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# Long-term persistence in the sea surface temperature fluctuations

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## Abstract

We study the temporal correlations in the sea surface temperature (SST) fluctuations around the seasonal mean values in the Atlantic and Pacific Oceans. We apply a method that systematically overcome possible trends in the data. We find that the SST persistence, characterized by the correlation  $C(s)$  of temperature fluctuations separated by a time period  $s$ , displays two different regimes. In the short-time regime which extends up to roughly 10 months, the temperature fluctuations display a non-stationary behavior for both oceans, while in the asymptotic regime it becomes stationary. The long-term correlations decay as  $C(s) \sim s^{-\gamma}$  with  $\gamma \sim 0.4$  for both oceans which is different from  $\gamma \sim 0.7$  found for atmospheric land temperature.

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## 1. Introduction

The oceans cover almost three quarters of the Earth's surface and have the greatest capacity to store heat. Thus, they are able to regulate the temperature on land even in sites located far away from the coastline. This property of the oceans suggests that they may possess a strong temperature persistence, i.e., a strong tendency that the water temperature of a particular day will remain the same the next day. Persistence can be

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characterized by the auto-correlation function  $C(s)$  of temperature variations separated by a time period  $s$ . Recently, quantitative studies of the persistence in atmospheric land temperatures revealed that atmospheric land temperature fluctuations exhibit long-range power law correlations  $C(s) \sim s^{-\gamma}$  with  $\gamma \approx 0.70$  [1–4]. In this letter, we study the persistence in sea surface temperature (SST) records at many sites in the Atlantic and Pacific Oceans using the detrended fluctuation analysis (DFA) method [5,6]. We find that for all time scales the SST fluctuations exhibit stronger correlations than atmospheric land temperature fluctuations. The long-term persistence of the SST is characterized by a correlation exponent  $\gamma \sim 0.4$  for both oceans.

We have analyzed both types of SST data sets that are available, the monthly SST for the period 1856–2001 and the weekly SST for the period 1981–2001. For the period 1856–1981, the monthly SST data sets were obtained by Kaplan et al. [7] who used optimal estimation in space applying 80 empirical orthogonal functions to interpolate ship observations of the United Kingdom Meteorological Office database [8]. After 1981, the monthly data correspond to the projection of the National Center for Environmental Prediction (NCEP) optimal interpolation (OI) analysis [9,10]. The weekly SSTs also correspond to the NCEP OI analysis. The data are freely available from <http://ingrid.ideo.columbia.edu/SOURCES/>.

## 2. Methodology

We focus on the temperature fluctuations around the periodical seasonal trend. In order to remove the periodical trend, we first determine the mean temperature  $\langle T_a \rangle$  for each month/week by averaging over all years in the time series. Then, we analyze the temperature deviations  $\Delta T_i = T_i - \langle T_a \rangle$  from these mean values. The persistence in the temperature fluctuations can be characterized by the auto-correlation function,

$$C(s) \equiv \langle \Delta T_i \Delta T_{i+s} \rangle = \frac{1}{N-s} \sum_{i=1}^{N-s} \Delta T_i \Delta T_{i+s}, \quad (1)$$

where  $N$  is the length of the record and  $s$  is the time lag. A direct calculation of  $C(s)$  is hindered by the level of noise present in the finite temperature series and by possible non-stationarities in the data. To reduce the noise, we study the temperature profile function,

$$Y_k = \sum_{i=1}^k \Delta T_i. \quad (2)$$

We can consider the profile  $Y_k$  as the position of a random walker on a linear chain after  $k$  steps. According to the random walk theory, the fluctuations  $F(s)$  of the profile in a given time window of length  $s$  are related to the correlation function  $C(s)$ . For the relevant case of long-range power law correlations,

$$C(s) \sim s^{-\gamma}, \quad 0 < \gamma < 1, \quad (3)$$

the fluctuations increase as a power law [11,12],

$$F(s) \sim s^\alpha, \quad \alpha = 1 - \gamma/2. \quad (4)$$

For uncorrelated data ( $\gamma \geq 1$ ), we have  $\alpha = 1/2$ . To find how the fluctuations scale with  $s$ , we divide the profile into non-overlapping intervals of length  $s$ . We calculate the square fluctuations  $F_v^2(s)$  in each interval  $v$  and obtain  $F(s)$  by averaging over all intervals,  $F(s) \equiv \langle F_v^2(s) \rangle^{1/2}$ . Here, we use two methods that differ in the way fluctuations are measured. In the fluctuation analysis (FA), the square of the fluctuations is defined as  $F_v^2(s) = (Y_{(v+1)s} - Y_{vs})^2$  where  $Y_{vs}$  and  $Y_{(v+1)s}$  are the values of the profile at the beginning and the end of each segment  $v$ , respectively. In the DFA, we determine in each interval the best polynomial fit of the profile and define  $F_v(s)$  as the variance between the profile and the best fit in the intervals. Different orders  $n$  of DFA (DFA1, DFA2, etc.) differ in the order of the polynomial used in the fitting procedure. By construction, FA is sensitive to any kind of trend and thus equivalent to the Hurst and the power spectrum analyses. In contrast, DFA $n$  removes a polynomial trend of order  $n - 1$  in the temperature record and thus, it is superior to the conventional methods.

To characterize the persistence, we have applied the FA and DFA methods to 36 (46) monthly SST records and 64 (35) weekly SST records in the Atlantic (Pacific) Ocean.

### 3. Results and discussion

Fig. 1(a–c) show three typical plots of the monthly temperature profile function  $Y_t$  for a land station (Prague), a site in the Atlantic Ocean, and a site in the Pacific Ocean, respectively. Parabolic-like profile functions which are concave (convex) may indicate the presence of a positive (negative) linear trend (see Eq. (2)). However, Fig. 1(d)

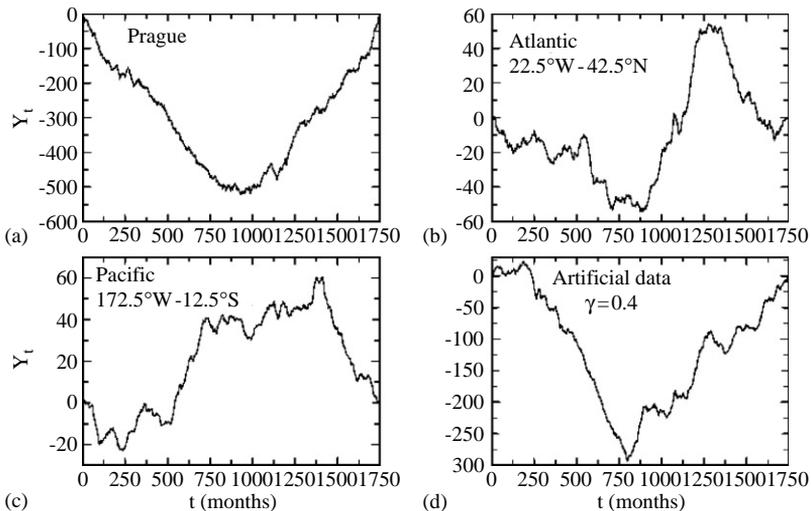


Fig. 1. Typical temperature profile functions for the last 146 yr (monthly data): (a) Prague; (b) Atlantic Ocean (22.5W, 42.5S); (c) Pacific Ocean (172.5W, 12.5S); (d) artificial correlated data with  $\gamma = 0.4$ .

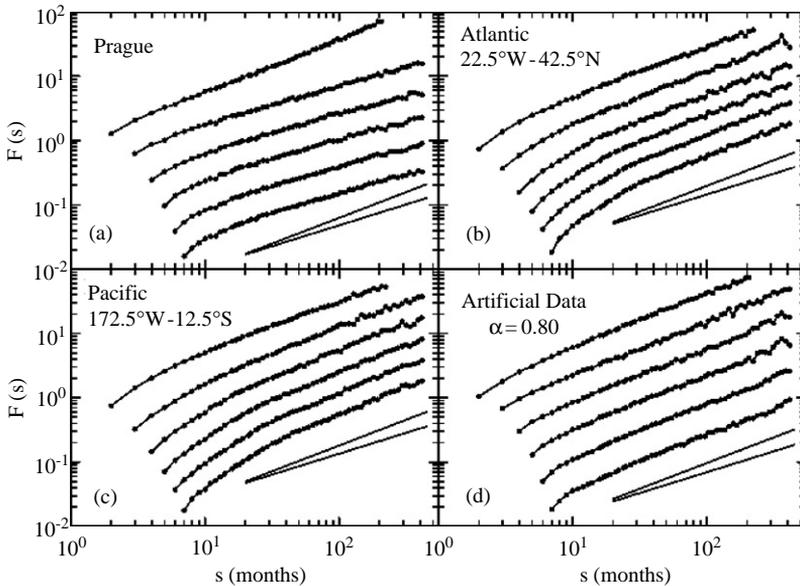


Fig. 2. (a–d) Log–log plots of the FA and DFA curves for the data shown in Fig. 1. From top to bottom curves correspond to FA, DFA1–DFA5. Lines of slope 0.8 and 0.65 have been drawn to compare the typical SST long-term fluctuation exponent with the atmospheric land temperature fluctuation exponent.

illustrates that pure correlated data may also lead to parabolic-like profile functions. Trends and correlations can be distinguished and characterized by comparing the FA and DFA results [6,13]. Fig. 2 shows log–log plots of the FA and DFA curves for the profiles shown in Fig. 1. Fig. 2(a) shows that at large times Prague temperature fluctuations display a power law behavior. The fluctuation exponent obtained from the FA (0.81) is greater than the values given by the DFA1–5 (0.65). This difference is probably due to the effect of the well-known urban warming of Prague. The fluctuation exponent  $\alpha \approx 0.65$  is consistent with the earlier finding, where the whole Prague record (218 yr) has been analyzed [1,13]. Fig. 2(a) shows that the FA (and the similar Hurst and power spectrum methods) may lead to spurious results because of the presence of trends, yielding a large overestimation of long-range correlations. Fig. 2(d) shows the FA and DFA results for the artificial data used in Fig. 1(d). Although the profile function suggested the presence of a trend, the FA and the DFA show no evidence of any trend (see Refs. [14,15]). Fig. 2(b) and (c) show the FA and DFA results for two typical sites in the Atlantic and Pacific Oceans, respectively. Here, for long-time scales, FA and DFA curves are straight lines with roughly the same fluctuation exponent  $\alpha \sim 0.8$ . This shows that (a) trends do not falsify the FA result and therefore may be regarded as much less important than for Prague temperatures, and (b) long-range correlations also occur in SSTs. These correlations are stronger than the correlations in the atmospheric land temperatures, since the fluctuation exponent  $\alpha \sim 0.8$  corresponds to a correlation exponent  $\gamma \sim 0.4$ . As in the case of atmospheric land temperatures [1],

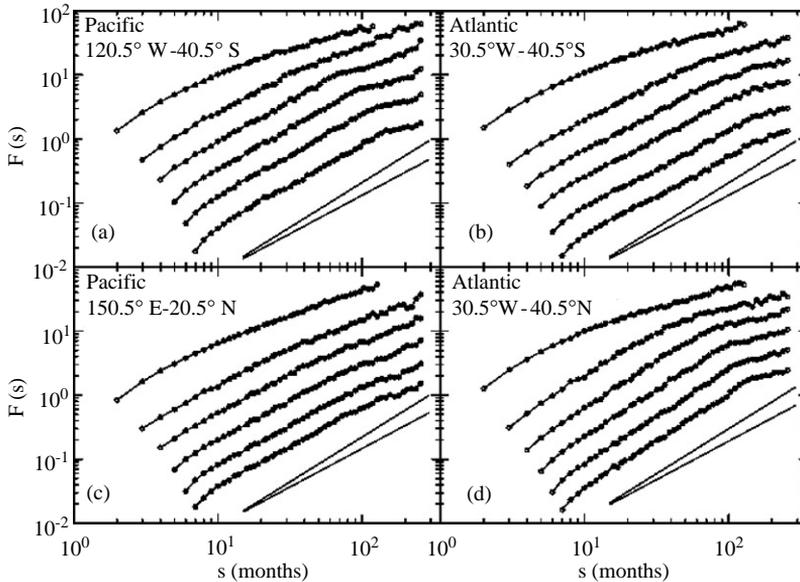


Fig. 3. (a–d) Log–log plots of the FA and DFA curves for the last 20 yr (weekly data) for typical sites in the Atlantic and Pacific Oceans. From top to bottom curves correspond to FA, DFA1–DFA5. Lines of slopes 1.2 and 1.4 have been drawn to compare the short-time SST fluctuation exponent obtained in the northern Atlantic with the short-time SST fluctuation exponent for the rest of the oceans.

the range of this persistence law seems to exceed one decade and is possible even longer than the range of the SST series considered.

In contrast to Prague, there is a pronounced short-time regime which ends roughly at 10 months. This regime can be better revealed by the analysis of the weekly SST series. Fig. 3 shows the FA and DFA results for 4 sites in the Atlantic and Pacific Oceans. This figure shows that for short times, the SST exhibits a persistence which is considerably stronger than both the SST long-term persistence and the atmospheric land temperature persistence. The typical SST short-time fluctuation exponent is  $\alpha \approx 1.2$ . However, in the northern Atlantic (latitudes from  $30^\circ$  to  $50^\circ$  north) we have found even higher fluctuation exponents. Fig. 3(d) shows the results for a typical site in the northern Atlantic, yielding  $\alpha \approx 1.4$ . The fact that  $\alpha$  is above 1 means that the variance of the original temperature fluctuations in a time window  $s$  increases as  $s^{\alpha-1}$ , i.e., as  $s^{0.4}$  in the northern Atlantic and  $s^{0.2}$  in the rest of the oceans for time scales below 10 months. This non-stationary behavior must be contrasted with the atmospheric land temperature fluctuations where the variance stays constant and the persistence decays with a nearly universal exponent  $\gamma \sim 0.7$ . Non-stationary behavior has also been found in the analysis of marine stratocumulus cloud base height records [16].

We like to suggest the following interpretation for the difference in the short-term persistence between the northern Atlantic and the rest of the oceans. In the northern Atlantic, the dominant mode of interannual variability in the atmospheric circulation

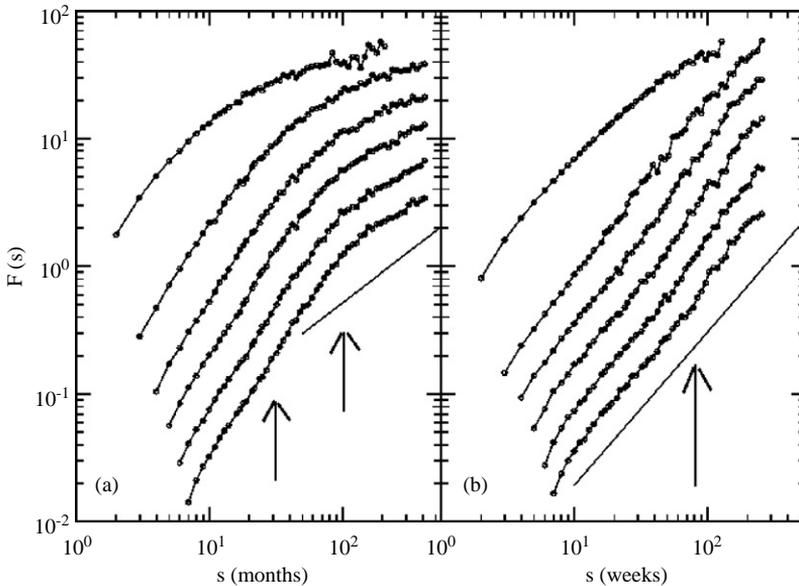


Fig. 4. Log–log plots of the FA and DFA curves at  $92.5^{\circ}\text{W}$ – $2.5^{\circ}\text{S}$  in the tropical Pacific region. The arrows indicate the position of the crossovers. (a) Monthly SSTs for the last 146 yr. A line of slope 0.8 has been drawn to note the influence of the oscillation on the results; (b) weekly SSTs for the last 20 yr. A line of slope 1.2 representative of the short-time regime has been included.

is the North Atlantic Oscillation (NAO) [17,18]. This weather phenomenon highly influences the climate in the eastern part of North America and northern Europe and is usually characterized by the NAO index which is based on the normalized difference in sea level pressure between Ponta Delgada, Azores ( $26^{\circ}\text{W}$ ,  $38^{\circ}\text{N}$ ) and Akureyri, Iceland ( $18^{\circ}\text{W}$ ,  $66^{\circ}\text{N}$ ). The NAO index varies from positive values in winters to negative values in other seasons. During the last 20 yr, the NAO index has displayed a persistent and exceptionally strong positive phase [17]. Since the sea level pressure and the SST are coupled variables, it is likely that the observed persistence in the NAO index is also revealed by the greater fluctuation exponent found in SSTs in the same period.

In order to find how representative the values of the fluctuation exponents are, we have studied the distribution of the short- and long-term exponents for both the Atlantic and the Pacific Ocean. For the long-term exponents, we exclude those sites in the tropical Pacific region where the El Niño southern oscillation (ENSO) takes place [19]. The reason for this is that ENSO is a cyclic phenomenon which warms the east equatorial Pacific Ocean every 3–6 yr. This cycle cannot be detrended and strongly affects the DFA results on scales between 2 and 20 yr. At small scales below 2 yr, higher order DFA is able to remove the trend. At larger scales, well above 20 yr, the oscillations cancel each other and the fluctuations again become dominant. However, for obtaining reliable results on the scaling above 20 yr, we need data covering far

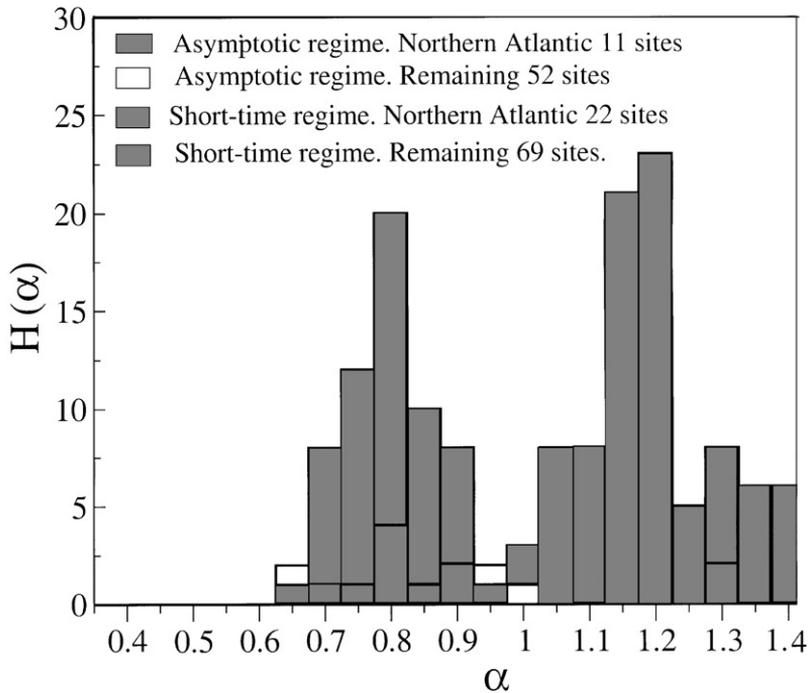


Fig. 5. Histograms for the short- and long-time fluctuation exponents.

more than 200 yr. Those data are not available, and therefore we cannot specify the long-term exponents in the ENSO region. Fig. 4 shows the results from our fluctuation analysis for a typical site in the tropical Pacific region, both for the weekly and the monthly data. Below 2 yr, the exponent is close to 1.2, and is therefore similar to the short-term exponent for the rest of the sites. Above 2 yr, the influence of the oscillations shows up. First, the exponent crosses over to a larger value, and then, above 3 yr for DFA1 and above 8 yr for DFA5, crosses over to a very low value. This effect of oscillations on the DFA analysis was recently described in Refs. [6,14]. We expect that at much larger scales, the exponent will gradually increase approaching the value  $\alpha \sim 0.8$  as for the sites outside the ENSO regime. However, the data sets are too short to observe this effect.

Fig. 5 summarizes our results for the short- and long-term exponents for both the Atlantic and the Pacific Oceans. As said before, for the short-term exponents, sites in the ENSO region are included in the histogram, while for the long-term exponents they are not. The histogram shows that the short-term exponents for the northern Atlantic ( $\alpha = 1.38 \pm 0.04$ ), where the NAO takes place, are well distinct from the short-term exponents of the remaining sites ( $\alpha = 1.17 \pm 0.08$ ). For the asymptotic long-term exponents ( $\alpha = 0.8 \pm 0.08$ ) there is not such a clear distinction between the northern Atlantic area and the rest.

## 4. Conclusion

In summary, we have studied the persistence of the SST in the Atlantic and Pacific Oceans. We found that, in contrast to land stations, there exist two pronounced scaling regimes. In the short-time regime that roughly ends at 10 months, the fluctuations of the temperature profile, in a given time window  $s$ , scales as  $s^\alpha$ , with an exponent  $\alpha$  in the northern Atlantic ( $\alpha \sim 1.4$ ) that differs from the rest of the oceans ( $\alpha \sim 1.2$ ). This behavior is well distinct from the temperature fluctuations on land, where  $\alpha$  is close to 0.65 above typically 10 days. The fact that in the short-time regime  $\alpha$  is well above 1 points to an intrinsic non-stationary behavior where the variance of the original temperature fluctuations in a time window of size  $s$  increases with  $s$  as  $s^{\alpha-1}$ . This non-stationary behavior crosses over to stationary behavior at time scales above 10 months, where now the fluctuation exponent reaches the value  $\alpha \sim 0.8$  for all sites considered in both oceans. This result reveals that pronounced long-term correlations govern the SST, with an exponent  $\gamma \sim 0.4$ . The persistence in the SST is due to the capacity of the oceans to store heat [20]. The oceans also contribute to the temperature persistence on land but in a less direct way, i.e., by coupling to the atmosphere. This may be the reason why the persistence of atmospheric land temperatures is less pronounced. In the view of our results, it is interesting that coastline stations (like Melbourne, Sydney, and New York) show the same persistence exponent like inland stations (like Prague and Luling). Finally, we also like to emphasize that the scaling laws we find here may serve as further non-trivial test-bed for the state-of-the-art global climate models (see Ref. [21]).

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