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### Permalink

<https://escholarship.org/uc/item/1d505252>

### Journal

Polar Geography, 23(2)

### ISSN

1088-937X

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### Publication Date

1999-04-01

### DOI

10.1080/10889379909377669

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Peer reviewed

# INCREASING NORTH ATLANTIC CLIMATE VARIABILITY RECORDED IN A CENTRAL GREENLAND ICE CORE<sup>1</sup>

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*Abstract:* Greenland ice-core data show that the multiannual variability in North Atlantic climate has been increasing in the latter part of the Holocene. Statistically significant trends were established before the Industrial Revolution. A general inverse correlation exists between variability and temperature, and may be linked to North Atlantic oceanic heat transport.

## INTRODUCTION

Much climate research is focused on prediction of changes in mean conditions, and studies of paleoclimatic variability often are designed to seek periodicities that reveal the active processes controlling average climate. Total climate variability also is of interest (Houghton et al., 1995), because adaptation to changing climates involves economic costs regardless of whether the changes were caused by "signal" or "noise." Indeed, climate changes and weather extremes that occur more rapidly than the few-decades time scale of economic discounting are likely to be more important economically than slower trends over centuries (e.g., Watson et al., 1996).

Assessing climate variability of the past is complicated by the difficulty in obtaining long, high-resolution records with stable baselines. Any paleoclimatic data reflect the complex interplay of the "recorder" with local and regional climate, which in turn can respond to changes over larger areas. We wish to learn about climate changes

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<sup>1</sup>We thank the GISP2 Science Management Office; the 109th New York Air National Guard; the Polar Ice Coring Office; the National Ice Core Laboratory; the National Science Foundation Office of Polar Programs; numerous colleagues at GISP2, GRIP, and elsewhere; two reviewers; and the editor. RBA also thanks the D. & L. Packard Foundation for partial funding.

over significant areas rather than about details of interaction between local climate and a variable "recorder."

Fortunately, ice-core records such as those from central Greenland provide the desired high time resolution over long times, and record many climatic variables with considerable fidelity (e.g., Mayewski and Bender, 1995). Central regions of the ice sheet have changed little over the last glacial-interglacial cycle (e.g., Cuffey and Clow, 1997; Raynaud et al., 1997), so the paleoclimatic records are not greatly complicated by changes in the "recorder." Numerous studies have demonstrated strong linkages between ice-core data and local climate conditions over the coring site, and between those local conditions and climate in broader regions (e.g., Dibb and Jaffrezo, 1997; White et al., 1997; Appenzeller et al., 1998). The linkages are not perfect, of course, but strong signals are present and interpretable (e.g., Mayewski and Bender, 1995).

Snow accumulation reflects conditions in central Greenland, and the position or strength of the storm track to central Greenland (e.g., Bromwich et al., 1993; Kapsner et al., 1995). Chemical data reflect production and transport from regions around and beyond the North Atlantic basin, and serve as tracers for broad patterns of atmospheric circulation extending well beyond Greenland (Mayewski, Meeker, Morrison et al., 1993; Mayewski, Meeker, Whitlow et al., 1993; Biscaye et al., 1997; Mayewski et al., 1997; Saltzman et al., 1997).

Here, we use ice-core data on snow accumulation and chemistry from a central Greenland ice core to estimate the total variability of elements of the North Atlantic climate during the recent warm interval, the Holocene. Our main finding is that much variability has persisted throughout this warm interval, but that variability reached a minimum during the middle Holocene and has been increasing since. A general inverse correlation between variability and temperatures, especially if inferred winter-time temperatures are considered, suggests a possible linkage of variability to oceanic heat transport.

## METHODS

The Greenland Ice Sheet Project II (GISP2) deep ice core was collected by a U.S. consortium approximately 28 km west of the summit of the Greenland ice sheet, at 72.6°N Latitude, 38.5°W Longitude, and 3200 m elevation (Mayewski, Wumkes, et al., 1994). Mean annual (20 m) temperature is approximately -31.4°C, and accumulation is about 0.24 m ice/year (Alley and Anandakrishnan, 1995). At the same time, the Greenland Ice Core Project (GRIP) core was collected at the summit of the ice sheet by a European consortium. Comparisons between the two cores<sup>2</sup> show remarkably good agreement in ice younger than ~110,000 years.<sup>3</sup>

GISP2 chemical data were collected for approximately bi-yearly samples throughout the Holocene. Clean sampling, numerous blanks, and other now-standard protocols were used to insure data quality (e.g., Mayewski, Meeker, Morrison, et al., 1993; Mayewski, Meeker, Whitlow, et al., 1993). Accumulation was determined as the distance between successive summer peaks identified visually (Alley et al., 1993; Alley,

<sup>2</sup>See papers in *Journal of Geophysical Research*, v. 102, no. C12, 1997.

<sup>3</sup>Ice-flow disturbances complicate interpretation of older ice (Alley, Gow et al., 1995).

Shuman et al., 1997; Spinelli, 1996; cf. Meese et al., 1997), corrected for measured densities and for ice-flow thinning (Alley et al., 1993; cf. Cuffey and Clow, 1997). Accumulation rates were linearly interpolated to match the chemical sampling intervals for comparability of results.

Chemical concentrations in the ice reflect atmospheric loading, but fluctuations of concentrations in the ice may be magnified because colder, dustier times typically have reduced snow accumulation and hence less dilution of the chemicals. Corrections for this effect can involve simple models or robust multivariate analytical techniques (cf. Mayewski et al., 1997). We chose to adjust the chemical data for accumulation-rate changes, reducing fluctuations in chemical time series, following Alley, Finkel et al. (1995) and Alley, Mayewski et al. (1997). For the Holocene, the adjustments are small enough that casual inspection of the adjusted and original time series shows no differences.

We focus especially on sodium, calcium, methanesulfonate (MSA), and snow accumulation, although for completeness we also report results for nitrate, ammonium, potassium, and magnesium. Sodium is primarily from sea salt; changes in sodium in Greenland records are related to changes in vigor of atmospheric circulation or distance from marine sources. Calcium is primarily from continental dust; changes in calcium in Greenland records are related to changes in dust availability, dryness, and transport vigor from continental regions beyond Greenland and probably beyond the North Atlantic basin (e.g., Mayewski, Meeker et al., 1994; Biscaye et al., 1997; Mayewski et al., 1997). Methanesulfonate is produced by certain phytoplankton; records in Greenland depend on productivity in the typically cold-water source regions and on windiness and atmospheric chemistry between the source regions and the GISP2 site (e.g., Whung et al., 1994; Saltzman et al., 1997).

Time-series analyses of these data have revealed clear trends, periodicities, and events (e.g., O'Brien et al., 1996; Mayewski et al., 1997; Saltzman et al., 1997; Stager and Mayewski, 1997). Here we calculate the evolutionary pattern of the total variability. A general and robust measure of variability is the root-mean-square deviation of some quantity from its typical or mean value, as expressed by the standard deviation. Often, it is more instructive to normalize this variability by dividing by the mean value to obtain the coefficient of variation. We have considered other measures of variability, but restrict attention to standard deviations and coefficients of variation for simplicity and because of their robust nature.

We calculated standard deviations and coefficients of variation in a rectangular window (all points in the window are given equal importance) of chosen length, which we then shifted along the Holocene time series in steps of one-tenth the window length. We assigned the variability in a window to the age of the midpoint of the window. This procedure was then repeated for other window lengths. Results that are largely independent of variation in window length are considered to be of interest. We assess significance of these results using *F*-tests and regression analyses. Preliminary results of the accumulation-rate variability were given in Alley et al. (1999); here we provide additional details and comparisons.

Previous workers have suggested that variability is linked to site temperature (e.g., Ditlevsen et al., 1996; Mayewski et al., 1997; Alley et al., 1999). Several methods of assessing paleotemperatures have been developed. The most commonly used is the isotopic ratio of accumulated snow. The validity of this indicator is discussed at

considerable length by Jouzel et al. (1997). For the central Greenland ice cores, several site-specific calibration techniques have been used to improve isotopic paleothermometry (Cuffey et al., 1994; 1995; Johnsen et al., 1995; Cuffey and Clow, 1997; Dahl-Jensen et al., 1998; Severinghaus et al., 1998), so that rather confident paleothermometry from isotopes and other indicators is possible. We have obtained mean annual temperatures by using the calibrations of Cuffey and Clow (1997) and Johnsen et al. (1995) to express isotopic values as temperature deviations from recent levels, and then averaging these similar GRIP and GISP2 values to obtain the curve in Figure 2. Variability of isotopic ratios has been assessed for the GISP2 (Stuiver et al., 1995) and GRIP cores (Ditlevsen et al., 1996), and further analyses of GISP2 data are planned.

Summertime temperatures have been estimated independently based on frequency of occurrence of the rare melt features in the core (Alley and Anandakrishnan, 1995). The theoretical basis for melt thermometry requires more assumptions than, and lacks the high time resolution of, calibrated isotopic paleothermometry; hence, less confidence can be placed in the summertime records.

We calibrated the melt thermometer for the Holocene of central Greenland by interpolating between warmer and colder sites with higher and lower frequency of occurrence of melt layers over the most recent centuries. We also used measured temperature variability during summer at GISP2 and a simple model for dependence of melting on temperature (Alley and Anandakrishnan, 1995). Agreement of these spatial and temporal calibrations improves our confidence. One main assumption is that changes in melt frequency reflect changes in mean summertime temperature rather than changes in variability of summertime temperature. The relative similarity of variability levels for many climate variables between the time of peak melting and the recent times of reduced melting can be used post-facto to partially justify the analysis. Somewhat lower variability of other climate variables during the decrease in melt frequency during the later Holocene suggests caution in interpreting details of the trend.

To obtain a crude estimate of wintertime temperatures, we treat mean annual temperature as the average of summer and winter values. This is clearly an oversimplification, as it ignores fall and spring. We thus view this as a tool for generating hypotheses, but not for testing them.

## RESULTS

The main outcomes of our calculations are presented in Figures 1 and 2, and in Table 1. In Figure 1, we use a color scale to represent coefficients of variation as a function of window length and age for four selected variables: snow accumulation, sodium, calcium, and methanesulfonate (MSA). Window-to-window changes are larger for shorter windows, as expected, but otherwise it is evident that results are not strongly dependent on window length. The clear result for all four indicators is that a highly variable early Holocene was followed by a less-variable middle to late Holocene, and then by an increase in variability toward today, especially over the last one to two millennia. Increases were established for most variables well before the Industrial Revolution.

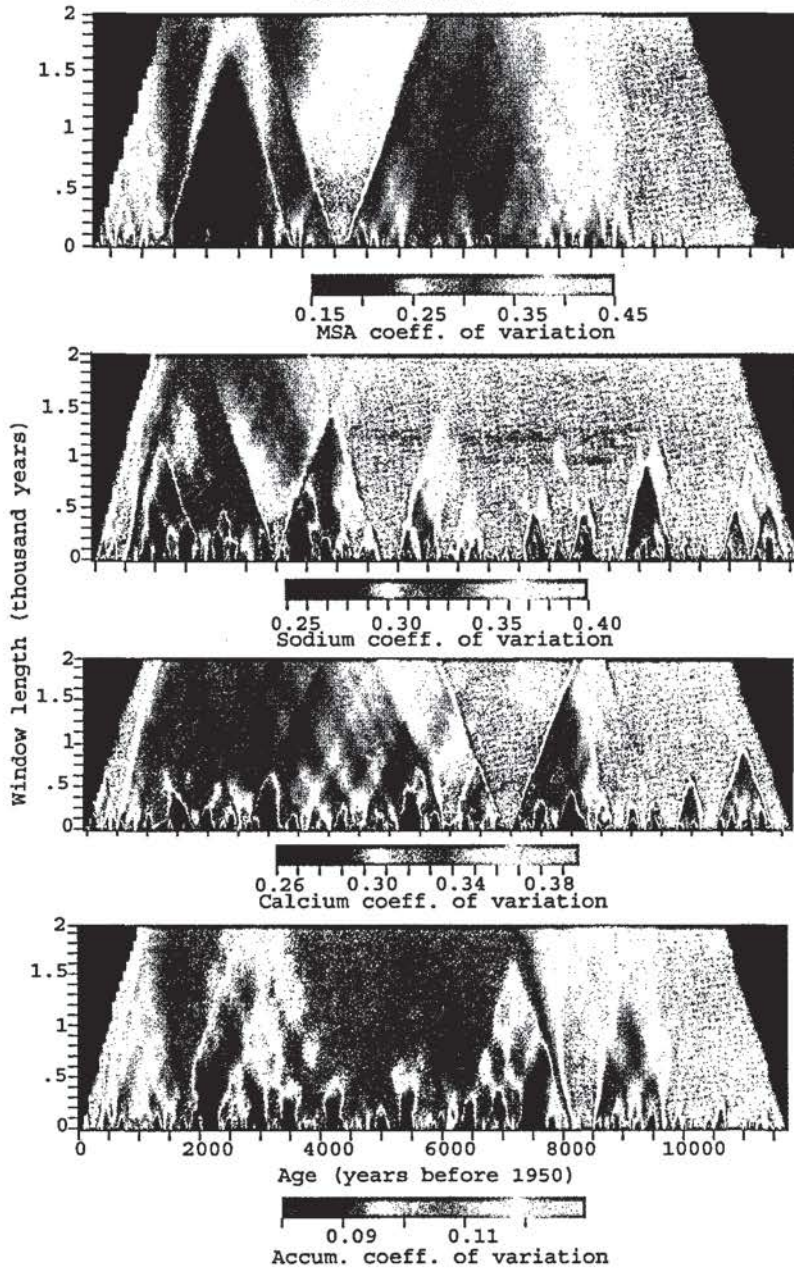
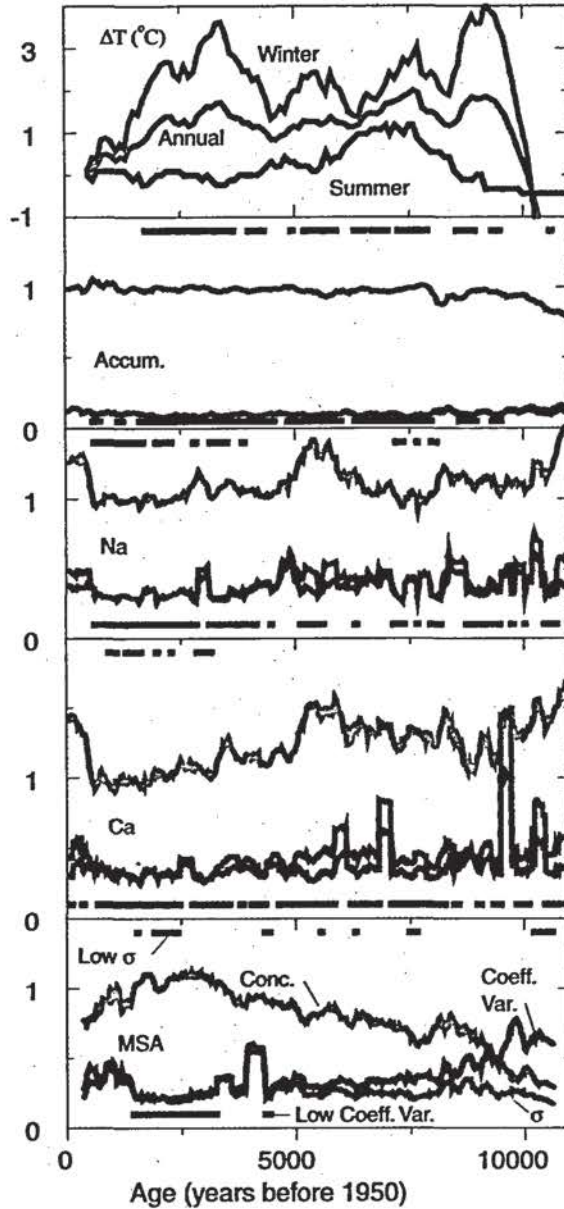


Fig. 1. Coefficients of variation as a function of window length and time in the Holocene, from top to bottom, for MSA, sodium, calcium, and snow accumulation. The color scale shows the variability, with redder color indicating higher variability. The black regions at each end for longer windows indicate no data because windows centered on these times would extend into the future or into the pre-Holocene. The color scale was adjusted for each panel to display the full range of variability, as indicated on the scale bars. The general decrease and then increase in variability toward the present are exhibited clearly. The sampling lengths chosen caused a few of the earliest-Holocene, small-window grid cells to lack sufficient MSA data for confident display, as shown in black.



**Fig. 2.** Data on level and variability of accumulation, sodium, calcium, and MSA for approximately 200-year windows in the Holocene, together with temperature estimates (top panel). Shown in the lower four panels are the snow accumulation and the estimated atmospheric loading of sodium, calcium, and MSA, normalized by typical values in the millennium before the Little Ice Age (upper curves), and the standard deviation and coefficient of variation (as indicated) for these values. The lower four panels also have black bars showing times during which the standard deviation (top) and coefficient of variation (bottom) were not significantly larger than the minimum value reached during the Holocene, based on  $F$ -tests at the 99% confidence level. Temperature and MSA curves stop just before the present because of data availability and averaging lengths chosen.

TABLE I

Timing of Variability Extrema<sup>a</sup>

Indicator	Standard deviation		Coefficient of variation	
	Min. time, abp	Conf. incr. to present, pct.	Min. time, abp	Conf. incr. to present, pct.
Accum.	2,115	>99	2,115	>99
MSA	10,624	99	2,269	>99
Na <sup>+</sup>	1,992	>99	2,837	>99
Cl <sup>-</sup>	1,624	80	11,343	<50
Ca <sup>++</sup>	1,598	>99	2,978	>99
Mg <sup>++</sup>	605	>99	8,091	<50 <sup>b</sup>
K <sup>+</sup>	9,967	90	9,967	<50 <sup>c</sup>
NH <sub>4</sub> <sup>+</sup>	194	80	2,861	>99
NO <sub>3</sub> <sup>-</sup>	2,421	99	2,626	>99

<sup>a</sup>Ages of Holocene minima in variability of paleoclimatic indicators, and the statistical confidence that variability shows an increasing trend from that point to the youngest sample, based on *t*-tests of the slopes from linear regression. Results are shown for both standard deviations and coefficients of variation, for windows of approximately 220 years length or approximately 110 samples.

<sup>b</sup>Second-lowest value at 1820 abp gives >99% confidence of increase to present.

<sup>c</sup>Second-lowest value at 837 abp gives >99% confidence of increase to present.

Figure 2 shows the time series, the standard deviation, and the coefficient of variation for the same four indicators for 222-year-long windows. The values (accumulation rate and estimated atmospheric loadings) have been normalized by the pre-Little Ice Age level to obtain curves that plot close to unity. Times during which the standard deviation was not significantly different from the minimum level it achieved during the Holocene, based on an *F*-test with >99% confidence, are indicated by black bars near the top of each panel, and times during which the coefficient of variation was not significantly different from its minimum Holocene value with >99% confidence are indicated by the black bars near the bottom of each panel.<sup>4</sup> Crudely, this provides a division between "lower-variability times" (black) and "higher-variability times" (white) for standard deviations and coefficients of variation.

The earliest and the most recent one to two millennia of the Holocene tend to fall in the higher-variability range for indicators plotted and others not shown. All indicators include lower-variability times during the middle Holocene, so there have been decreases and then increases in variability toward today. If variability were randomly distributed in time, the observed common occurrence of higher variability in recent times would be statistically unlikely. This can be emphasized further by conducting *t*-tests on slopes of regression lines of variability versus time. If we construct such lines from the time of minimum variability to the youngest samples, using degrees of freedom appropriate for non-overlapping windows, we find in almost all cases (Table 1)

<sup>4</sup>Uncertainty in the mean and in the standard deviation contributes similar uncertainty to the coefficient of variation.



that there is a highly significant increasing trend of variability toward today. In most cases, variability has not yet returned to the early Holocene levels; the anthropogenic effect on nitrate is a notable exception. We must note that in most cases a regression line from the highest level of variability reached during the Holocene to recent shows a significant downward trend, but these lines provide a statistically significantly poorer fit to the recent data.

## DISCUSSION

Many possible causes can be envisioned for changes in climate variability in Greenland and surrounding regions of the North Atlantic basin. During the early Holocene, the downwind effects of the remnants of the Laurentide ice sheet in Canada may have been significant (Stuiver et al., 1995). However, the apparent decrease in variability through the mid-Holocene seems to lag the shrinkage of the Laurentide ice significantly (Dyke and Prest, 1987). The Laurentide ice in Hudson Bay collapsed about 8400 years ago (Barber et al., 1999), leaving a small and shrinking ice cap well before minimum Holocene climate variability was achieved by most indicators in central Greenland. The Laurentide ice thus may have contributed to early Holocene variability, but is insufficient by itself to explain the entire signal.

The strength of the ice-albedo feedback, in which colder conditions cause expansion of highly reflective snow, sea ice, and glaciers that cause further cooling, is greater during cold times than warm and tends to zero as the area of snow and ice tends to zero; hence, cooling is expected to increase variability. Indeed, previous workers (Stuiver et al., 1995; Ditlevsen et al., 1996; Mayewski et al., 1997) have shown the strong inverse correlation between climate variability and temperature over glacial-interglacial cycles, with variability greater during colder times (although with possibly reduced climate variability at millennial frequencies during the coldest times; Alley and Clark, 1999).

The ice-albedo feedback is linked to general wintertime conditions. Especially in the ocean around Greenland, extensive sea ice develops when the North Atlantic is cold and North Atlantic heat transport is low; enhanced heat transfer in the North Atlantic reduces sea-ice extent and the strength of the ice-albedo feedback. For Greenland, North Atlantic freezing essentially increases continentality. We speculate based on general comparison of continental versus marine climates that the farther heat and moisture must be transported by the atmosphere, the more variability can be introduced. North Atlantic ocean heat transport is more important in the total heat budget of the winter than of the summer, so one might expect that colder times, and especially times with colder winters, would be more variable.

In light of these considerations, we calculated correlations between the climate variability and reconstructed summer, winter, and mean annual temperatures. We wish to emphasize that sufficient uncertainties remain in reconstructed summer and winter temperatures that the results of this regression must be considered suggestive rather than conclusive. Results are given in Table 2.

In no sense do the reconstructed temperatures allow us to predict climate variability accurately with high confidence (low correlation coefficients). However, we find many highly significant correlations. The general trend is for colder times to correlate with greater variability in the snow accumulation and in wind-blown marine (MSA,

TABLE 2

Variability-Temperature Correlations<sup>a</sup>

Indicator	Temperature					
	Winter		Mean annual		Summer	
	<i>r</i>	Conf., pct.	<i>r</i>	Conf., pct.	<i>r</i>	Conf., pct.
Accum. <sup>b</sup>	-0.58	>99	-0.62	>99	-0.37	>99
MSA	-0.29	>99	-0.39	>99	-0.38	>99
Na <sup>+</sup>	-0.06	75	-0.04	65	0.09	85
Cl <sup>-</sup>	-0.08	75	-0.01	65	0.13	95
Ca <sup>++</sup>	0.07	75	0.03	65	-0.15	95
Mg <sup>++</sup>	-0.09	80	-0.13	90	-0.23	97
K <sup>+</sup>	-0.48	>99	-0.43	>99	-0.13	95
NH <sub>4</sub> <sup>+</sup>	-0.15	90	-0.03	65	0.45	>99
NO <sub>3</sub> <sup>-</sup>	0.10	90	0.09	80	0.01	50

<sup>a</sup>Correlation coefficients, *r*, and confidence level that the sign of the correlation coefficient has been determined correctly, between coefficients of variation for selected climate variables and estimates of temperatures in central Greenland. Negative *r* indicates that variability increases as temperature drops.

<sup>b</sup>Accumulation.

Na<sup>+</sup>, Cl<sup>-</sup>) and continental (K<sup>+</sup>, Mg<sup>++</sup>, Ca<sup>++</sup>) indicators; there also may be a tendency for warmer times to correlate with higher variability for the middle- to low-latitude or continental biogenic indicators NO<sub>3</sub><sup>-</sup> and NH<sub>4</sub><sup>+</sup> (Mayewski, Meeker, Morrison et al., 1993; Mayewski, Meeker, Whitlow et al., 1993; Mayewski et al., 1997). Na<sup>+</sup> and Cl<sup>-</sup> show a slightly stronger negative correlation with derived winter temperature than with mean-annual temperature (a suggestive though not conclusive observation) probably because the input of these marine species is tied primarily to winter-time circulation as inferred from the maxima in concentration (flux) during this season (Mayewski et al., 1990). There is sufficient covariation of mean-annual, summertime, and wintertime temperatures to preclude any strong conclusions in any event. The inverse correlation between snow-accumulation variability and temperature, and especially with mean-annual and wintertime temperatures, is suggestive, with correlation-coefficient magnitudes of 0.6. We thus hypothesize that in the Holocene, colder times and times of increased variability have occurred together, with both possibly linked to reduced North Atlantic ocean heat transport.

Strengthening this link, Kreutz et al. (1997) found in glaciochemical records from West Antarctica and GISP2 for the last 1200 years that the generally cold Little Ice Age showed generally enhanced variability compared to warmer, preceding times. Interestingly, the warming of the 20th century has not reduced the glaciochemical variability to pre-Little Ice Age levels (red in the youngest data on the lowermost rows of Fig. 1), suggesting continuing persistence of Little Ice Age atmospheric conditions (Kreutz et al., 1997) or offsetting effects in which some other factor has increased climate variability as Little Ice Age conditions have waned.

## CONCLUSIONS

A simple analysis of Greenland ice-core data shows that there have been significant changes in variability during the Holocene. In general, a highly variable early Holocene was followed by a less variable (although still quite variable) mid-Holocene, and then by an increase in variability toward the present. The trends toward the present are statistically significant; based on extrapolation of this, the simplest hypothesis is that the natural trend is toward increasing variability in the coming centuries to millennia.

In accord with previous workers, we hypothesize that the extent of ice in and around the North Atlantic is important in controlling variability, and that this is at least in part linked to ocean heat transport. We thus expect that snow accumulation and wind-blown marine and continental indicators would show enhanced variability during colder times, and especially during times with colder winters. The Holocene data support a linkage between higher variability and colder conditions, and can be interpreted as providing weak support for importance of colder winters. However, occurrence of high variability in this century suggests that additional factors are active; one cannot rule out the possibility that human perturbations of the climate system are important. If higher oceanic heat transport reduces North Atlantic climate variability, the possibility that human activities could decrease ocean heat transport (e.g., Stocker and Schmittner, 1997) leads to the hypothesis that climate variability may increase in the North Atlantic and surrounding regions.

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