

CONCLUSIONS

Covariations of the SSTs on the North Icelandic Shelf with temperature anomalies from the North Atlantic realm suggest that the variability at multidecadal to centennial time scales in these records reflects regional climate signals rather than local temperature fluctuations. A positive and significant correlation between our SST record from the North Icelandic Shelf and inferred insolation, together with modeling experiments, supports the hypothesis that solar forcing is an important constituent of natural climate variability in the northern North Atlantic region.

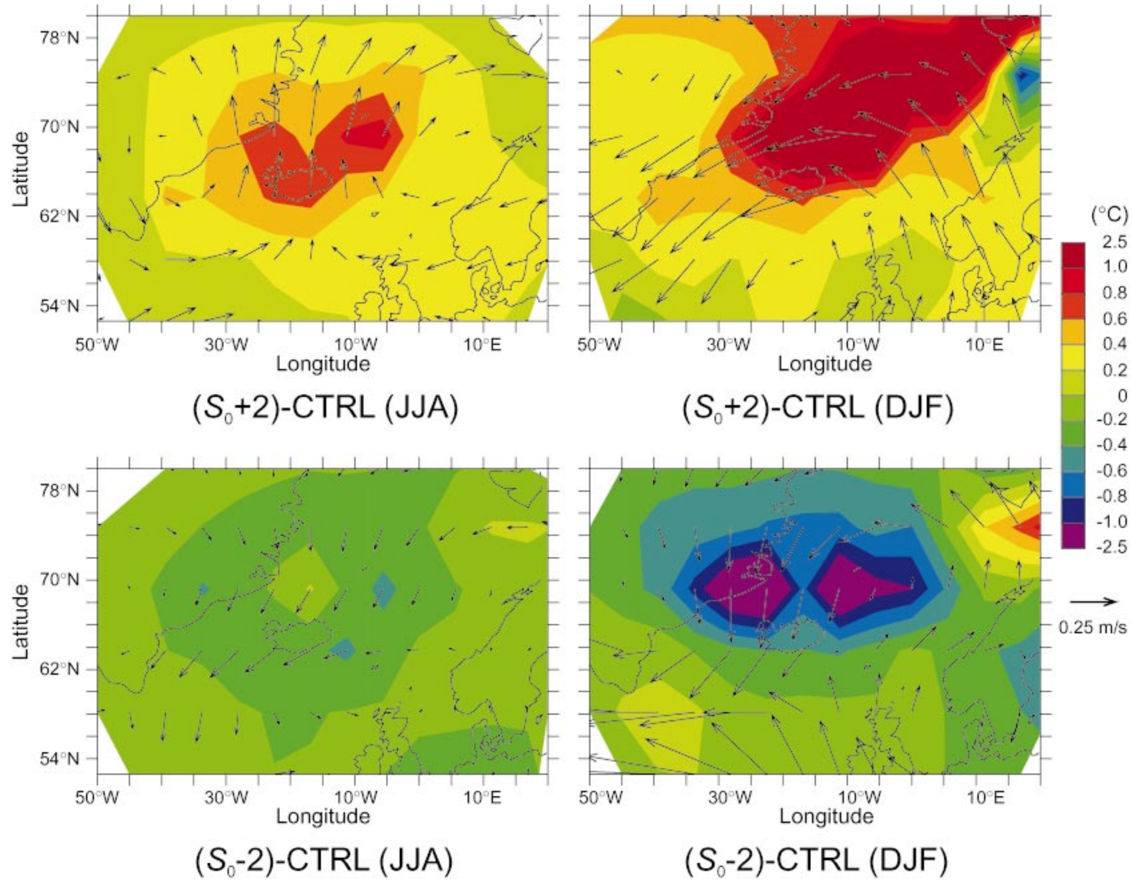

Figure 4. Modeled surface temperature and wind anomalies (at 800 hPa level; arrows) around Iceland between present-day control experiment (CTRL) and experiments with increased (S_0 + 2; top) and decreased (S_0 − 2) solar forcing for June–July–August (JJA; left) and December–January–February (DJF; right).

ACKNOWLEDGMENTS

We are grateful to the Institut Paul-Emile Victor for the IMAGES coring operation aboard the *Marion Dusfresne*, to André Paul, Bremen, for kindly providing his Fortran codes for calculating daily insolation, and A.E.J. Ogilvie and an anonymous reviewer for their valuable comments. We thank the National Natural Science Foundation of China (contracts 40276013, 40131020), the Danish Natural Science Research Council (Ole Rømer grant to Seidenkrantz), Deutsche Forschungsgemeinschaft Research Center ''Ocean Margins'' and Shanghai Priority Academic Discipline for financial support. This paper is a contribution to the HOLSMEER project, financed by the European Commission's 5th Framework Programme (contract EVK2-CT-2000-00060).

REFERENCES CITED

Bard, E., Raisbeck, G., Yiou, F., and Jouzel, J., 2000, Solar irradiance during the last 1200 years based on cosmogenic nuclides: Tellus, v. 52B, p. 985–992.

Berger, A.L., 1978, Long-term variations of daily insolation and Quaternary climatic change: Journal of the Atmospheric Sciences, v. 35, p. 2362–2367.

Cronin, T.M., Dwyer, G.S., Kamiya, T., Schwede, S., and Willard, D.A., 2003, Medieval Warm Period, Little Ice Age and 20th century temperature variability from Chesapeake Bay: Global and Planetary Change, v. 36, p. 17–29.

Cubasch, U., Voss, R., Hegerl, G.C., Waszkewitz, J., and Crowley, T.J., 1997, Simulation of the influence of solar radiation variations on the global climate with an ocean-atmosphere general circulation model: Climate Dynamics, v. 13, p. 757–767.

Goosse, H., and Fichefet, T., 1999, Importance of ice-ocean interactions for the global ocean circulation: A model study: Journal of Geophysical Research, v. 104, p. 23,337–23,355.

Jiang, H., Seidenkrantz, M.-S., Knudsen, K.L., and Eiríksson, J., 2001, Diatom surface sediment assemblages around Iceland and their relationships to oceanic environmental variables: Marine Micropaleontology, v. 41, p. 73–96.

Juggins, S., and ter Braak, C.J.E., 1992, CALIBRATE—A program for species-environment calibration by (weighted-averaging) partial least squares regression: London, University College, Environmental Change Research Centre.

Larsen, G., Eiríksson, J., Knudsen, K.L., and Heinemeier, J., 2002, Correlation of late Holocene terrestrial and marine tephra markers, north Iceland: Implications for reservoir changes: Polar Research, v. 21, p. 283–290.

Lean, J., 2002, Solar forcing of climate change in recent millennia, *in* Wefer, G., et al., eds., Climate development and history of the North Atlantic realm: Berlin, Springer-Verlag, p. 75–88.

Lean, J., Beer, J., and Bradley, R., 1995, Reconstruction of solar irradiance since 1610: Implications for climate change: Geophysical Research Letters, v. 22, p. 3195–3198.

Lohmann, G., Rimbu, N., and Dima, M., 2004, Climate signature of solar irradiance variations: Analysis of long-term instrumental, historical, and proxy data: International Journal of Climatology, v. 24, p. 1045–1056.

Mann, M.E., and Jones, P.D., 2003, Global surface temperatures over the past two millennia: Geophysical Research Letters, v. 30, no. 15, 1820, doi: 10.1029/2003GL017814.

Mann, M.E., Bradley, R.S., and Hughes, M.K., 1998, Global-scale temperature patterns and climate forcing over the past six centuries: Nature, v. 392, p. 779–787.

Opsteegh, J.D., Haarsma, R.J., Selten, F.M., and Kattenberg, A., 1998, ECBILT: A dynamic alternative to mixed boundary conditions in ocean models: Tellus, v. 50A, p. 348–367.

Rind, D., 2002, The Sun's role in climate variations: Science, v. 296, p. 673–677.

Stuiver, M., Grootes, P.M., and Braziunas, T.F., 1995, The GISP2 $\delta^{18}O$ climate record of the past 16,500 years and the role of the Sun, ocean, and volcanoes: Quaternary Research, v. 44, p. 341–354.

Waple, A.M., Mann, M.E., and Bradley, R.S., 2002, Long-term patterns of solar irradiance forcing in model experiments and proxy based surface temperature reconstructions: Climate Dynamics, v. 18, p. 563–578.

Manuscript received 19 August 2004
Revised manuscript received 17 September 2004
Manuscript accepted 22 September 2004

Printed in USA