JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 102, NO. D10, PAGES 11,219-11,224, MAY 27, 1997

Observation of atmospheric and climate dynamics from a high resolution ice core record of a passive tracer over the last glaciation

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Abstract. Here we present a temporal analysis of diluted calcium from the Greenland Ice Core Project Summit ice core over a length corresponding to the duration of the last glacial period (92 - 8 ka). Our analysis suggests that this signal can be split into two distinct temporal components whose dynamics are characterized by respective timescale regimes. Timescales longer than approximately 200 years show a strong negative correlation with the temperature proxy δ^{18}O signal. This we interpret as a result of the temperature dependence of processes governing source area efficiency. At faster timescales, $\leq$ 200 years, correlation with the temperature proxy is significantly weakened, while its variability or mean absolute deviation is negatively correlated with the δ^{18}O; this we believe is a sign of the turbulent nature or "storminess" of the atmosphere during the glacial climate. Furthermore, this component of the signal displays intermittency and multifractality supporting our interpretation of an observation of atmospheric dynamics. This then provides a signal of atmospheric and climate dynamics back to 92 ka.

Introduction

Comparison between chemical deposits transported by the atmosphere (tracers) and the temperature proxy δ^{18}O (Figure 1a) in ice cores has revealed that previously identified climate oscillations [*Dansgaard et al.*, 1993] are also present as features in these tracer time series [*GRIP Members*, 1993]. Dynamics of the climate system are characterized by many different physical processes operating over a wide range of timescales [*Peixoto*, 1992]. Changes in these processes during the glacial climate are reflected in the profiles of chemical deposition over Greenland [*GRIP Members*, 1993]. With the deposition over this area strongly dependent on local source area conditions and transport processes in the atmosphere, the climatic variability of these two components will influence the temporal dynamics embedded within the tracer signals. Retrieval of this dynamical information may reveal some of the important physical characteristics of climate change over a wide range of timescales.

Ice core records thus provide a natural, temporal probe from which have been extracted various time series of heavy stable isotopes [*Johnsen et al.*, 1989], trace elements [*Herron and Langway*, 1985], and continental dust [*Hammer et al.*, 1985]. The δ^{18}O isotope, as a proxy for temperature covering the Wisconsin and Holocene periods, indicates that the climate system has undergone a number of dramatic oscillations in the North Atlantic/Arctic region [*Dansgaard et al.*, 1993]. Recently, the signal has been shown to contain a range of characteristic timescales [*Ditlevsen et al.*, 1996] revealing differences in atmospheric and climate dynamics between the Wisconsin and Holocene periods.

Data

Calcium, originating from terrestrial dust, can be considered a passive tracer in atmospheric flow and has been retrieved with a temporal resolution $\leq \frac{1}{2}$ year over the depth interval 1300 - 2790 m corrsponding to 8 - 92 ka (K. Fuhrer et al, Causes of dust variability in the GRIP (Greenland) ice core in the last 100,000 years, submitted to Nature, 1996). The calcium concentration (Figure 1b) is dense and noisy during cold deep glacial periods while low and relatively quiet during the warmer interstadials. Such features are puzzling for two reasons. First the main source area for dust over Greenland today is the North American plains which were largely ice covered during the last glacial period and therefore inefficient as a dust source [*Hammer et al.*, 1985]. Second the precipitation rate was much lower during the colder glacial climate [*Alley et al.*, 1993] reducing the quantity of wet-deposited dust (dry deposition leaves thin layers in the profile, representing a minute fraction of the dust). *Dansgaard et al.* [1989] have qualitatively attributed this to dramatic shifts in weather patterns from dry, stormy conditions

Paper number 97JD00029
0148-0227/97/97JD-00029$09.00

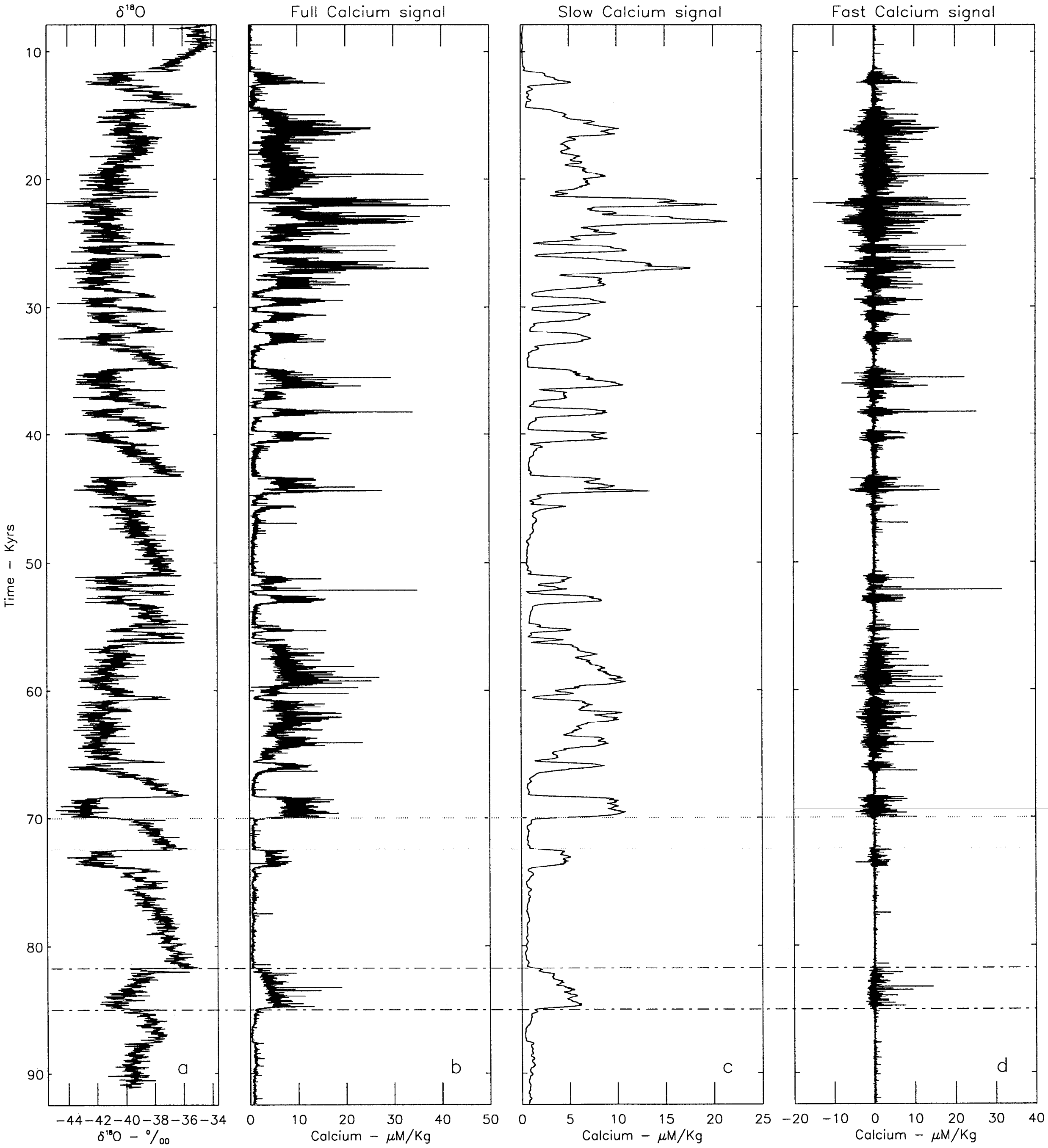

Figure 1. Time series of (a) δ^{18}O and (b) calcium for the period 92 - 8 ka, equivalent to a depth interval of 1300-2700 m, from the GRIP summit ice core. The ice core has been dated using the δ^{18}O signal, which as a proxy for temperature reveals the seasonal cycle where annual resolution is possible. Dating is then found through counting the annual layers back to 14 ka (1600 m); an ice flow model is used for the remainder, producing accurate dating back to 100 ka. In this analysis, only high resolution calcium data from the accurately dated glacial period are used, but it should be noted that the Holocene ice contains calcium of the order of or less than that observed at 9 - 8 ka. The Calcium data are obtained by measuring the chemical contents in continuously melted samples of the core with the highest resolution of 10 mm, at a depth of 2700 m, corresponding to a temporal resolution of approximately $\frac{1}{2}$ year. For homogeneity, the signal has been averaged onto a $\frac{1}{2}$ year time grid resulting in 169,197 points covering the last glacial period. The best obtainable resolution for δ^{18}O over the same period is 15 years corresponding to 5550 points. A running mean of these full signals defines a temporal "average" or climatology for separation times T, producing (c) slow components of the full signal at $T_c = 200$ years, the residual of which is (d) the fast component. A warm and cold period during the Wisconsin glaciation is highlighted by the grey dashed and black dot-dashed lines respectively.

to more humid, calmer states, perhaps more reminiscent of presentday conditions.

The dust content is governed by source area dynamics and variations in transport properties of the atmospheric flow to and around the arctic. Source area conditions are dependent on regional climates and on glaciation and sea level changes [*Peltier*, 1994] for exposed marine shelves acting as "glacial deserts" with falling sea levels e.g. the Bering Straits [*Hammer et al.*, 1985]. *MacAyeal* [1993] has shown through a simple binge/purge model that the sea level could rise abruptly by 3.5 m over 250 years due to large ice-surges [*Bond and Lotti*, 1995], while a drop in sea level will occur at much longer timescales resulting from the slow growth rate (centimeters per year) of glaciers via precipitation. Data from a Barbados coral core [*Fairbanks*, 1990] reveal that prior to the last glacial maximum sea levels were approximately 90 m below present values, roughly the depth of the Bering Straits today. Thus the sensitivity of source regions such as exposed marine shelves to climate change could have a dramatic influence on the volume of dust present in the glacial atmosphere of the northern hemisphere and may explain some of the large-scale changes in the calcium profile.

Dynamics of the storm tracks across the North Atlantic are thought to have had a dominant effect on transport and deposition over Greenland [*Rind et al.* 1986]. In addition, a possible splitting of the jet stream around the Laurentian ice sheet of North America [*Rind*, 1987] may have resulted in the "switching" between two air paths arriving over Greenland [*Newell and Zhu*, 1994], each with possibly different flow characteristics reflected in the tracer transport. Thus air arriving over Greenland could have originated from or passed over different source regions of dust, possessing different transport characteristics during the various climate states.

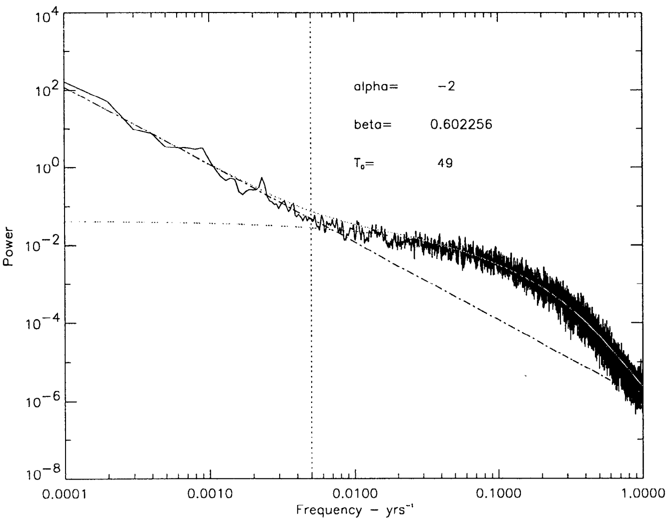

Figure 2. Power spectra for the full calcium signal, calculated using a sliding Hanning window. The typically red noise spectral slope (black dot-dash line, gradient ~ -2) at long frequencies, significantly differs from the stretched exponential fit (dark grey dashed line with fitting parameters $\beta = 0.6$, $f_0 = 1/49$ yr^{-1}) of frequencies with periods shorter than 200 years. The light grey solid line is a result of the combined empirical functions.

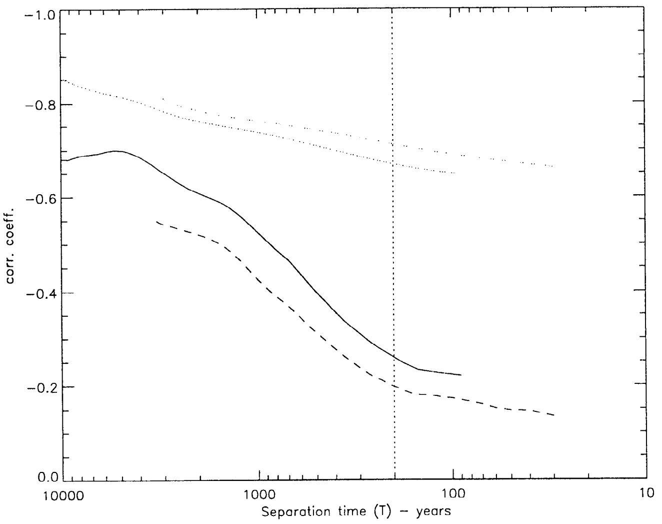

Figure 3. Correlation between the fast components of δ^{18}O and calcium as a function of the separation timescale, T (black lines). The solid line indicates calculations made taking 15 year averages of both signals for the period 92 - 8 ka, while the dashed line is with 5 year averages over the shorter period 56 - 8 ka, the higher-resolution emphasizing the negative correlation cutoff at around 200 years. The grey lines show negative correlation between slow components of δ^{18}O and the fast signal's (Figure 1d) mean absolute deviation (the second order statistic variance, would overweight in favour of the extreme outliers) as a function of separation time T (solid and dashed lines are as before).

Although there is no direct way of separating these features in the calcium deposits, it would be expected that changes in source area extent would take place at timescales that are long in comparison with typical timescales of atmospheric flow.

Spectral Analysis

The power spectrum of the full calcium signal reveals a significant change in its spectral scaling properties at a frequency of $f \sim 1/200$ yr^{-1} Figure 2. Below this point, the signal shows a spectral slope of -2 indicating a simple Markov process as often observed in stochastic climate signals [*Hasselman*, 1976]. At faster timescales the signal can be fitted to the form $P(f) \sim \exp -(f/f_0)^{\beta}$, with $\beta = 0.6$ and $f_0 = 1/49$ yr^{-1}, which has been used to describe spectral properties in the dissipative range (high frequencies) of atmospheric signals [*Sano et al.*, 1989]. An approximate split between the "slow" and "fast" components of the signal can be made by taking the running mean over a time T as the slow component or "climatology" and the residual as the fast component. We will denote T the separation timescale. This corresponds to a low- and high-pass filtering. The resulting slow and fast components of the full signal are displayed in Figures 1c and 1d.

Correlations

Figure 3 displays the correlation between δ^{18}O and the fast elements of the signal as a function of separation timescale, T. The signal at $T = 10$ kyr shows a strong negative correlation which is significantly reduced by $T_c = 200$ years. This breakdown in correlation suggests that longer timescales are a direct result of processes dependent on temperature, while for $T < 200$ years. this direct relationship no longer exists. The slow signal (Figure 1c) we interpret as dynamics of source area efficiency, providing a background level of dust transported in the atmosphere. At these timescales, we expect one of the major mechanisms to be the result of variable sea levels periodically exposing shallow marine shelves at high latitudes, with the potential of acting as new source areas.

The fast component of the calcium signal being uncorrelated with δ^{18}O reveals a linear independence from the slow component of calcium. It is then a nontrivial observation that the amplitudes of the fast signal's fluctuations appear to be dependent on temperature (dashed/dot-dashed regions Figure 1), which can be seen when considering the mean absolute deviation of the full signal around the running mean at $T_c = 200$ years as a new signal. Running means over a period T are then a measure of the fast signals temporal climatology. Correlation between slow components of this new signal and δ^{18}O as a function of T reveals a strong negative correlation over the full spectrum of timescales, (Figure 3). This suggests that atmospheric transport and deposition over Greenland is modulated by temperature, perhaps as a result of changing storm track positions across the North Atlantic between different glacial climate states.

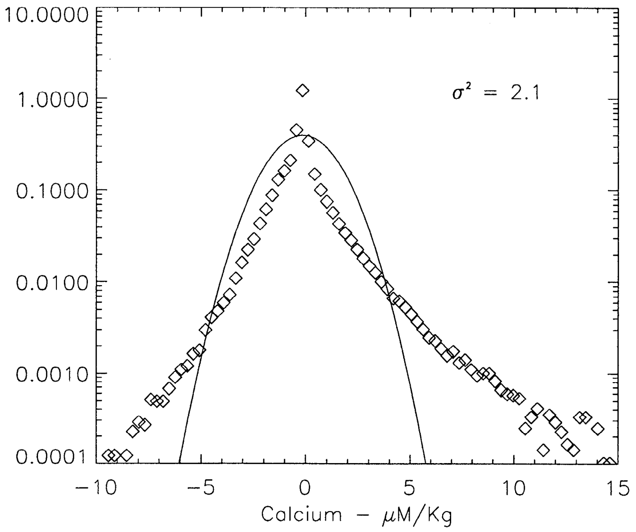

Figure 4. The probability density function (diamonds) on a log-normal plot for the fast component of the calcium signal (Figure 1d). The solid line describes the shape of a Gaussian distribution with variance equal to that of the data. Clearly, the fast signal differs from such a distribution, suggesting that nontrivial dynamics are present.

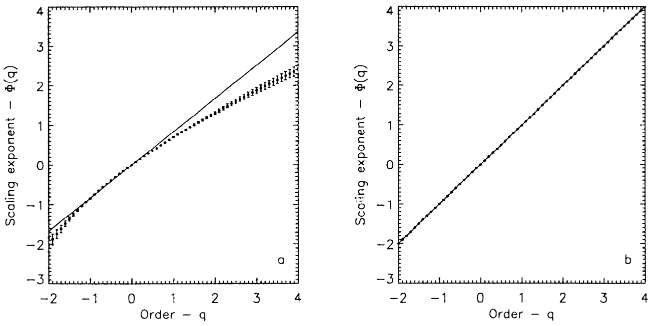

Figure 5. A plot of the scaling exponent $\Phi(q) = qd_{q+1}$ versus q for both (a) fast and (b) slow components of calcium. The $\Phi(q)$ is obtained from the linear regression of $\log\langle p(l)^q\rangle$ on $\log l$ over the respective timescales of the fast and slow components of calcium. The solid lines have the gradient of the base dimension d_0, that is $q = -1$, where a value of $d_0 < 1$ indicates an underlying fractal structure; deviation from this linear relationship at higher orders of q is a signature of multifractality. In Figure 5a $d_0 \simeq 0.83$, and curvature is observed, while in Figure 5b $d_0 = 1.00$, and the linear agreement is trivially maintained for all values of q.

Multiscaling

The fast signal at $T_c = 200$ years (Figure 1d) with a kurtosis around 38 ($\gg 3$) has a probability density function (pdf), Figure 4, which strongly differs from the Gaussian distribution one would expect from a trivial additive noise process. This intermittent nature of the signal suggests [*Antonia et al.*, 1984] that it is generated by a complex dynamics rather than a purely random process, analogous to similar features observed at the dissipation scales of a passive tracer in turbulent flow [*Jensen et al.*, 1992]. Further, such dissipative signals should also possess multiscaling properties which can be determined from the ensemble averaged density function [*Paladin and Vulpiani*, 1987] $\langle p(l)^q\rangle = \sum_{i=1}^{N(l)} p_i(l)^{q+1} \sim l^{qd_{q+1}}$, where d_q is the scaling dimension of a qth order signal with average density p over timescales l. $N(l)$ is the number of intervals of length l covering the full length of the signal. Figure 5 shows the dependence of d_q on q for both the slow and fast components of the Calcium signal. Any noise within the signal has the effect of blurring any nontrivial scaling, which is quantified by the error bars of Figure 5. The slow signal is observed to scale trivially with dimension $d_q = 1$, which is obtained for any in-dependent identically distributed random signal (in one dimension). Positive components of the fast signal, representing periods exceeding the 200 year running mean "background" calcium deposits, display nontrivial scaling (fractal), that is $d_0 < 1$, up to time scales of 200 year duration. The nonlinear dependence of d_q on q is a sign of nontrivial temporal correlation structure of the signal. At present, there appears to be no sign of universality in the form of such functions between different complex systems, thus analogies drawn with the properties of dissipation scales in fluid flow which operate at significantly different timescales to those in the observed calcium signal are currently speculative.

Discussion

Figure 1d reveals that there is a considerable difference in the variability of the fast signal between warm and cold periods. This indicates a change in the dynamical properties of transport mechanisms to Greenland between the two climate states if we accept that the fast fluctuations ($T_c \ll 200$ years) are a result of atmospheric variability with positive components as a signal of intense dust laden storms and negative values as a result of cleaner or more subdued storms. *Kapsner et al.* [1995] point out that a decrease in accumulation over Greenland during periods of major cooling is largely explained by a southerly shift of the storm tracks. They then go on to suggest that although storm frequency to higher latitudes would be reduced, increased temperature gradients would generate stronger, more efficient storms. These would be capable of generating the observed increase of aerosols in ice cores [*Mayewski et al.*, 1993] during such periods. The calcium signal as a passive tracer in atmospheric flow clearly possesses properties consistent with such an interpretation and is a more "direct" signal of the atmospheric state than other proxies.

While the dynamics leading to the observed multiscaling are not fully understood, in view of the above interpretation, we believe the intermittency and multifractal properties of the fast signal contain additional information on transport properties within the glacial atmospheric flow. In drawing an analogy with dissipative systems, the nontrivial temporal correlation structure may be a signature of the energetic or "turbulent" state of the atmosphere. *Ditlevsen et al.* [1996] have shown that atmospheric circulation during the last glaciation was more turbulent than it is today, identified from the pdf structure of the temperature proxy δ^{18}O appearing Gaussian during the Holocene while displaying an intermittent distribution during the last glacial maximum. Thus the calcium signals intermittency for the fast fluctuating components, as a result of the infrequent excursions of storms to Greenland, suggests that it provides an atmospheric signal back to 92 ka while the multiscaling contains important information for further understanding the atmospheric properties between different climate states. If our interpretation is correct, it is remarkable that the nongaussian statistics and scaling properties survive at these timescales which are long in comparison with the typical timescales, days to weeks, of weather systems.

Acknowledgments. We would like to thank K. Fuhrer for sharing with us the ice core data. Thanks to S. Johnsen, H. Svensmark, J.-P. Steffensen, and C.U. Hammer for valuable discussions. The work was partly funded by the Carlsberg Foundation and partly by the Environment Program of the Commission of the European Communities.

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(Received April 2, 1996; revised November 5, 1996; accepted November 5, 1996.)