Scaling of Atmosphere and Ocean Temperature Correlations in Observations and Climate Models

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Power-law scaling of near surface air temperature fluctuations and its geographical distribution is analyzed in 100-yr observations and in a 1000-yr simulation of the present-day climate with a complex atmosphere-ocean model. In observations and simulation detrended fluctuation analysis leads to the scaling exponent $\alpha \approx 1$ over the oceans, $\alpha \approx 0.5$ over the inner continents, and $\alpha \approx 0.65$ in transition regions [spectrum $S(f) \sim f^{-\beta}$, $\beta = 2\alpha - 1$]. Scaling up to decades is demonstrated in observations and coupled atmosphere-ocean models with complex and mixed-layer oceans. Only with the complex ocean model the simulated power laws extend up to centuries.

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Temporal correlations within the climate system are of physical and practical interest. Daily and seasonal correlations enable weather and climate prediction, and correlations on longer time scales characterize the interaction of climate components. Therefore, the analysis of correlations within the different compartments of the climate system and its realistic physical modeling are fundamental in climate research. Continental and maritime temperature measurements show different scaling of averaged power spectra up to 10 yr [1]. Employing detrended fluctuation analysis (DFA) [2] to 16 continental stations in North America, Europe, and Australia reveals the same scaling law from months up to decades, coined "universal law" with the DFA power-law exponent $\alpha \approx 0.65$ [3,4]. Coupled atmosphere-ocean models have been reported to violate this power law with consequences for estimating the simulated global warming effect [5]. This conclusion is based on seven simulations with increasing greenhouse gas and aerosol concentrations (so-called scenarios [6]) in ten regions near observational stations. In coupled atmosphere-ocean models with constant greenhouse gas concentrations (control runs) [7,8], scaling and memory properties have not been determined by DFA.

The first aim of this Letter is to extend the fluctuation analysis of observed data to all areas where sufficient data have been measured [9] and to detect the geographical distribution of the scaling law. In addition to the regions mentioned above, this includes the northern and the tropical Atlantic Ocean, South America, South Africa, India, the Indian Ocean, and Southeast Asia. The second aim addresses the capability of global climate models to reproduce the observed scaling and memory utilizing a 1000 yr simulation with a complex coupled atmosphere-ocean model in a constant greenhouse gas environment. This reveals the 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.

The observational global data are a combination of near surface air temperatures over land and sea surface temperatures (SST) interpolated to a $5° \times 5°$ grid [9]. Monthly data are available since 1856; however, the predominance of missing values in the global data set limits the correlation analysis to a belt from North America to Europe (including the North Atlantic), India and Southeast Asia, and small areas in the Southern Hemisphere. We restrict the analysis to those grid points with less than 10% missing data after 1900. The central Asian station Krasnojarsk (93 E, 52 N; 1915–1999) is compared with the corresponding grid data.

The Earth's climate is simulated by a global circulation model which couples atmosphere and ocean. The atmospheric model ECHAM4 (European Centre Hamburg Model version 4, horizontal resolution $3.75° \times 3.75°$ and 19 vertical levels [10]) describes the atmospheric dynamics, radiation, the hydrological cycle, and includes land surface and soil. The ocean is simulated by the comprehensive model HOPE (Hamburg Ocean Primitive Equation, horizontal resolution $2.8° \times 2.8°$ and 20 vertical levels [11]) including sea ice dynamics, the thermo-haline circulation, and global ocean transports. The coupled ECHAM4/HOPE simulation has been performed as a "present-day control run" (with fixed atmospheric composition of greenhouse gases) to obtain a reference for other simulations during historic time intervals [12]. The coupled run simulates 1000 yr with flux correction after 2200 yr spin-up of the uncoupled ocean model. A study of deep-ocean transports in four coupled atmosphere-ocean models reveals differences that may depend on the model complexity, ocean spin-up time, and atmosphere-ocean coupling [8]. The ECHAM4/HOPE simulation is compared with a simulation of ECHAM4 coupled to a simple so-called mixed-layer (ML) ocean model [13] and to an ocean replaced by a climatological SST with an annual cycle only. The ML model incorporates the top 50-m layer as a heat reservoir driven to climatological SST without horizontal advection. In the simulations, the temperature T_{2m} in 2-m height is analyzed instead of the observed near surface temperatures over land and SST. Over the oceans, T_{2m} shows the same fluctuations as the SST on time scales beyond 1 yr.

The temporal correlations are deduced by the detrended fluctuation analysis, which has been applied to daily station temperature fluctuations in observations [3,4] and model simulations [5]. The DFA determines time scale dependent fluctuations in stationary anomaly sequences with long time correlation. First, the anomaly time series, defined as deviations from the annual cycle, is integrated to the so-called profile. In time segments of length τ, the fluctuation $F(\tau)$ of the profile with respect to linear fits in each segment is determined and then averaged over all segments. Note that "detrended" does not refer to the original time series. Polynomial trends of order $N-1$ in the time series are eliminated by the DFA-N, which subtracts polynomial fits of order N from the profile in each segment [5] (hence linear trends will be subtracted by DFA-2). For power laws in the correlation function, $C(\tau) \sim \tau^{-\gamma}$, the fluctuation function is $F(\tau) \sim \tau^{\alpha}$ and the power (or variance) spectrum is $S(f) \sim f^{-\beta}$ with $\beta = 2\alpha - 1$ and $\alpha = 1 - \gamma/2$ [4,14]. The power-law exponents for stationary processes with long time memory lie between white noise ($\alpha = 0.5$, $\beta = 0$) and flicker or $1/f$ noise ($\alpha = \beta = 1$).

In a first step, the fluctuation functions are calculated at locations in central Asia and the North Atlantic for observations and simulations. The estimation of the power-law exponent α in the global data sets is outlined. In a second step, global distributions of α for observations and simulations are presented and a sample estimation of the statistical error of α is derived from independent intervals of the ECHAM4/HOPE simulation.

In central Asia [Fig. 1(a)], the fluctuation function in the station Krasnojarsk shows a power law $F(\tau) \sim \tau^{\alpha}$ with $\alpha \approx 0.5$ ranging from 1 yr to decades. The interpolated grid data [9] agree with this value in DFA-1 and DFA-2 (note that the trend $+0.6$ C/100 yr is rather weak in this region). This behavior is obtained in the ECHAM4/HOPE and ECHAM4/ML simulations. In the North Atlantic [Fig. 1(b)], the observed grid data show $\alpha \approx 0.9$ in DFA-1 and DFA-2. The ECHAM4/HOPE simulation reveals a smaller value, $\alpha \approx 0.8$, which, however, extends to longer time scales. The ECHAM4/ML simulation shows $\alpha \approx 1$ in the 1–5-yr range; above that $\alpha \approx 0.65$ is observed (this agrees incidentally with [3,5]). Obviously, these inner-continental and maritime results differ from $\alpha \approx 0.65$ reported for continental stations [3,5]. To determine reliable exponents α in observed data, the upper limit for an estimation has to be well below 100 yr. Therefore, in the following global analyses the exponent will be estimated in the 1–15-yr range. The power law for centennial time scales will be calculated in 15–150 yr.

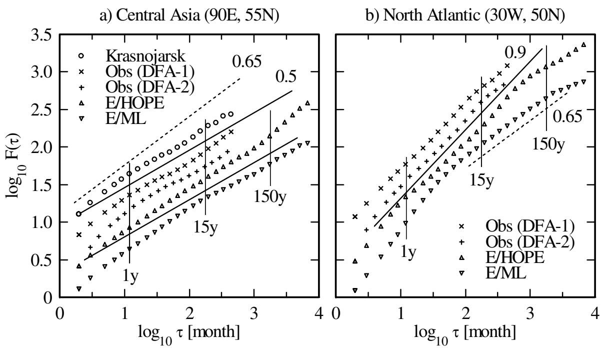

FIG. 1. Fluctuation functions $F(\tau)$ for temperature (a) in central Asia (90 E, 55 N) and (b) in the North Atlantic (30 W, 50 N), calculated for the station Krasnojarsk (93 E, 52 N), and corresponding regions in the observed grid data set (Obs), ECHAM4/HOPE (E/HOPE), and ECHAM4/ML (E/ML) simulations. DFA-1 is used if not indicated otherwise. Slopes are (a) 0.5 (solid line) and 0.65 (dashed line) and (b) 0.9 (solid line) and 0.65 (dashed line).

The global distribution of temperature power-law exponents is derived from the observed monthly near surface temperatures over land and SST data [9]. Although differences of the fluctuation function $F(\tau)$ between DFA-1 and DFA-2 are weak (see Figs. 1(a) and 1(b) and [3]), the global data are analyzed with caution using DFA-2. Below, all simulated data, which are trend-free, are analyzed using DFA-1. This apparent change of the DFA order does not lead to inconsistencies in the results.

Figure 2 shows the estimated exponents α in land areas with early measurement efforts and along ship routes. Inner-continental areas in North America and central Asia show $\alpha < 0.6$, whereas parts of the northern and

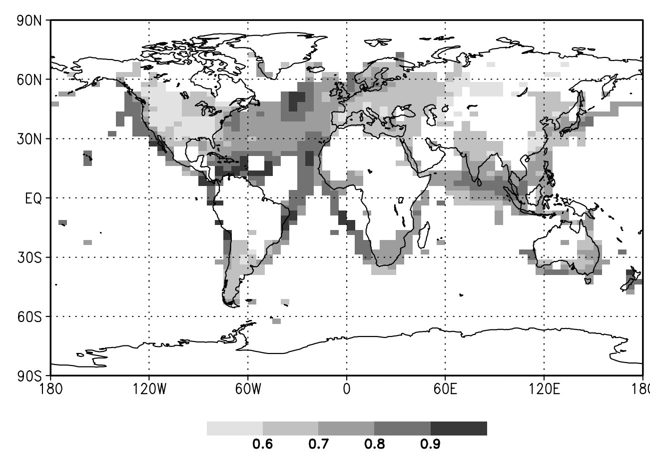

FIG. 2. Fluctuation exponent α in observed sea surface and near surface air temperatures over land estimated by DFA-2 in 1–15 yr. The analysis is restricted to grid points with at least 90% data after 1900.

the tropical Atlantic, of the eastern North Pacific, and of the Indian Ocean reveal a distinct increase, $\alpha \approx 0.9$. Notable is the general tendency of α increasing from land to sea. In the transition regions, the vicinity of the coasts and over land under maritime influence, α lies in the range of 0.6–0.7 which corresponds to $\alpha \approx 0.65$ [3–5]. It is not surprising that an analysis of single station data, which is mostly available in these transitions regions, yields this result.

The observations are compared with a 1000-yr simulation of the coupled atmosphere-ocean model ECHAM4/HOPE in a constant greenhouse gas environment. The model output is analyzed in the same manner as the observations except that DFA-1 is used (instead of DFA-2), since the 1000-yr run is free of trends. Figure 3 displays the fluctuation exponent α of the simulation within the 1–15-yr range of $F(\tau)$. This pattern agrees closely with that observed in Fig. 2, apart from the Indian Ocean and Southeast Asia, where smaller α values are simulated compared to the observations. The inner continents reveal no memory with $\alpha \approx 0.5$, and $0.6 < \alpha < 0.7$ (light shading) prevails over land areas under maritime influence and the Indian Ocean. The North Atlantic, North Pacific, and the Southern Ocean show exponents up to $\alpha = 1$ (areas with $\alpha > 0.7$ have dark shading), that is $1/f$ noise ($\beta = 2\alpha - 1 \approx 1$). An exception is the eastern tropical Pacific where the almost periodic El Nino/Southern Oscillation phenomenon with time scales of 3–7 yr inhibits power-law scaling within the 1–15-yr range [15].

To check whether the result for α is merely a statistical coincidence, the 1000-yr simulated data set is used to estimate the variability of α. The output is split in ten nonoverlapping intervals of 100-yr length and the α values are estimated in the 1–15-yr range. The mean of the ten intervals agrees well with Fig. 3. The standard deviation (Fig. 4) is 0.025–0.05 in most regions, with larger deviations in the Southern Ocean, where α itself is large. Considering this standard deviation, confidence can be attributed to the simulated long term memory and to its observed and simulated geographical distribution.

The results presented so far show that the simulation with constant atmospheric greenhouse gas concentration reproduces the observed long time memory. In scenario simulations with increasing greenhouse gas concentration and a temperature increase of the order of 5 K during the next century, the power-law memory has been reported to vanish [5]. According to the present analysis, the reason for this deviation cannot be attributed to a general failure of the coupled models. Possibly, the ocean with its long time scales cannot achieve an equilibrium while greenhouse gas concentrations increase in the atmosphere, and power-law scaling may be inappropriate.

As fluctuation functions at individual grid points of the simulation still show power-law behavior up to 1000 yr (Fig. 1), DFA-1 scaling is estimated in the long range from 15 to 150 yr. The fluctuation exponent (Fig. 5) decreases slightly, except for the North Pacific, where the $1/f$ spectrum vanishes completely. In contrast, the North Atlantic and the Southern Ocean, the other two core areas with the $1/f$ spectrum, remain unaffected. The regions of zero memory expand across the tropical belt. The areas with α between 0.6 and 0.7 follow these changes. In the Northern Hemispheric midlatitudes, they remain in the vicinity of the coasts, apart from the North Pacific and its surroundings. This control run yields power-law memory extending beyond the observational record length. In this long time range, neglected impacts such as solar low-frequency variability or glacier dynamics may affect the result.

To search for the origin of the power-law behavior, ECHAM4 is coupled to the simple ML ocean model [13], and to an ocean replaced by a climatological SST with an annual cycle only. ECHAM4 coupled to the ML model reproduces the main quantitative characteristics

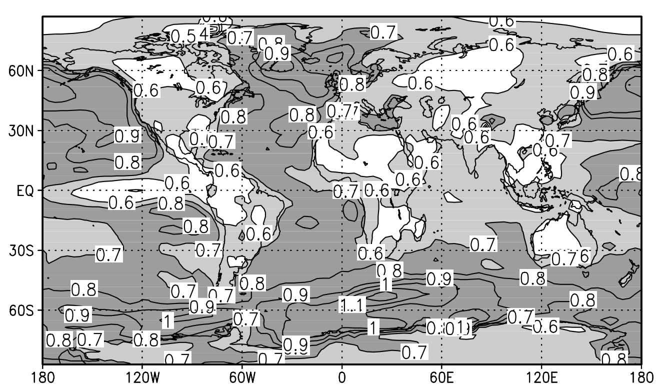

FIG. 3. Fluctuation exponent α in the 1000-yr coupled atmosphere ocean simulation estimated in 1–15 yr [$\alpha < 0.6$ (white), $0.6 < \alpha < 0.7$ (light shading), and $\alpha > 0.7$ (dark shading)].

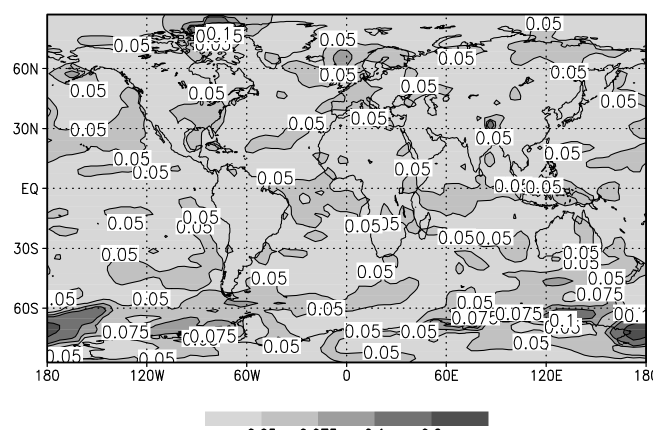

FIG. 4. Standard deviation of the fluctuation exponent α obtained in ten 100-yr intervals of the 1000-yr coupled simulation. For all intervals α is estimated in 1–15 yr (isolines in 0.025 intervals up to 0.1, and 0.2).

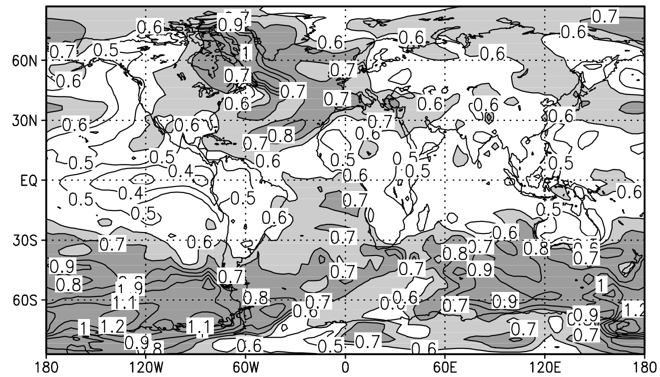

FIG. 5. Fluctuation exponent α in the 1000-yr coupled simulation, as in Fig. 2, but estimated in 15–150 yr [$\alpha < 0.6$ (white), $0.6 < \alpha < 0.7$ (light shading), $\alpha > 0.7$ (dark shading)].

of the ECHAM4/HOPE simulation (Figs. 1 and 3) in the 1–15-yr range. However, on longer time scales of 15–150 yr, memory fades away approaching $\alpha \approx 0.5$. The ECHAM4 simulation with prescribed climatological SST shows no memory at all. Obviously, the power law observed in the decadal range can be reproduced by an atmosphere coupled with a ML model, whereas the centennial memory requires a dynamic ocean model.

In summary, we have analyzed the spectral behavior of global fields of observed and simulated surface temperatures using detrended fluctuation analysis. Observations yield the previously found $\alpha \approx 0.65$ in coastal regions and areas under maritime influence for time scales ranging from 1 to 15 yr. These are the areas where the major part of observational stations is located [3–5]. In the inner continents, memory is absent ($\alpha \approx 0.5$). Higher values occur in the northern and the tropical Atlantic ($\alpha > 0.9$). A 1000-yr coupled model simulation supports these findings and shows that $\alpha \approx 0.5$ in all inner-continental areas and $\alpha \approx 1$ in the North Atlantic, the North Pacific, and the Southern Ocean. That is, $\alpha \approx 0.65$ characterizes a transition region between the continental white and midlatitude maritime $1/f$ spectrum. The variability of α, as estimated by ten 100-yr intervals of the simulation, lies within 0.025–0.05, with few exceptions mainly in the Southern Ocean. Thus there is confidence in the model performance and in the observed and simulated continent-ocean contrast. According to the simulation, the power law extends up to 15–150 yr. Since this correlation is found only if the atmosphere is coupled to the complex ocean model, the origin of the memory can be traced back to the internal long time ocean dynamics. The main results of this Letter follow in brief: (i) The exponent $\alpha \approx 0.65$ is predominantly confined to coasts and land regions under maritime influence. (ii) Coupled atmosphere-ocean models are able to reproduce the observed behavior up to decades. (iii) Long time memory on centennial time scales is found only with a comprehensive ocean model.

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