Two millennia of North Atlantic seasonality and implications for Norse colonies

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δ^{18}O values of mollusks recovered from near-shore marine cores in northwest Iceland quantify significant variation in seasonal temperature over the period from ∼360 B:C: to ∼A:D: 1660. Twenty-six aragonitic bivalve specimens were selected to represent intervals of climatic interest by using core sedimentological characteristics. Carbonate powder was sequentially micromilled from shell surfaces concordant with growth banding and analyzed for stable oxygen (δ^{18}O) and carbon (δ^{13}C) isotope values. Because δ^{18}O values record subseasonal temperature variation over the lifetime of the bivalves, these data provide the first 2,000-year secular record of North Atlantic seasonality from *ca.* 360 cal yr B.C. to cal yr A.D. 1660. Notable cold periods (360 B.C. to 240 B.C.; A.D. 410; and A.D. 1380 to 1420) and warm periods (230 B.C. to A.D. 140 and A.D. 640 to 760) are resolved in terms of contrast between summer and winter temperatures and seasonal temperature variability. Literature from the Viking Age (*ca.* 790 to 1070) during the establishment of Norse colonies (and later) in Iceland and Greenland permits comparisons between the δ^{18}O temperature record and historical records, thereby demonstrating the impact of seasonal climatic extremes on the establishment, development, and, in some cases, collapse of societies in the North Atlantic.

climate change | stable isotopes | Vikings | micromilling

Seasonality of temperature, the difference between summer and winter temperatures, is one of the most important characteristics of climate (1) playing a significant role in the distribution of plants and animals and in determining the surface characteristics of the ocean (2). The reconstruction of seasonality on a regional scale is vital for gaining a better understanding of past climate dynamics (3, 4) including the extent and rate of change of natural climate variability (5). Research focused on regions that are sensitive to climate change and that influence large-scale atmospheric and oceanic circulation patterns is particularly significant in further enhancing our understanding of past climate. One such region, the north Icelandic shelf, is particularly sensitive to changes in North Atlantic climate regimes (6, 7) because it is situated between opposing atmospheric/oceanic fronts (Fig. 1). Icelandic climate is dominantly controlled by convection strength of the Atlantic and Arctic Ocean currents that are in turn forced by prevailing atmospheric conditions and the advection of water masses in the North Atlantic region influenced by local hydrographic conditions (8). Although it borders the Arctic Circle, Iceland experiences a cool temperate maritime climate because of the influence of the Irminger Current from the south, an offshoot of the warm North Atlantic Current (Fig. 1). However, Iceland's coastal waters are also chilled by the East Icelandic Current that branches off the East Greenland Current that carries cool Polar/Arctic water and sea ice (9).

Variation in the intensity of ocean currents can cause fluctuations in salinity and temperature on decadal scales, as demonstrated during the "Great Salinity Anomaly" from 1965 to 1971, when minima in salinity and temperature time series were observed off the coast of Iceland (10). The maximum temperature deviation was observed in 1967 when temperatures were ∼3.0 °C below the 1950–1958 mean (11). This cold period was also associated with a sustained negative North Atlantic Oscillation (NAO) index (12). The NAO is a meridional variation in pressures between the subpolar and subtropical Atlantic—the dominant mode of variability in the North Atlantic region, especially in winter (13). One node of the NAO is the Icelandic Low, a region of low atmospheric pressure that dominates atmospheric conditions in Iceland (8).

Reconstructions of North Atlantic atmospheric and oceanic conditions have focused mainly on the ice core records of Greenland but more recently have also been derived from marine sediment records. Marine cores contain abundant paleoclimatic proxy data, including carbonate content, foraminiferal diversity, and ice-rafted debris. Recent investigations of the marine environment off the northwest and northern coasts of Iceland have revealed significant millennial-, centennial-, and decadal-scale variability over the Holocene (14–19). These hydrographic changes on the north Icelandic shelf reflect larger scale ocean-atmosphere circulation changes and regional climate variation in the North Atlantic. Indications of significant climate change during the early and middle Holocene, as well as more recent changes such as the Little Ice Age and the Medieval Warm Period have been found by variations in foraminiferal assemblages, δ^{18}O values of foraminifera, coccoliths, and diatoms, and from ice-rafted debris. These studies are, however, restricted to decadal-scale resolution because of limitations imposed by low rates of sediment accumulation.

Results and Discussion

In order to examine climate variability at higher (subannual to subseasonal) resolution, bivalves were selected from cores at stratigraphic intervals from notable warm and cold periods, as evidenced by the chemistry and sedimentology of cores. Twenty-six bivalve shell surfaces were sequentially micromilled along their growth axes, and the carbonate powders analyzed for stable oxygen (δ^{18}O) isotopes. δ^{18}O trends primarily reflect changes in ambient water temperature, thereby establishing a record of subseasonal temperature variation over the lifetime of individual bivalves (∼2 to 9 years). Temperatures reconstructed from micromilled mollusks were combined to develop a 2,000-year record of climatic snapshots ∼2–9 years in duration that reveal significant variability in maximum and minimum annual temperatures from *ca.* 360 cal yr B.C. to cal yr A.D. 1660 (Fig. 2).

δ^{18}O values of bivalve carbonate ($\delta^{18}O_{(CaCO3)}$) are dependent on temperature and the δ^{18}O of the water ($\delta^{18}O_{(H2O)}$) from which it is precipitated (20, 21). A constant water value of 0.1‰ was assumed, on the basis of measured values of shelf-bottom water

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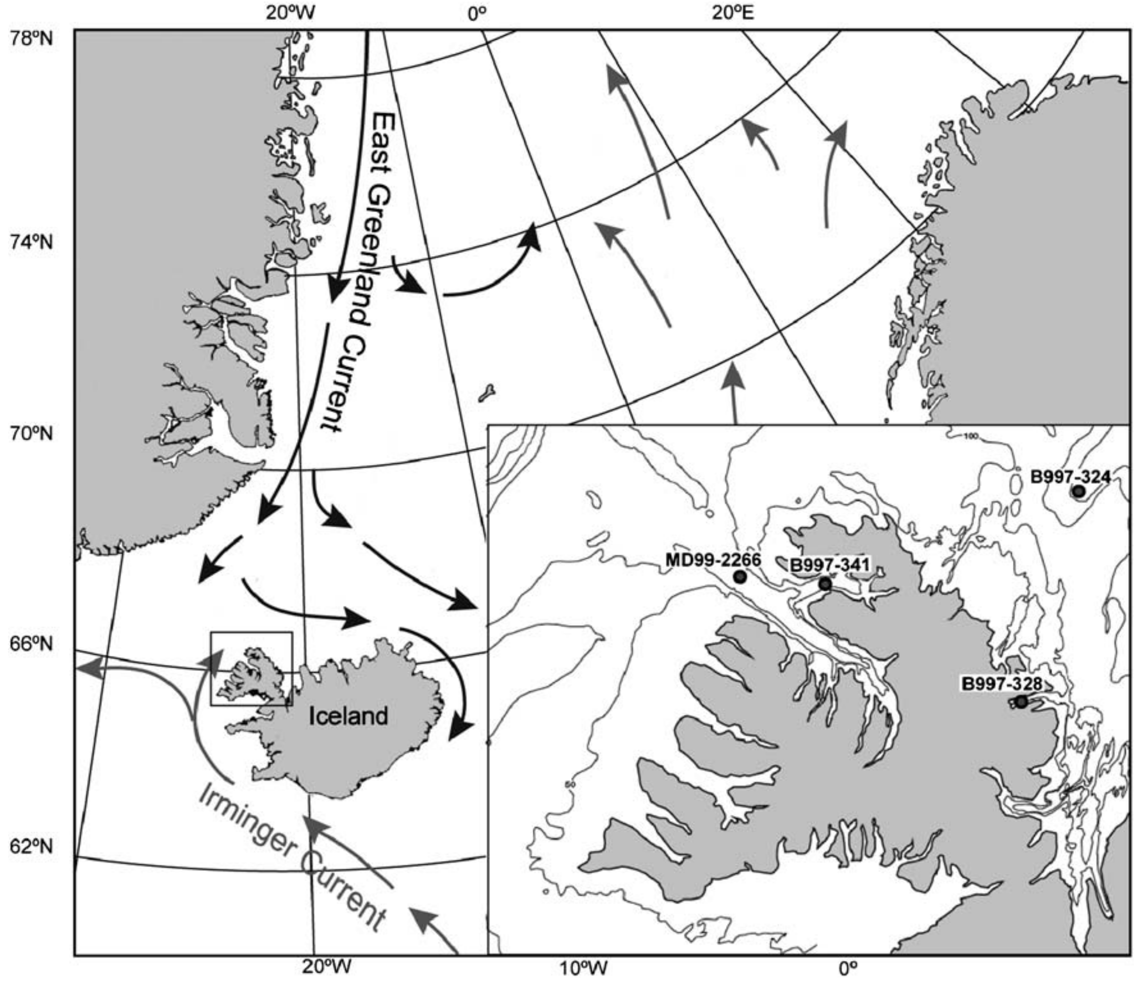

Fig. 1. Map of Iceland and surrounding area. Black arrows represent colder currents of Arctic origin; gray arrows represent warm currents of Atlantic origin. *Inset*: Close-up of study area of the northwest peninsula and core location.

in this region. The influence of variable $\delta^{18}O_{(H2O)}$ values on $\delta^{18}O_{(CaCO3)}$ is much less significant than that of temperature. $\delta^{18}O_{(H2O)}$ values covary with salinity, and the relationship between them can be expressed by a mixing equation specific to the region of study. By using the range of salinities (33.99–35.15‰) measured in this area since 1938 by the Marine Research Institute

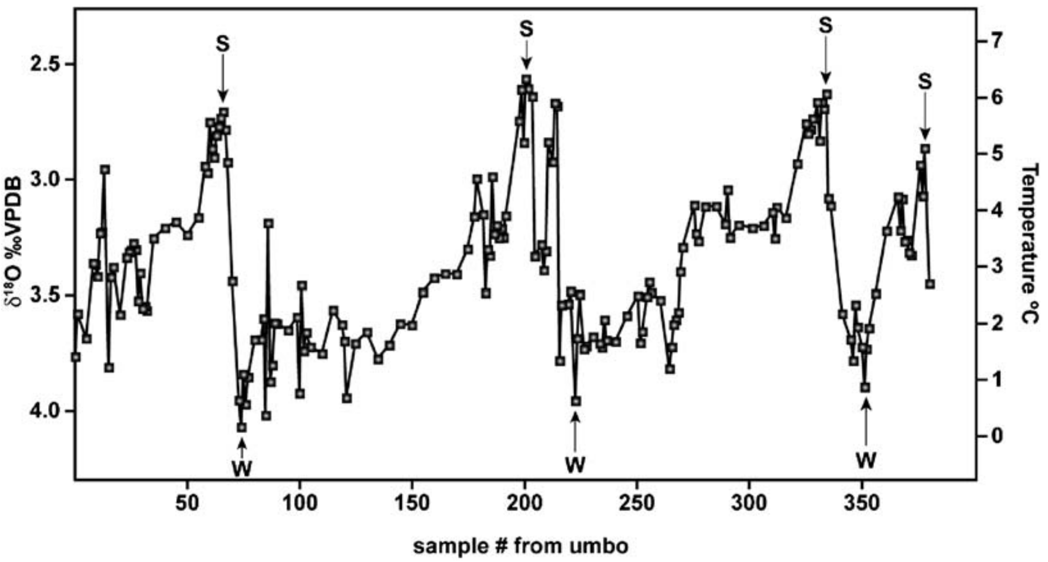

Fig. 2. Example $\delta^{18}O$ data of shell B997-328\248.75–257.25 cm (left axis) and corresponding temperatures (right axis). Arrows point to maximum and minimum annual temperatures. This bivalve lived through four summers (S1–S4) and three winters (W1–W3).

of Iceland (22), the maximum range in $\delta^{18}O_{(H2O)}$ values using the regional salinity-isotope equation (19) is ∼0.16‰, corresponding to an environmental temperature uncertainty of ∼ ± 0.6 °C. The measured temperature range for northern Icelandic water over the same time span is −1 to 11 °C (22) and indicates that the $\delta^{18}O_{(CaCO3)}$ values measured from marine bivalves are controlled mainly by changes in water temperature rather than changes in $\delta^{18}O_{(H2O)}$.

$\delta^{18}O$ values of the two oldest bivalves in our study record a cold period from ∼360 B.C. to 240 B.C. that exhibit some of the lowest temperatures of our entire time series, with maximum summer temperatures of only 4.0 and 6.5 °C and minimum annual temperatures between −1.0 and 1.0 °C (Fig. 3). Temperatures rapidly increase such that the bivalve data from ∼230 B.C. display maximum annual temperatures between 8.0 and 11.5 °C and a minimum temperature of 5.0 °C. Subsequently, a bivalve at ∼130 B.C. recorded the highest temperature of the entire 2,000-year record at 13.0 °C. The interval from ∼230 B.C. to A.D. 40 was one of exceptional warmth in Iceland, coinciding with a period of general warmth and dryness in Europe known as the Roman Warm Period, from ∼200 B.C. to A.D. 400 (23). On the basis of $\delta^{18}O$ data, reconstructed water temperatures for the Roman Warm Period in Iceland are higher than any temperatures recorded in modern times.

A return to cooler conditions by ∼A.D. 410 was indicated by maximum annual temperatures of 4.0 to 6.5 °C and minimum annual temperatures of –0.5 to 2.0 °C. Both summer and winter temperatures displayed the same variability. This period coincided with prevailing cooler and wetter conditions experienced by much of Europe at this time, during the "Dark Ages Cold Period," ∼A.D. 400 to 600 (24). Climatic improvement following the Dark Ages occurred earliest in Iceland at ∼A.D. 470, with a ∼2 °C increase in both the average maximum and average minimum annual temperatures.

The warming trend in Iceland continued with another period of exceptional warmth from ∼A.D. 600 to 760. The average maximum annual temperature recorded from this time was 11 °C, the highest of our time series. Unlike the Roman Warm Period, however, this interval featured more variability in minimum annual temperatures that had ranges that were more than twice as large as the maximum temperature variability. The warm interval from ∼A.D. 600 to 760 may correspond to the onset of the Medieval Warm Period in Iceland. Again, the warming in Iceland preceded the rest of Western Europe, where the maximum warmth began ∼A.D. 800–850 (25).

Iceland was initially settled ∼A.D. 865–930 (26), and it has often been assumed that the periods of Icelandic settlement, as well as the settlements established in Greenland (∼A.D. 985), represented conditions favorable for sea voyages, i.e., warm temperatures and a lack of sea ice (23, 25). The Icelandic sagas recorded the earliest settlement of Iceland and generally indicated a favorable climate that supported large farms and abundant crops (27). Our reconstructed temperatures show that both summer and winter temperatures were high immediately preceding settlement (Fig. 3). In the period immediately following the settlement of Iceland, summer temperatures remained high, but winter temperatures decreased significantly. By ∼A.D. 960, however, maximum temperatures remained at ∼7.5 to 9.5 °C, but minimum temperatures from ∼1.0 to 3.6 °C were on average almost 6.0 ° C lower than during the initial wave of settlement. Summer temperatures then also decreased, and by ∼A.D. 990, maximum summer temperatures reached only 6.0 °C, and only 5.0 °C by ∼A.D. 1080.

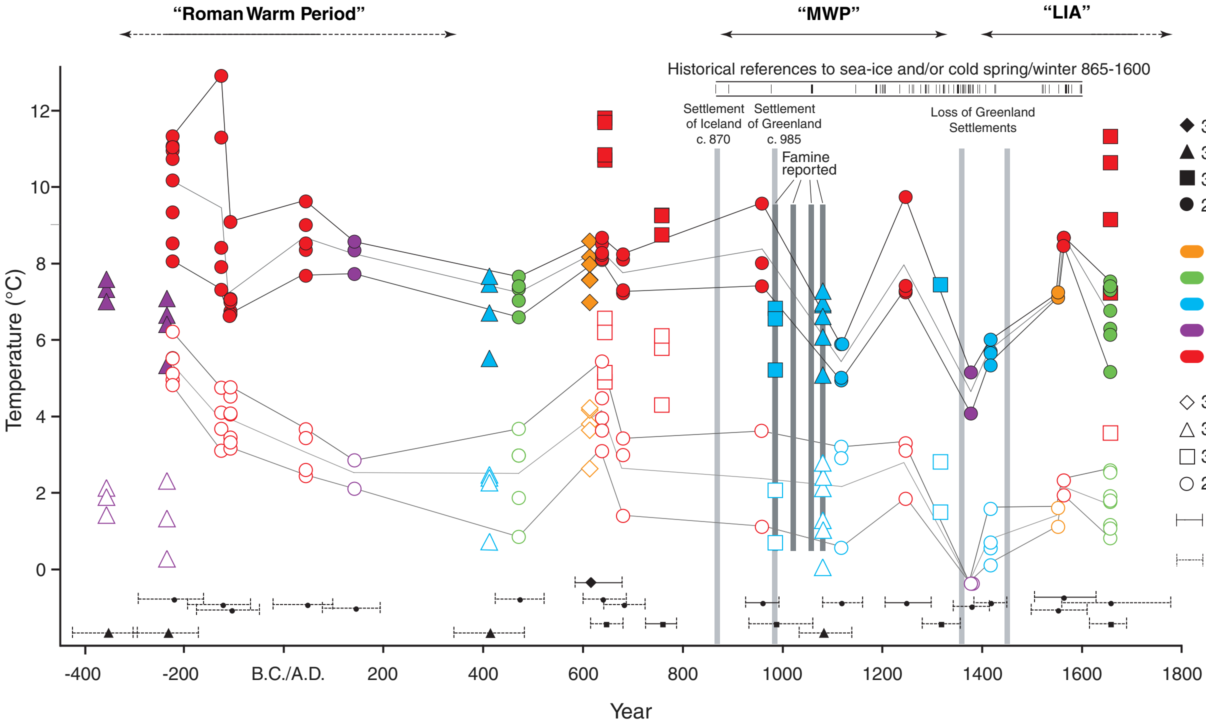

Fig. 3. Variation of seasonality in temperature from 360 B.C. to A.D. 1660 derived from $\delta^{18}O$ values of bivalve carbonate. Minimum $\delta^{18}O$ values (maximum annual temperatures) are represented by filled symbols, and maximum $\delta^{18}O$ values (minimum annual temperatures) are represented by open symbols, recovered from each shell. Black lines connect the maximum, average, and minimum highest temperatures for shells from core MD99-2266; gray lines connect the maximum, average, and minimum lowest temperatures. Temperatures were calculated by using the aragonite fractionation equation of Patterson et al. with a $\delta^{18}O_{(H2O)}$ value of 0.1‰. This equation was chosen over other temperature-fractionation equations because it gave the correct temperatures for modern micromilled molluscs from Iceland (*SI Text*) and New York. Also shown are the major climate periods and dates of the settlements of Iceland and Greenland and the abandonment of the Greenland settlements. Historical references to the appearance of sea ice within sight of the Icelandic coast and records of cold springs and winters (30) are represented by the black bar graph at the top.

Deteriorating conditions were recorded for the year A.D. 975 and for A.D. 1055–1056 in one version of the *Landnámabók* (the Book of Settlements) that was written during the first few centuries of settlement on Iceland. Several great famines occurred in the first century following settlement, such that "men ate foxes and ravens" and that "the old and helpless were killed and thrown over cliffs" (28). The 6.0 °C decrease in summer temperatures appears to have been disastrous for the Nordic settlers of Iceland, especially because it was the summer temperatures and the length of growing seasons that determined crop yields and the amount of forage available for the livestock central to the Icelandic economy (29). Although hay for forage was the most important crop, grain cultivation had also been established throughout much of the country shortly after settlement but became limited to barley (a shorter-season crop) by the early 1200s, and by the 1500s it was abandoned altogether (26). Low summer temperatures were recorded from ∼A.D. 990 to 1120, and winter temperature variability increased markedly. The Sagas and Annals recorded this variability through descriptions of alternating intervals of harsh and mild climate that included times of crop abundance and warm winters but also times of crop failure and extensive and long-lasting sea ice (30).

Molluscan δ^{18}O values indicate that a warming trend occurred after ∼A.D. 1120 and that by ∼A.D. 1250 the summer temperature maximum reached 10.0 °C, temperatures not reached since the first written record of Iceland 300 years earlier when winter temperatures hovered around 2.0 °C. This period of warming was short-lived, however, and by ∼A.D. 1320, the average summer and winter temperatures were already 2.0 °C lower in just 70 years. This cooling trend continued until ∼A.D. 1380, when the lowest summer and winter temperatures since settlement were recorded by the mollusk time-series record, at 4.5 and −0.5 °C, respectively. The timing of these minima corresponds to lows in the central Greenland ice core record (31). Historical documents recorded severe weather and sea ice in the late 1300s and early 1400s (32), and the sailing route from Iceland to Greenland that had been previously ice-free was abandoned by 1342 (25). By ∼A.D. 1360 the Western settlement in Greenland was abandoned, and by ∼A.D. 1450 the Eastern settlement followed suit (33).

Following the period of cold climate between ∼A.D. 1380 and 1420, temperatures began to increase. Written documents from A.D. 1145 to 1572 mentioned incidents of severe sea ice, although there is a lack of data from ∼A.D. 1430 to 1560 (32). The two most recent bivalves in our series, ∼A.D. 1660, recorded relatively low average summer and winter temperatures in one specimen (6.7 and 1.7 °C). The other specimen displays high temperatures, particularly, high winter temperatures that approach the temperatures present during the initial settlement of Iceland, with average summer and winter temperatures of 8.2 and 5.5 °C, respectively. Accordingly, sea ice off the coast of Iceland is rarely mentioned in the historical annals written by priests and farmers during a mild climatic interval between ∼A.D. 1640 and 1670 (34). Likewise, the weather of London during the year of the Great London Fire of 1666 is well known to have been hot and dry (35).

Together, the high-resolution reconstruction of climate on the basis of δ^{18}O values from mollusks preserved in near-shore marine cores from Iceland and descriptions from the Norse Sagas, Annals, and Book of Settlements provides a unique opportunity to better understand Holocene climate change and its effect on human populations, their settlements, and livelihood. Historical documents indicate that sea exploration in the North Atlantic and the subsequent settlement of Iceland and Greenland occurred during a period of sustained and consistent warmth. High winter temperatures at this time suggest that passages from Norway to Iceland and Greenland would have remained ice-free year round. Following the first hundred years of settlement in Iceland, decreases in summer and winter temperatures resulted in more frequent crop failures and winters that were harder to survive. Greater variation in winter temperatures would have made subsistence strategies more difficult to implement. Colder winter temperatures would have also resulted in greater frequency and duration of sea ice, making sea travel more difficult, perhaps contributing to the abandonment of the Greenland settlements a few decades after the September 1408 wedding in Hvalsey—the last recorded Norse event in Greenland (36).

The mollusk data show a generally decreasing trend in average summer and winter temperatures from ∼300–200 B.C. (beginning of the Roman Warm Period) to ∼A.D. 1400 (beginning of the Little Ice Age), except for the increase between A.D. 600 and 1000 and at A.D. 1250. The reconstructions on the basis of mollusk data from this study are supported when compared with trends derived from other climate proxies in the Icelandic cores, such as the total carbonate percentage (Fig. 4*C*) and the δ^{18}O values of benthic foraminifera (Fig. 4*D*). None of the records show a major shift that encompassed the entire Medieval Warm Period, although there are minor peaks in both the mollusk-derived temperature and carbonate records around A.D. 950–960 and A.D. 1250. The interval between these peaks coincides with a period of cooler temperatures in western central Europe, on the basis of documentary evidence (37), as well as a

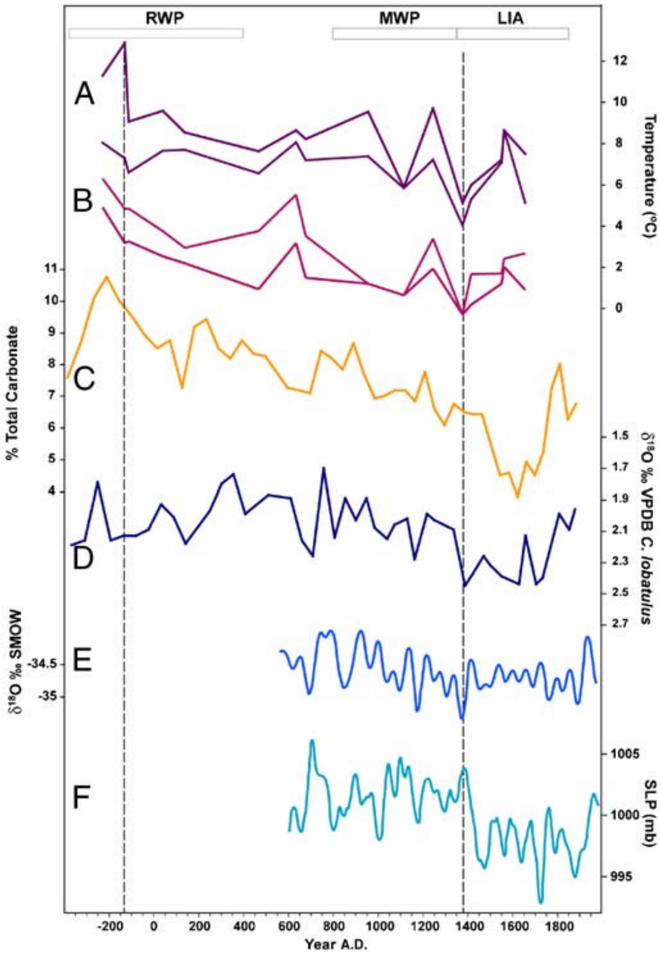

Fig. 4. (*A*) The range of the maximum temperatures and (*B*) minimum temperatures obtained from shells from core MD99-2266. (*C*) Percentage of total carbonate from core B997-328 (17). (*D*) δ^{18}O values from the benthic foraminifera *Cibicides lobatulus*, also from B997-328 (17). (*E*) δ^{18}O values of ice from the core at Crête, Central Greenland, smoothed by a 60-year filter (31). (*F*) Icelandic Low sea level pressure proxy on the basis of ion concentration from Greenland Ice Sheet Project Two (GISP2) (37). Dashed lines are through the maximum highest temperature and minimum lowest temperature reconstructed from bivalves from core MD99-2266.

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glacial expansion in northern Europe (38). The timing of temperature minima from the mollusk-derived data and the foraminifera δ^{18}O values occurred at ~A.D. 1400, although the carbonate content data show that the lowest temperatures were at ~A.D. 1540. The temperature minima derived from mollusk δ^{18}O values also coincides with minima in δ^{18}O values of the central Greenland ice core (Crête) (Fig. 4*E*). An apparent decrease in sea level pressure of the Icelandic Low (Fig. 4*F*) would have forced a major change in the atmospheric circulation throughout the region that led to a deepening of the Icelandic Low and increased winter circulation over the North Atlantic (39). The Greenland Ice Core data, together with the total carbonate from the Icelandic marine cores, suggest that this trend continued for several centuries. The high-resolution seasonal temperature record derived from the mollusk δ^{18}O values, in contrast, shows a clear increase in temperatures after A.D. 1400, which may demonstrate that there was a more localized climate influence on Iceland. Climate reconstruction on the basis of high-resolution data, such as seasonal temperature records derived from δ^{18}O values of micromilled mollusks, may also detect shorter-term climatic fluctuations that may otherwise be masked by time-averaged data like ice cores and carbonate content.

Materials and Methods

Mollusk Carbonate Processing. Twenty-six mollusks were selected from periods in marine cores that reflect extremes in carbonate content and δ^{18}O of *C. lobatulus*, a benthic foraminifera. The mollusks were located in x-radiographs of the cores, extracted, and cleaned, and one valve from each mollusk was mounted on a microscope slide and fixed on a motorized, computer-controlled micropositioning stage. Three-dimensional coordinates are then entered into the computer along lines of shell growth, generating a cubic spline digitized path that accurately represents growth lines. Intermediate paths are interpolated, allowing the stage to move along these sample paths as a drill bit mills carbonate from the shell parallel to growth lines. Sampling resolution varies with the size and growth rate of the shell. Sample paths were typically 30–60 μm wide and 20–50 μm in depth. For some specimens, we analyzed every third or fifth microsample to locate the apparent maximum and minimum values. Subsequently, we would analyze all samples adjacent to the apparent minima and maxima in order to verify that we captured the full seasonal range.

Laboratory Analysis. Carbonate samples were roasted in vacuo at 200 °C for 1 hour to remove moisture and volatile organic contaminants. Samples were reacted with 103% phosphoric acid at 70 °C by using a Kiel III carbonate preparation device directly coupled to a Thermo-Finnigan MAT 253 gas-isotope-ratio mass spectrometer, in the Saskatchewan Isotope Laboratory. Isotopic analyses were corrected for phosphoric acid fractionation and contribution of ^{17}O to the 45/44 and 46/44 mass ratios. Results are calibrated to the International Atomic Energy Agency powdered carbonate standard NBS-19 [accepted value $+1.95‰\delta^{13}$C and $-2.2‰\delta^{18}$O relative to Vienna Pee Dee belemnite (VPDB)].

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Supporting Information

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1. Dunhill G, Andrews JT, Kristjansdottir GB (2004) Radiocarbon date list X: Baffin Bay, Baffin Island, Iceland, Labrador Sea, and the Northern North Atlantic. Occasional Paper No. 54, Institute of Arctic and Alpine Research, pp 1–78.

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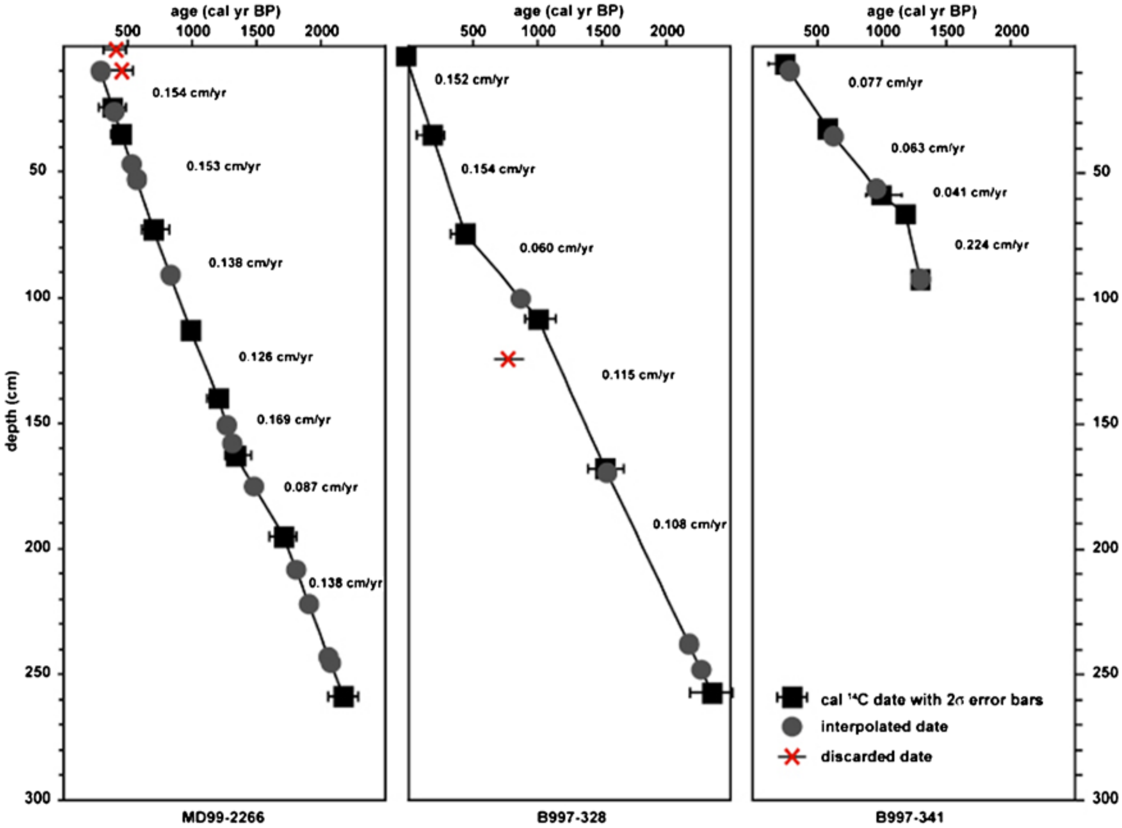

Fig. S1. Age-depth models for cores MD99-2266, B997-328, and B997-341 on basis of calibrated radiocarbon ages (see Table S2).

Other Supporting Information Files

Table S1 (DOCX)
Table S2 (DOC)

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