Millennial climate variability: GCM-simulation and Greenland ice cores

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[1] The low frequency variability of the near surface temperature in a climate simulation is compared with Greenland ice core $\delta^{18}O$ time series during the holocene. The simulation is performed with the coupled CSIRO atmosphere-ocean model under present-day conditions. The variability, analyzed by the detrended fluctuation analysis, reveals power-law scaling of the power-spectrum for frequency f, $S(f) \sim f^{-\beta}$, and long term memory (LTM) given by $\beta > 0$. The near surface temperature shows intense LTM in the North Atlantic south of Greenland, weak LTM in parts of the Antarctic ocean and the tropical Atlantic, and no LTM in the Pacific ocean. The power-law exponent $\beta \approx 0.5$ near Greenland agrees with ice core temperature proxies up to time scales of 1000 years. The LTM of the surface temperature is explained by the high low frequency variability of the zonally averaged streamfunction in the Atlantic with maxima in the Arctic ocean.
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1. Introduction

[2] Observed near surface temperature time series show power-law spectra $S(f) \sim f^{-\beta}$ for frequency f with exponents $\beta = 0\ldots 1$ on time scales beyond one year [*Fraedrich and Blender*, 2003, hereinafter referred to as FB]. In the inner continents spectra with exponents $\beta \approx 0$ (white) are found while over major parts of the oceans β reaches values of the order of 1 (corresponding to $1/f$-spectra or flicker noise). In wide regions along the coasts the exponents vary in $\beta = 0.2 \ldots 0.4$. These spectra with $\beta > 0$ represent long term memory (LTM) up to the decadal time scale considered. A possible mechanism and an analytical two layer diffusion model for the $1/f$-spectrum of the sea surface temperature is proposed by *Fraedrich et al.* [2004]. This study shows that although the atmospheric variability is not correlated on long time scales, the atmospheric forcing is able to cause LTM even in linear models.

[3] LTM corresponds to the slow decay of the correlation function $C(t) \sim t^{\beta-1}$ for long times t; this is related to the nonintegrability of $C(t)$ and leads to the absence of a typical time scale. Furthermore, $\beta \geq 1$ indicates that the time series are nonstationary and inhibit conventional statistical analysis for the derivation of climate means and variances. Thus, the assessment of climate changes and trends is made difficult by the presence of natural low frequency climate variability. Of further relevance is the inherent relationship between $1/f$-spectra and extreme value distributions [*Antal et al.*, 2001].

[4] In a 1000 years simulation of a coupled atmosphere-ocean general circulation model (AOGCM), FB could show that the observed spectra are reproduced and that the simulated LTM extends up to centennial time scales. The main ingredient is a dynamical ocean model while the uncoupled atmosphere, either forced by climatological sea surface temperatures or coupled to a mixed layer model, is not sufficient.

[5] In a trend analysis of a 1000 years simulation with the coupled atmosphere-ocean model CSIRO/Mark 2, *Hunt* [2001] finds variability on all time scales without restriction by the total duration of the simulation. This appears mainly in the near surface temperature over the oceans and not in precipitation. Since the variability penetrates deep into the mixed layer, the origin of the LTM is attributed to the thermal inertia of the ocean. There is no correlation between individual areas.

[6] From a 500 years simulation *Hunt* [1998] concludes that external forcing is not required for LTM and leads at most to an amplification. This agrees with the detection of the observed LTM in global warming scenarios simulations [*Blender and Fraedrich*, 2003]. For a discussion on the relevance of external forcings for the observed and simulated long term memory see *Blender and Fraedrich* [2004]. Thus we conclude that LTM is a robust feature of the internal atmosphere-ocean dynamics and does not depend on time-dependent external forcings.

[7] To extend the analysis of LTM to millennial time scales, we consider a 10,000 years simulation with an AOGCM and verify the data with Greenland ice core $\delta^{18}O$ time series [*Grootes et al.*, 1993; *GRIP Members*, 1993]. These ice core data reveal sufficient temporal resolution to access spectral properties on the considered time scales. The low frequency variability of Greenland and Antarctic ice cores has been analyzed by *Roe and Steig* [2004] who find that the millennial scale variability is determined largely by regional processes with little influence between Northern and Southern Hemisphere. As a model they suggest an autoregressive process AR(1) with an additional threshold rule and a time scale of $\tau = 400 \pm 200$ years.

[8] For the present analysis it is decisive that the variability is considered as a manifestation of nonlinearly coupled processes with a wide distribution of time scales [*Ashkenazy et al.*, 2003]. Thus we neglect individual periods, which are mainly due to external forcings. This is valid on the millennial time scales considered here below the astronomical periods. The power-spectrum follows a self-

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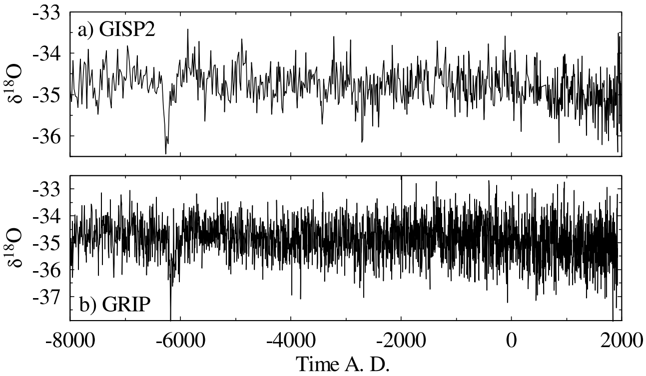

Figure 1. δ^{18}O time series of the (a) GISP2 and the (b) GRIP ice core records during the last 10,000 years.

similar scaling expressed by a power-law without characteristic frequencies.

[9] The aim of this Letter is to compare - on the millennial time scale - the low frequency variability of Greenland ice core $\delta^{18}O$ data with near surface temperature simulations. We use a 10,000 years simulation with a complex coupled atmosphere-ocean model (with sea ice) under present-day conditions. The spectral behavior is determined by the detrended fluctuation analysis (DFA [*Peng et al.*, 1994]). As a possible origin of the LTM the zonally averaged circulation in the Atlantic is considered.

2. Data and Method

[10] The model simulation is compared to the two Greenland ice core δ^{18}O time series GISP2 and GRIP [*Grootes et al.*, 1993; *GRIP Members*, 1993] during the holocene (for comparison with the simulation we choose the last 10,000 years, Figure 1). The annual averages are mapped to 10 year intervals for the detrended fluctuation analysis (DFA [*Peng et al.*, 1994]). The AOGCM is described by *Hunt* [2001]. The atmospheric model with resolution 5.62° × 3.2° is coupled to a dynamic ocean and thermodynamic sea ice model. Land ice and vegetation are fixed. In the 10,000 years AOGCM simulation the first period of 5,000 years is disregarded as spin-up.

[11] The power-spectra are determined by DFA which extracts long time correlations in stationary time series. This method yields the fluctuation function $F(t)$ which measures fluctuations of the time series on time scales t. First, the anomaly time series are integrated to the so-called profile. The profile time series is partitioned in segments of duration t, and linear fits are calculated separately for each segment. The fluctuations $F(t)$ are the means of the variances of the profile with respect to the fits. For power-laws in the power-spectrum, $S(f) \sim f^{-\beta}$, the fluctuation function is $F(t) \sim t^{\alpha}$, with $\beta = 2\alpha - 1$. Long term memory is indicated by exponents $\alpha > 0.5$. The exponent α equals the Hurst exponent obtained by the rescaled range analysis [*Hurst*, 1951]. The analysis of FB reveals an uncertainty $\Delta\beta \approx 0.1$ for the spectral exponent β.

3. Results: Long Term Memory and Scaling

[12] The global distribution of the DFA scaling exponent α for the near surface temperature during (a) 5–40 years and (b) 100–1000 years is shown in Figure 2 (the Eastern tropical Pacific needs to be disregarded due to the cyclic ENSO events). The exponent in 5–40 years (Figure 2a) proves the capability of the model to reproduce the observed distribution during the last 100 years (FB). The long time exponent (Figure 2b) shows that a power-law scaling is still present in the North Atlantic and Greenland, but lower values appear in the North Pacific, the South Atlantic, and the Southern Ocean.

[13] Figure 3 shows the scaling of the DFA fluctuation functions $F(t) \sim t^{\alpha}$ for the ice core data and at two model grid points in the North Atlantic with high α. The grid points are sea ice free (50W, 60N) and partially sea ice covered (30W, 65N). All curves show long term memory scaling: the sea ice free area $\alpha \approx 0.9$ ($\beta \approx 0.8$), the partially sea ice covered area $\alpha \approx 0.7$ ($\beta \approx 0.4$), GRIP $\alpha \approx 0.7$ ($\beta \approx 0.4$), and GISP2 $\alpha \approx 0.84$ ($\beta \approx 0.68$). Due to the uncertainty $\Delta\alpha \approx 0.05$ of α obtained in simulations (FB) the differences between GRIP and GISP2 cannot be considered as significant. The area with high α values is a major region of evaporation accumulated as ice in Greenland [*Cullather et al.*, 2000].

[14] Partial sea ice cover at (30W, 65N) is obvious from the low temperatures of the model time series (Figure 4a). Figure 4c shows the distinct non-Gaussian frequency distribution. In contrast, the sea ice free grid point (50W, 60N) displays enhanced low frequency variability of the near surface temperature (panel b). This behavior is explained by the power spectrum $S(f) \sim f^{-\beta}$ with $\beta = 0.8$ (obtained by DFA, see Figure 2), which is just below the limit $\beta = 1$ for

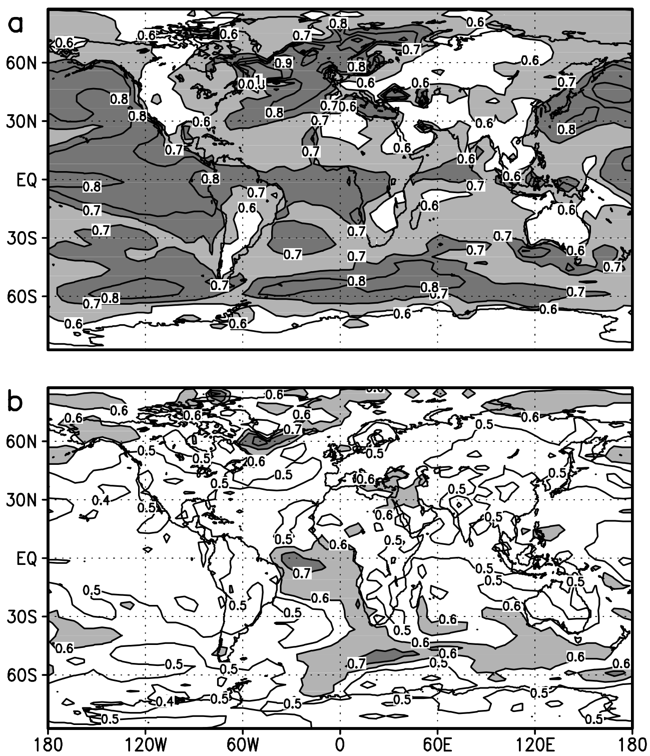

Figure 2. Fluctuation exponent α of the near surface temperature obtained by DFA in the model simulation during (a) 5–40 years and (b) 100–1000 years (0.6–0.7 light, >0.7 dark shaded).

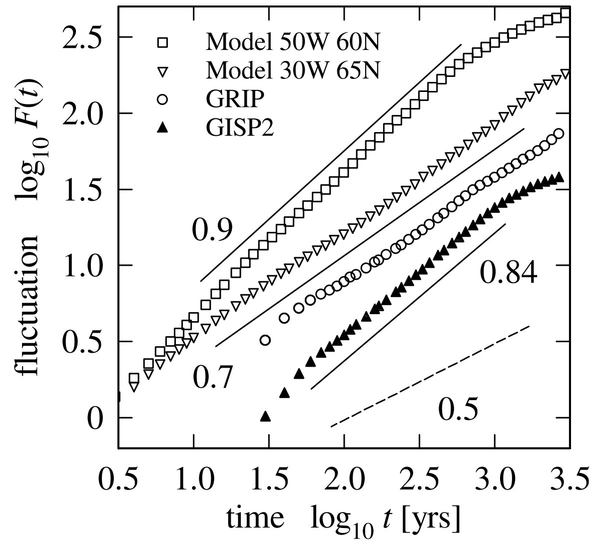

Figure 3. Fluctuation functions for the near surface temperature in the model in (50W, 60N, sea ice free) and (30W, 65N, partial sea ice cover) and the δ^{18}O time series GRIP (○), GISP2 (△) obtained by DFA. Slopes for long term memory with $\alpha = 0.7$ ($\beta = 0.4$), $\alpha = 0.84$ ($\beta = 0.68$), $\alpha = 0.9$ ($\beta = 0.8$), and white noise ($\alpha = 0.5$, $\beta = 0$, dashed) are included.

nonstationary time series ($S(f) \sim 1/f$). Obviously, the strong long term memory of the near surface temperature fluctuations (50W, 60N) prevails over an ice free ocean, and sea ice acts as an insulator reducing heat fluxes from the sea water underneath. Note that the LTM is not related to the type of frequency distribution, since the ice free area (panel d) indicates no clear deviation from a Gaussian shape.

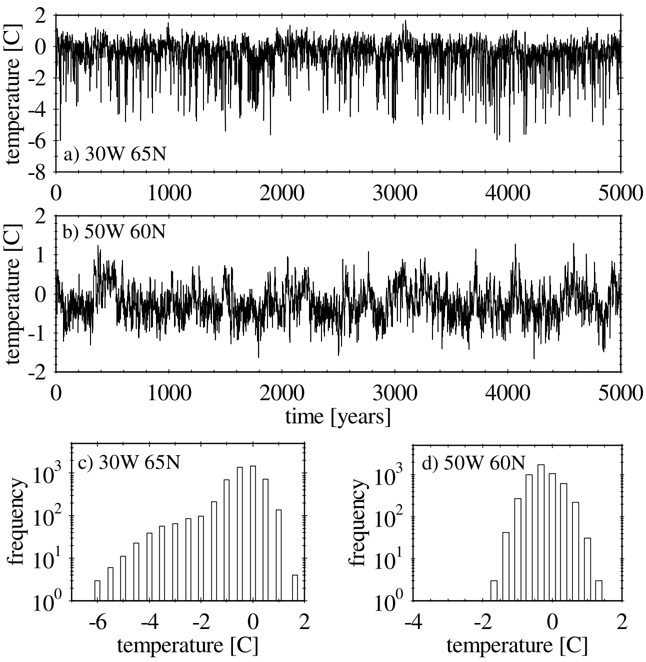

Figure 4. Model near surface temperature at (a) 30W, 65N (partial sea ice cover), and (b) 50W, 60N (sea ice free). (c and d) Corresponding frequency distributions.

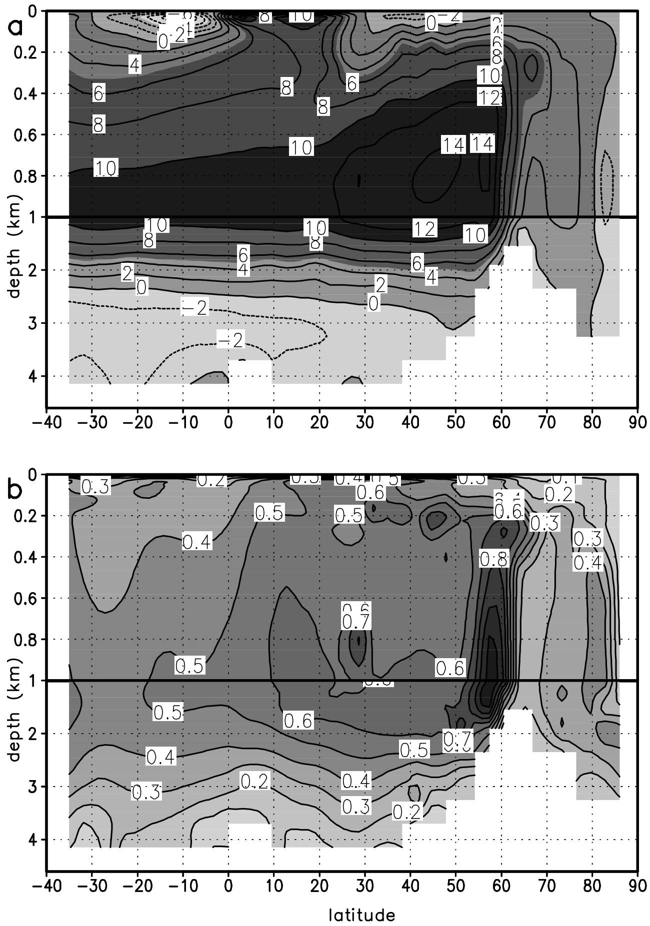

Figure 5. Zonally averaged Atlantic stream-function [Sv], (a) mean and (b) standard deviation.

[15] To reveal the origin of the LTM in the atmospheric temperature, the ocean circulation in the Atlantic is analyzed using the zonally averaged stream-function. Figure 5 shows the mean (Figure 5a) and the standard deviation (Figure 5b). Long term memory is determined pointwise by the DFA fluctuation exponent (Figure 6). In the Arctic Sea

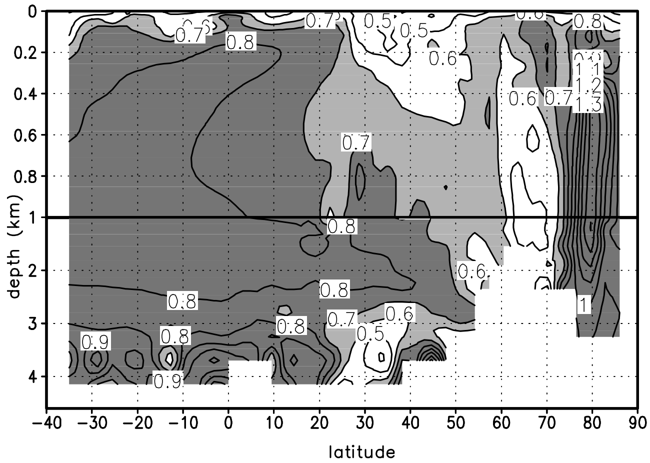

Figure 6. Fluctuation exponent α of the zonally averaged stream-function in an Atlantic cross section during 100–1000 years (0.6–0.7 light, >0.7 dark shaded).

large values of the order of $\alpha \approx 1$ (1/*f*-spectrum) are obtained in the subsidence regions. Memory with intermediate exponents of $\alpha \approx 0.8$ spans the interior of the basin. The interlocking between subsurface circulation and near surface temperature becomes obvious by the comparison with Figure 2. The Arctic and the tropical regions with temperature long term memory appear as osculation points of the stream-function variability on the corresponding time scale.

[16] The stream-function in the Pacific (not shown) reveals long term memory at the bottom of the tropical ocean (below 3km, 20S-20N). This result is comparable to the abyssal circulation in the Atlantic (Figure 6). In the upper ocean layers, and in particular in the subsurface region, there is no LTM on centennial time scales.

[17] Antarctic ice core spectra during the holocene reveal less clear results (not shown): The Vostok ice core with a much coarser resolution shows no scaling behavior in the millennial time range. Similarly, the Dome-C ice core reveals no memory. Only the result for the Taylor Dome core is reconcilable with weak long term memory ($\alpha \approx 0.65$). Thus, the lack of observed long term memory agrees with the model simulation near Antarctica (Figure 2).

4. Summary and Discussion

[18] Low frequency variability of Greenland ice core $\delta^{18}O$ time series is compared with the near surface temperature in a climate simulation. External solar or volcanic forcings are not incorporated in the simulation. This analysis shows that (i) Greenland ice cores reveal scaling with long term memory up to millennial time scales during the holocene. (ii) This long term memory is reproduced by a 10,000 years simulation with a coupled complex atmosphere-ocean model including sea ice. The model region with long term memory south of Greenland is a major source of the ice accumulated in Greenland. The agreement is quantitative, $S(f) \sim f^{-0.5}$, and within the bounds prescribed by variability of the ice core data. (iii) The previously found range of scaling and long term memory is thus extended from centuries to millennia (FB). (iv) The origin can be traced back to the internal long term memory of the Atlantic zonally averaged circulation.

[19] In the tropical Atlantic, long term memory in the zonally averaged stream-function corresponds to the memory in regions of a shallow mixed layer. But, there is no long term memory in the Pacific. In agreement with the low frequency results in Antarctic ice cores, the simulation hints to absence of long term memory in this continent.

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