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Bipolar Changes in Atmospheric Circulation During the Little Ice Age

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Annually dated ice cores from Siple Dome, West Antarctica, and central Greenland indicate that meridional atmospheric circulation intensity increased in the polar South Pacific and North Atlantic at the beginning (~1400 A.D.) of the most recent Holocene rapid climate change event, the Little Ice Age (LIA). As deduced from chemical concentrations at these core sites, the LIA was characterized by substantial meridional circulation strength variability, and this variability persists today despite strong evidence for an end to LIA cooling. Thus, increased late 20th century storm variability may be in part a result of the continuation of these climatic fluctuations.

The LIA (nominally ~1400 to 1900 A.D.) is recorded in several Northern Hemisphere and equatorial paleoclimatic records; it was a period of cold, dry conditions and increased atmospheric circulation (*1–4*). It now appears that several LIA-type events have occurred throughout the Holocene (*2*) and that relatively minor forcings may be responsible for these events (*5*).

Although it was a globally distributed event, the LIA was not a 500-year period of global cooling. High-resolution tree ring records from several areas (*6*) have suggested that although there is substantial decadal-scale variability related to temperature changes over the last 2000 years, no distinct LIA signal is recorded. Indeed, it is possible that the LIA was not simply a cooling everywhere but instead a period of both warm and cold anomalies that varied in importance geographically (*7*). Such patterns can be attributed to changes in atmospheric circulation strength (*8*). Although instrumental records of atmospheric circulation strength do not encompass the entire LIA period, ice-core glaciochemical records can provide a proxy for this climate parameter (*2*). Here we present results of annually dated, multivariate chemical records from a new ice core at Siple Dome, West Antarctica, and the previously described Greenland Ice Sheet Project Two (GISP2) (*2*) ice core that allow a comparison of changes in regional atmospheric circulation in the South Pacific and North Atlantic, respectively, throughout the last 1150 years (Fig. 1).

Siple Dome (81.654°S, 148.808°W; Fig. 1) is sensitive to changing coastal meteorological conditions because of its low elevation (621 m) and because many cyclones pass across the relatively flat Ross Ice Shelf to the site (*9, 10*). In 1994, a 150-m ice core was collected 5 km north of the Siple Dome summit (*10*). Annual layers are evident in the core (*11*), and ice with an age of 1150 years before the present (2000 A.D.) is present at a depth of 150 m (the dating error is estimated to be ~1%). The average accumulation rate is 13.3 cm of ice equivalent per year.

The concentrations of sea-salt species (namely, Na^+, Cl^-, Mg^{2+}, and K^+) in Antarctic and Greenland surface snow decrease exponentially with both distance inland and elevation because coarse mode sea-salt aerosols fall out of the air during transport (*10, 12*). Therefore, changes in the concentration of these species in the ice core imply fluctuations in the frequency and intensity of tropospheric aerosol transport to a particular site (*10, 12*). Sea-salt deposition occurs at Siple Dome primarily during the austral winter when cyclonic frequency is at a maximum (*9*). Fluctuations in the position and intensity of the Amundsen Sea Low (ASL) in response to atmospheric heating over the Pacific Ocean (*9*) are likely linked to Siple Dome glaciochemistry on interannual time scales. On longer time scales (decades to centuries), overall expansion (deepening) of the ASL associated with changes in the latitude of the Antarctic low-pressure belt, and hence the southern circumpolar vortex extent (*9*), is most likely responsible for increased aerosol transport. Similarly, in central Greenland, most sea salt is deposited in the boreal winter when the meridional air flow is intensified and the northern polar vortex is expanded (*2, 13*). Enhanced winterlike meteorological conditions in the South Pacific and North Atlantic therefore appear to be consistent with increased sea-salt concentrations at both of these sites. Na^+ is the most conservative sea-salt species in the Siple Dome and GISP2 records (*14*) and therefore provides the best single-species representation of changing sea-salt aerosol concentration.

The onset of LIA conditions in the GISP2 Na^+ record at ~1400 A.D. is abrupt [within ~20 years (*2*)] (Fig. 2). The record implies that this was the most dramatic change in atmospheric circulation (*2*) and surface temperature conditions (*15*) in the last 4000 years. Siple Dome Na^+ values also began to increase above the 1150-year mean at ~1400 A.D. (*16*). It appears (Fig. 2) that LIA conditions began ~28 years earlier at Siple Dome than at GISP2 (*16*). This offset is close to the combined dating error of the two records at that depth (estimated to be 12 to 20 years). Therefore, although it is possible that the difference is real, we conclude that changes in atmospheric circulation occurred abruptly and synchronously in the South Pacific and North Atlantic at ~1400 A.D.

Both the Siple Dome and GISP2 Na^+ records contain significant decadal-scale variability during the LIA. It appears that regional atmospheric circulation fluctuations were of similar magnitude and timing in both polar hemispheres (*16*). In particular, from 1680 to 1730 A.D., Na^+ concentrations were high in both records. During

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this period, summer temperatures were the lowest they had been in the last 500 years in both the Northern and Southern Hemispheres [1579 to 1730 A.D. (*7*)], and GISP2 biannual summer and winter $\delta^{18}O$ records were the most negative (*15*). In addition, during this period, vertical mixing in the oceans increased and sea surface temperatures decreased (*17*). Instrumental records from England and Switzerland, however, indicate that temperatures were warmer in the early 1700s (*6*). These records highlight that spatially variable temperature estimates are related to increased atmospheric circulation. The period 1680 to 1730 A.D. corresponds to the Maunder sunspot minimum (Fig. 2) (*18*). The similarity in timing between significant events in each record is intriguing; however, a mechanism linking them is unclear.

Further evidence that the ASL was a deep low during the LIA comes from an Antarctic Peninsula (Palmer Deep; 64°52′S, 64°13′W) magnetic susceptibility record (*19*), which shows that ocean mixing depths increased and productivity decreased. Both are related to increased wind speeds beginning at ~1400 A.D. (*19*). The marine core site is within the band of westerlies that is associated with the ASL (*9*). In addition, an Antarctic Peninsula (Siple Station; 75°55′S, 84°15′W) ice-core record indicates decreased microparticle concentrations during the LIA (*20*). Precipitation removes dust; therefore, during times of stronger cyclonic activity, particle concentrations may decrease (*20*). Westerlies bring most of the air to Siple Station; thus, the microparticle record is likely recording increased ASL strength during the LIA.

Ice-core $\delta^{18}O$ records have been used to imply that during the LIA, West Antarctica was warm whereas East Antarctica was cold (*20*). Analysis of modern meteorological conditions indicates that surface temperature anomalies are inverse between South Pole and Siple Station during times when atmospheric circulation increases (*20*). Storm activity at a particular site is generally associated with warmer temperature, so that during times of increased cyclonic activity, the temperature (and $\delta^{18}O$ values) may increase at sites that are heavily influenced by marine air masses such as the Antarctic Peninsula and portions of West Antarctica (*20*).

Enhanced zonal and meridional circulation in the polar regions during the LIA may also have affected mid- and low-latitude circulation. Stine (*21*) has provided evidence that precipitation increased (vegetation submergence) at ~1400 A.D. in California and Patagonia, possibly caused by shifts in the latitude belt of the westerlies. African lake level and diatom records (*4*) and equatorial ice-core dust records (*3*) suggest that aridity and wind speeds increased there during the LIA, related to increased zonal circulation. Changes in Sargasso Sea surface temperatures, salinity, and nutrient pumping have been linked to stronger westerlies and southwestward shifts in storm tracks during the LIA (*22*).

In searching for the cause of the LIA, we see no direct connection between LIA atmospheric circulation and insolation at this time. Insolation (*23*) at the core site latitudes is opposite in trend over the past 1200 years, and changes occurring just before and during the LIA were small. The LIA contained the most recent period of low solar output [Maunder, Spörer, and Wolf solar activity minima triple event (T_4) (*18*)] (Fig. 2). T_4, however, began at ~1300 A.D., ~100 years before the onset of LIA conditions in our Na^+ records. CO_2 decreased 6 ppb in the Law Dome, Antarctica, ice core between 1550 and 1800 A.D. (Fig. 2), which, on the basis of modeling results, would produce a global cooling of 0.13° to 0.21°C (*24*). Estimates of LIA cooling (*1*) are an order of magnitude greater (1° to 2°C), and the LIA started ~150 years earlier (Fig. 2). Major volcanic activity evidently did not increase in the last 600 years (*25*). Only two major volcanic events were recorded in the Siple Dome and GISP2 excess SO_4^{2-} ($xsSO_4^{2-}$) (*25*) records, the 1815 A.D. (Tambora) and 1259 A.D. eruptions (Fig. 2). Thus, no single factor appears to be responsible for bipolar changes during the LIA. Therefore, it likely involved complicated and nonlinear interactions of a number of forcing mechanisms acting together (*2*, *26*).

Although the gradual atmospheric warming during the 20th century (~0.5°C) is almost certainly linked to anthropogenic activity (*27*) and provides a definite end to LIA cooling (*1*), other components of the climate system may still be responding to LIA perturbations. As evidence, Sargasso Sea and Santa Barbara Basin surface temperatures have not fully recovered from LIA minima (*22*, *28*). In our records, Na^+ levels in modern (20th century) sections of each

Fig. 1. Location map for GISP2 (Greenland) and Siple Dome (Antarctica).

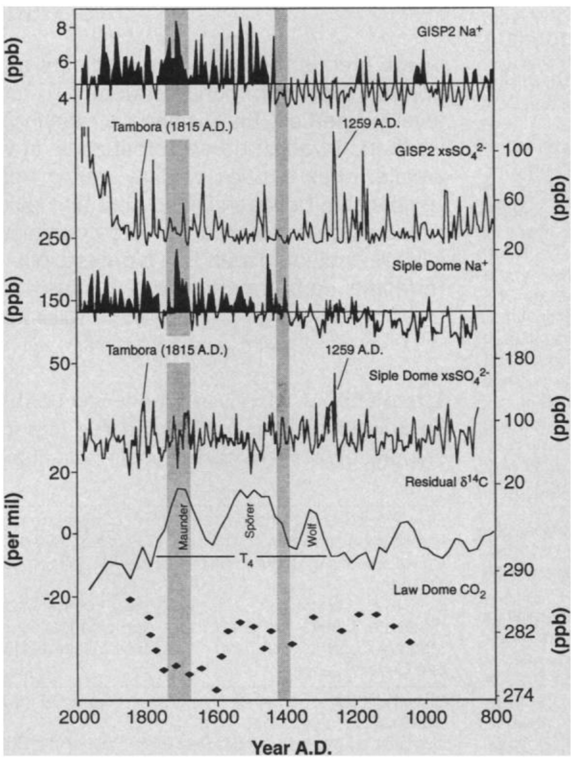

Fig. 2. Comparison of GISP2 and Siple Dome ice-core records with climate forcing factors. The GISP2 and Siple Dome Na^+ and $xsSO_4^{2-}$ (*31*) records (in parts per billion) were resampled to 5-year intervals (the lowest common resolution in both records is ~3 years). Two time periods discussed in the text are highlighted: 1680 to 1730 A.D. (period of coeval Na^+ increase in Siple Dome and GISP2 records) and 1399 to 1427 A.D. (onset of LIA conditions). Two prominent volcanic events at 1815 A.D. [Tambora (*25*)] and 1259 A.D. [possibly El Chichón (*25*)] were used to confirm the Siple Dome annual layer counting and to correlate with the GISP2 record. The obvious $xsSO_4^{2-}$ increase during the last century in the GISP2 record, attributed to anthropogenic emissions, is notably absent from the Siple Dome and other Antarctic $xsSO_4^{2-}$ records (*25*). Other potential climate forcing factors include solar activity [$\delta^{14}C$ residual series (*18*)] and CO_2 [the scale has been expanded to highlight LIA changes and does not include 20th century values (*24*)].

core are within the range of variability observed during the LIA (Fig. 2) (*10, 29*). Regardless of the date chosen for its termination, the LIA was one of the shortest cold intervals of the last 110,000 years (*30*) and was substantially shorter than some other major Holocene rapid climate change events (*2*). We suggest it is possible that, in terms of polar atmospheric circulation, conditions common during the LIA may have persisted into the 20th century and may still persist.

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The Influence of Island Area on Ecosystem Properties

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Island area is frequently a major determinant of the species composition of biological communities; community structure, in turn, often has important effects on ecosystem-level properties. Fifty islands of varying area were selected in an archipelago in the northern Swedish boreal forest zone, in which larger islands burn more frequently than smaller ones through wildfire arising from lightning strike, thus inducing a significant relationship between island area and plant species composition. This relationship was found to be a major factor in determining several ecosystem-level properties of these islands, including standing biomass, plant litter decomposition, nitrogen mineralization, terrestrial carbon partitioning, humus accumulation, and plant nitrogen acquisition.

Gradients of island area have frequently been used to help understand the factors responsible for structuring ecological communities (*1*), and it is apparent that the area of islands is important in regulating the occurrence and abundance of component species (*2*) as well as their interactions (*3*). There is an increasing awareness that individual species effects in communities are important determinants of ecosystem-level properties and, consequently, of functioning of the ecosystem (*4*). Therefore, it is expected that islands with different areas and thus different species compositions would contain different ecosystem-level attributes (*5*). However, there have been few attempts at using

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