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Long time memory in global warming simulations

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[1] Global power law scaling of near surface temperature spectra is determined in two scenario simulations and in NCEP re-analyses. The simulations use the coupled atmosphere-ocean models HadCM3 and ECHAM4/OPYC with greenhouse gas increase according to scenario IS92a in 1860–2099. Observations show a low-frequency power spectrum $S(f) \sim 1/f$ over the oceans, a white spectrum in the inner continents, and $S(f) \sim f^{-0.3}$ in the coastal areas. The global distribution of the power law exponents is reproduced in the two simulations even in the 21st century with a pronounced temperature increase. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 3319 Meteorology and Atmospheric Dynamics: General circulation; 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); *KEYWORDS:* Long time memory, Scenario simulations. **Citation:** Blender, R., and K. Fraedrich, Long time memory in global warming simulations, *Geophys. Res. Lett.*, *30*(14), 1769, doi:10.1029/2003GL017666, 2003.

1. Introduction

[2] Observed near surface temperature station time series show power law spectra $S(f) \sim f^{-\beta}$ with positive exponents β for long time scales. This is related to long time memory, as measured by the correlation function $C(t) \sim t^{\beta-1}$. Continental and maritime temperature measurements show different scaling of averaged power spectra up to 10 years [*Pelletier*, 1997; *Pelletier and Turcotte*, 1999]. Employing detrended fluctuation analysis (DFA, [*Peng et al.*, 1994]) to 16 continental stations in North America, Europe and Australia, reveals the same scaling-law from months up to decades with the power law exponent $\beta \approx 0.3$ [*Koscielny-Bunde et al.*, 1998]. On the Atlantic and the Pacific *Monetti et al.* [2003] report approximate $1/f$ spectra for the sea surface temperature at several sites. For time scales up to 30 million years long time memory with β roughly 1 is reported for sea level changes [*Hsui et al.*, 1993, Figure 1]. Power law scaling of long time memory in the Indian monsoon hints to predictability [*Rangarajan and Sant*, 1997]. Tropical convective variability behaves as $1/f$-noise for 1–30 days [*Yano et al.*, 2001]. For a critical assessment of the presence of power laws see *Talkner and Weber* [2000].

[3] Long time observations with at least 100 years in the area from North America to Eurasia, and globally distributed regions, mainly in the vicinity of the coasts, have been analysed by *Fraedrich and Blender* [2003] (henceforth called FB). The available data indicate that the power law exponent is $\beta \approx 0$ (white) over the interior continents, $\beta \approx 0.3$ in coastal regions, and reaches $\beta \approx 1$ over the oceans. FB also determined scaling and memory properties in a 1000 year control-run of a coupled atmosphere-ocean general circulation model (AOGCM). This reveals the observed spatial distribution of the power law exponent, its local variability, the temporal extent of the scaling-law, and the origin of the memory in the climate system. This result is based on a single simulation and the observational validation is restricted to populated areas and Atlantic ship routes.

[4] *Govindan et al.* [2002] and *Vyushin et al.* [2002] conclude that climate models are not able to reproduce the observed long time variability in global warming simulations, and thus raised concern about the relevance of the anthropogenic impact. This conclusion is based on seven simulations with increasing greenhouse gas and aerosol concentrations in 10 regions near observational stations. The authors claim to find no long time memory, i.e. white power spectra, $\beta = 0$, at several coastal stations, whereas, according to the observations of *Koscielny-Bunde et al.* [1998], $\beta \approx 0.3$ is expected. The apparent failure of the comprehensive models is highly relevant since the long time memory contributes to the total variance and superposes to external natural and anthropogenic impacts.

[5] The aim of this Letter is to detect the global distribution of long time memory in scenario simulations with two coupled atmosphere ocean models HadCM3 and ECHAM4/OPYC, and to compare this globally with NCEP re-analysis data. The increase of greenhouse gases is prescribed by the IPCC scenario IS92a for 1860–2099 in both simulations. The data and the model experiments are described in section 2 and the DFA is outlined in section 3. The results for single sites and global power law exponents exponents are presented in section 4. In section 5, the outcomes are summarised and discussed.

2. Observations and Scenario Simulations

[6] The observed data set is the NCEP re-analysis data (from NMC/NCAR, [*Kalnay et al.*, 1996]). The data is used in 1958–1998 with a resolution of 2.5° × 2.5°. Memory is analysed in monthly near surface (2 m) air temperature data. Over sea the spectral properties of the near surface temperature coincide with those of the sea surface temperature above one year time scale.

[7] Scenario simulations with two different atmosphere ocean models are used to explore the effect of different experimental designs. The models are HadCM3 (Hadley Centre, Bracknell, UK) and ECHAM4/OPYC (Max-Planck-Institut für Meteorologie, Hamburg, Germany). The models simulate the greenhouse gas increase according to the IPCC scenario IS92a [*Houghton et al.*, 1992]. In both simulations monthly near surface air temperature is analysed. The data, the models and the experiments are described at http://www.dkrz.de/ipcc/ddc/html/ISA92_all.html.

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[8] HadCM3 runs without flux adjustment in 19 levels and 2.5° × 3.75° horizontal resolution [*Gordon et al.*, 2000]. HadCM3 includes soil moisture, vegetation, snow and ice. The sea ice model includes ice advection, leads and snow-cover. ECHAM4 (the ECMWF/Hamburg climate model) is run with 19 levels and T42 resolution [*Roeckner et al.*, 1996]. ECHAM4 includes a soil model, snow and land ice, and idealised vegetation effects. The ocean model OPYC (Ocean isoPYCnal coordinates) includes a sea ice model with rheology [*Oberhuber*, 1992].

3. Method

[9] The power spectra are determined by the detrended fluctuation analysis (DFA) [*Peng et al.*, 1994]. DFA 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. 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 growth of any polynomial shape can be excluded by extensions of DFA [*Koscielny-Bunde et al.*, 1998].

[10] First, the anomaly time series, calculated by subtracting the monthly annual cycle, are integrated to the so-called profile. To determine the fluctuation function $F(t)$, 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. If the original time series shows trends or higher order polynomial growth types, then, instead of linear fits, polynomials of order N are fitted and subtracted in the segments; the method is then denoted as DFA-N. The aforementioned simple DFA is DFA-1 and does not, due to the integration, eliminate linear trends in the original time series. Here we apply DFA-2 to eliminate linear trends.

[11] Long time memory is defined as the non-integrability of the correlation function $C(t)$. A power law decay, $C(t) \sim t^{\beta-1}$, requires $\beta > 0$ for long times. For $\beta = 0$, or $\alpha = 1/2$, the spectrum is white, and for $\beta = 1$, or $\alpha = 1$, the spectrum is $1/f$ (flicker) noise. Larger values $\beta > 1$, or $\alpha > 1$, indicate that the analysed time series segment is nonstationary. The uncertainty of DFA exponents has been analysed by segmentation of time series in a long climate simulation (FB) and estimated as $\Delta\beta \approx 0.2$ ($\Delta\alpha \approx 0.1$).

4. Results

[12] First, the fluctuation function is determined by DFA-2 at three individual locations in the Atlantic and one near Galapagos for observations and the two models simulations. These fluctuation functions reveal whether power law scaling is possible and point at the accessible scaling ranges where the power law exponent can be fitted.

4.1. Single Locations: Observations and Simulations

[13] The analysis is first applied to temperature time series at four locations in the northern (30W, 50N), tropical (20W, 10S), and southern Atlantic (0W, 50S), and in the eastern tropical Pacific, near Galapagos (100W, 0N). The Atlantic regions are partly covered by long instrumental records obtained along ship routes (FB). The time series are determined at particular grid points and regional averages are not considered since the results show considerable horizontal gradients. Figure 1 shows the fluctuation functions $F(t)$ obtained by DFA-2 for the four locations in NCEP data and the two scenario simulations, HadCM3 and ECHAM4/OPYC. The complete available time series are used, i.e. 41 years NCEP and 240 years in the simulations. The fluctuation functions and the scaling behaviour in the four locations are:

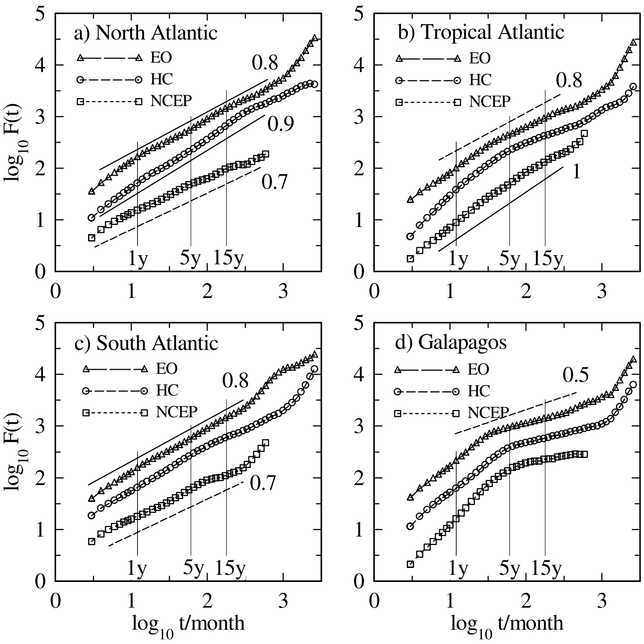

Figure 1. Fluctuation function $F(t)$ by DFA-2 for near surface temperature in (a) North, (b) Tropical, (c) South Atlantic, and (d) Tropical Pacific versus time. Data: NCEP (boxes), HadCM3 (circles), ECHAM4/OPYC (triangles). Curves are shifted for clarity; guideline slopes as indicated.

[14] 1) In the North Atlantic (Figure 1a), $F(t)$ scales between $t^{0.7}$ in NCEP data and $t^{0.9}$ in simulations, as found in FB for 100 years data. Due to the lack of significance, the uppermost decades should be disregarded. The uncertainty of power law exponents α is $\Delta\alpha \approx 0.1$ (FB), hence β has an uncertainty $\Delta\beta \approx 0.2$. Therefore, the difference between the two scenario simulations is possibly due to sampling and does not hint at a model discrepancy. Yet this single result shows that scenario simulations are able to reveal the same long time memory as observations or control simulations (FB).

[15] 2) In the Tropical Atlantic (Figure 1b), although the power law growth is less clear, a fit indicates long time memory with $\alpha = 0.8\ldots1$, with the largest memory in observations. The weak saddle-like growth in the HadCM3 simulation indicates an influence of ENSO (see Figure 1d below). However, this phenomenon is below the uncertainty 0.1 of α and not identified in NCEP and the other simulation.

[16] 3) In the South Atlantic (Figure 1c), simulations and observations show a power law exponent $\alpha \approx 0.8$. Thus, the Atlantic locations represent unambiguous scaling in near surface memory with exponents $\alpha = 0.7\ldots1$ and $\beta = 0.4\ldots1$.

[17] 4) The fluctuation functions near Galapagos (Figure 1d) deviate considerably from a power law. The reason is that any dominant oscillation or cyclic variation in the power spectrum generates a saddle-like behaviour [*Hu et al.*, 2001]

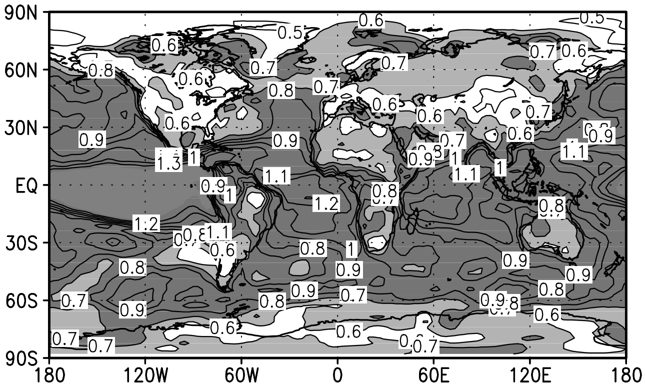

Figure 2. Fluctuation exponent α for NCEP 2 m-temperature by DFA-2 in 1–5 years. White: $0.5 < \alpha < 0.6$, light: $0.6 < \alpha < 0.7$, dark: $\alpha > 0.7$.

in the DFA fluctuation, centred around the oscillation and with a constant or weakly growing $F(t)$ above. This prevails for centuries and the exponent can be below 0.5. Due to the restricted length of most observed and simulated time series, a possible long time memory cannot be identified within the available time. Global patterns of the power law exponent α should disregard the regions influenced by ENSO.

4.2. Global Observations

[18] The analysis in section 4.1 sec$_{l}$oc is extended to the global distribution of the power law scaling of near surface air temperature in the 41 year NCEP re-analyses (Figure 2).

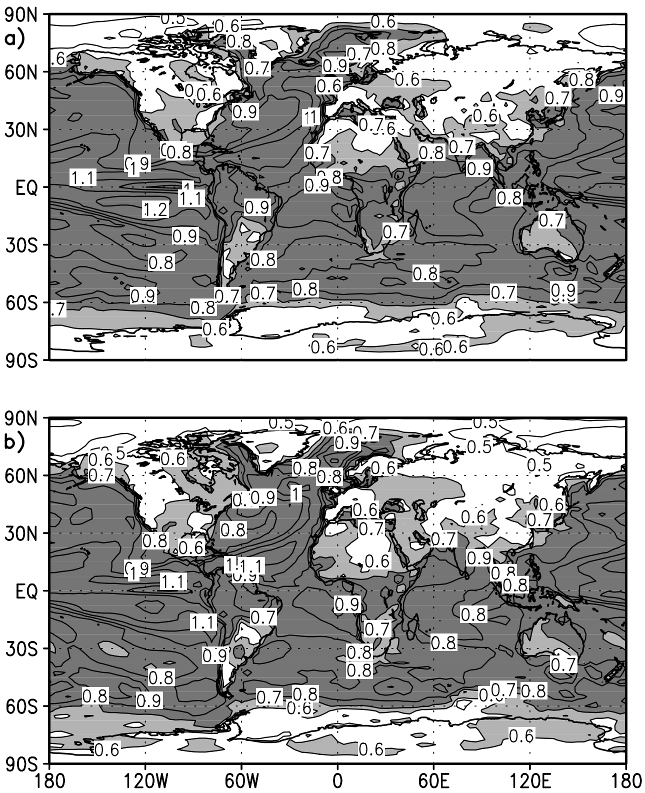

Figure 3. Fluctuation exponent α of near surface temperature in 1–15 years for the HadCM3 simulation, (a) 1860–2099, (b) 2000–2099. White: $0.5 < \alpha < 0.6$, light: $0.6 < \alpha < 0.7$, dark: $\alpha > 0.7$.

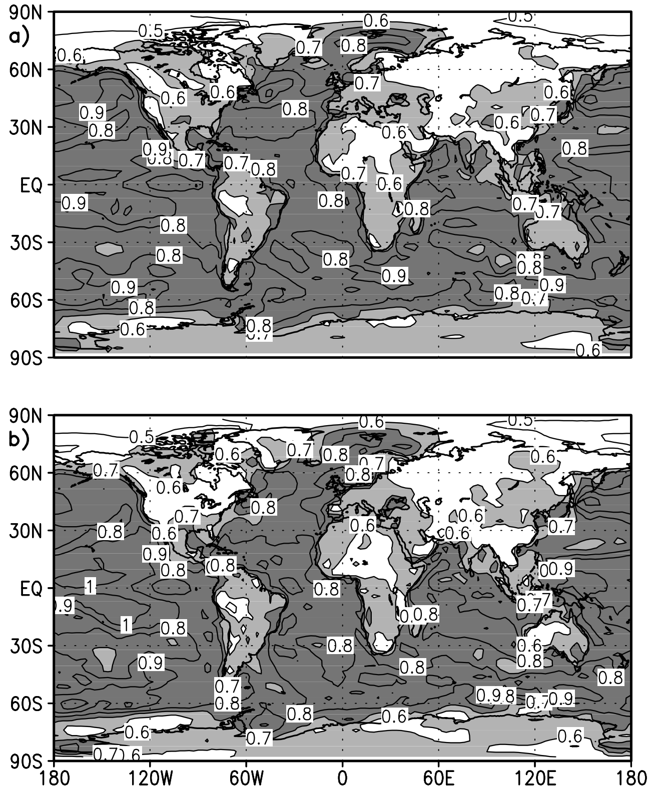

Figure 4. Fluctuation exponent α of near surface temperature in 1–15 years for the ECHAM4/OPYC simulation. (a) 1860–2099, (b) 2000–2099. White: $0.5 < \alpha < 0.6$, light: $0.6 < \alpha < 0.7$, dark: $\alpha > 0.7$.

Although the trend of roughly 0.5C in the last century is weak, the trend-eliminating DFA-2 version is used for consistency with the analysis of the scenario simulations. The power law is determined as the slope within 1–5 years (see Figure 1). The global pattern of α shows the main properties found in FB in restricted regions with 100 years data. Note that due to the shortness of the global NCEP data an increased uncertainty of the exponent cannot be avoided. In the inner continents, the fluctuation exponent is $\alpha \approx 0.5$, hence the spectrum $S(f)$ is white. Over the midlatitude oceans, α reaches 1, and, accordingly, $S(f) \sim 1/f$. In addition to the observations in FB, the North Pacific, the Southern Ocean, Antarctica and the Arctic region are now included. The result substantiates a maritime $1/f$-spectrum and the low memory near the poles, anticipated by a control simulation of a coupled atmosphere ocean model. The intermediate value $\alpha = 0.65$ is restricted to land areas under maritime impact.

4.3. Global Simulations

[19] Global maps of the power law exponent α are determined in the two scenario simulations using the results of the single site analysis in section 4.1. The period of intense warming in the 21st century is analysed separately and compared to the total experiment. Due to the use of the version DFA-2 it is possible to eliminate the strong temperature trend in the fluctuation analysis, which would otherwise lead to erroneously high fluctuations on long time scales. Comparisons with DFA-3 reveal the same results.

[20] Figure 3 shows the global patterns for the scenario simulation with HadCM3 for the total time interval in 1860–2099 and 2000–2099, and analogous for ECHAM4/OPYC in Figure 4. The power law exponent is determined by a fit in 1–15 years; also during 2000–2099. All analyses show high values of the exponents over the midlatitude oceans ($\alpha \approx 1$, $\beta \approx 1$) and white noise over the inner continents ($\alpha \approx 0.5$, $\beta \approx 0$).

[21] Most of the differences between the two scenario simulations lie within the uncertainty limits 0.1 of the exponent α (for example the Equatorial South America and Equatorial Africa show long time memory in the HadCM3 simulation but not in ECHAM4/OPYC). The control run simulation with ECHAM4/HOPE (FB) presents slightly higher exponents α in the Northern Atlantic and in the Antarctic ocean. Deviations of this magnitude are possibly related to the differences between the deep ocean circulation in simulations with different atmosphere ocean models [see e.g. *von Storch et al.*, 2000].

[22] Note that the report on the violation of long term memory in scenario simulations by *Govindan et al.* [2002] presents the interesting result $\alpha = 0.65$ in one coastal station (Seoul, ECHAM4/OPYC, their Figure 2d). This emphasises the relevance of apparently slight geographical displacements in global analyses.

5. Summary and Discussion

[23] We present evidence that long time memory is found in observations and scenario simulations. NCEP data is used to cover regions that are not accessible by individual station data, which, however, comprise shorter time scales. Scenario simulations with HadCM3 and ECHAM4/OPYC according to scenario IS92a are used to extend the earlier control run results to different model configurations and to account for a possible influence of intense temperature trends on long time memory. The two coupled models represent two entirely different model components and coupling schemes.

[24] The power spectrum is first analysed at four individual maritime locations to demonstrate the appearance of the low-frequency power law behaviour and to determine the appropriate ranges for the fit of a power law exponent in global data. The short duration of the NCEP data restricts scaling to 1–5 years whereas 1–15 years are possible in the two simulations. Particular emphasis is put on the period of intense warming during 2000–2099 in the scenario simulations. The low-frequency power spectrum is approximately $S(f) \sim 1/f$ over the oceans, $S(f) \sim$ const in the inner continents, and $S(f) \sim f^{-0.3}$ along the coastal transition zones. All results for the power law exponent agree, even during the intense warming of the 21st century in the scenario simulations.

[25] Obviously, the climate model simulates observed patterns of long time variability for present-day as well as for scenario conditions. The remaining deviations may help to improve the model configuration, such as parameterisations, atmosphere-ocean coupling and ocean spin-up.

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