



Climate Networks around the Globe are Significantly Affected by El Niño

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The temperatures in different zones in the world do not show significant changes due to El Niño except when measured in a restricted area in the Pacific Ocean. We find, in contrast, that the dynamics of a climate network based on the same temperature records in various geographical zones in the world is significantly influenced by El Niño. During El Niño many links of the network are broken, and the number of surviving links comprises a specific and sensitive measure for El Niño events. While during non-El Niño periods these links which represent correlations between temperatures in different sites are more stable, fast fluctuations of the correlations observed during El Niño periods cause the links to break.

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Networks are often used to formulate the dynamics of complex systems that are built from many interacting components (see, e.g., [1,2]). While in some cases the representation of the system as a network is obvious and the nodes and links are identified directly (e.g., cables connecting computers in a computer network) [3], there are cases in which the process that couples the individual interacting components is more complex and a link is guessed by tracking similarities in the dynamical behavior of two nodes [4].

Even when the usual traces of dynamics of interacting nodes on a network, such as partial synchronization, clusters with correlated dynamics, oscillatory synchronization [5], and phase slips [6], are evident, the mission of designing a generic tool that reliably extracts information about the network structure from measurements of the dynamics of nodes is still far from being accomplished.

In this Letter we develop a method for generating climate networks, which is suitable for tracking structural changes in these networks (dynamics of a network). These changes correspond, in our case, to strong climate changes due to El Niño. We find that networks constructed from temperature measurements on different sites in the world are changed dramatically during El Niño events in a similar way. These structural changes are seen even for geographical zones where the mean temperature is not affected by El Niño.

We analyze daily temperature records taken from a grid (available at [7]) in various geographical zones (shown in Fig. 1). To avoid the trivial effect of seasonal trends we subtract from each day's temperature the yearly mean temperature of that day. Specifically, if we take the temperature signal of a given site in the grid to be $\tilde{T}^y(d)$, where y is the year and d is the day (ranging from 1 to 365), the new filtered signal will be $T^y(d) = \tilde{T}^y(d) - \frac{1}{N} \sum_y \tilde{T}^y(d)$ (where N is the number of years available in the record) [8].

We compute for a time shift $\tau \in [-\tau_{\max}, \tau_{\max}]$ days for each pair of sites l and r on the grid, their cross correlation function $X_{l,r}^y(\tau > 0) = \frac{1}{365} \sum_d T_l^y(d) T_r^y(d + \tau) \equiv \langle T_l^y(d) T_r^y(d + \tau) \rangle_d$ and $X_{l,r}^y(\tau \leq 0) \equiv X_{r,l}^y(\tau > 0)$. The correlation strength of the link is chosen to be $W_{l,r}^y = \max(X_{l,r}^y) / \text{std}(X_{l,r}^y)$, where \max and std are the maximal value and the standard deviation of the absolute value of $X_{l,r}^y$ in the range of τ , respectively [9]. The time shift at which $X_{l,r}^y$ is maximal is defined as the time delay. Up to here, the prescription is similar to other methods (see, e.g., [10]).

From reasons that will become clear later, we are able to set a physical threshold Q so that only pairs l, r that satisfy $W_{l,r}^y > Q$ are regarded as significantly linked. Mathematically this can be represented by the Heaviside function $\Theta(x)$ as follows:

$$\rho_{l,r}^y = \Theta(W_{l,r}^y - Q). \quad (1)$$

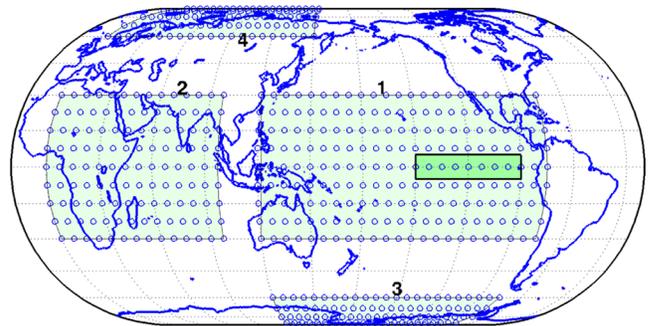


FIG. 1 (color online). The four geographical zones used for building the four climate networks studied. The dots represent the nodes of the network. The rectangular geographical zone inside zone 1 shows the standard basin for which El Niño effects on temperature and pressure are significantly observed [see Fig. 2(a)].

Some of the elements of the matrix ρ may blink as a function of y , i.e., appear and disappear. Thus, even though there are many pairs l, r that their correlation values $W_{l,r}^y$ in a specific year are above Q , some of these $W_{l,r}^y$ are sensitive to the choice of the beginning of the period y and to noise. In the present work we choose to discard the question of which pairs comprise the static network and concentrate on the structural changes of the network over time. Blinking links seem to be a signature of structural changes, so we distinguish between them and the more robust links that are stable during larger time periods.

In the next step we examine if a currently existing link $\rho_{l,r}^y$ existed in the earlier periods of the network. To accomplish this we define a new matrix, which takes into

account previous states of the links in the last k states of the network. We define a new matrix $M_{l,r}^y$ which counts the number of times a link appeared repeatedly:

$$M_{l,r}^y = \sum_{n=0}^{y-1} \prod_{m=y-n}^y \rho_{l,r}^m \quad (2)$$

A link (l, r) in the current network ρ appeared k times in a row before (including its current appearance) if and only if $M_{l,r}^y \geq k$. These links represent long lasting relations between temperature fluctuations in the zone. Counting them enables us to distinguish between the two qualitatively different groups of links, blinking links which are removed, and robust links which we include in the net-

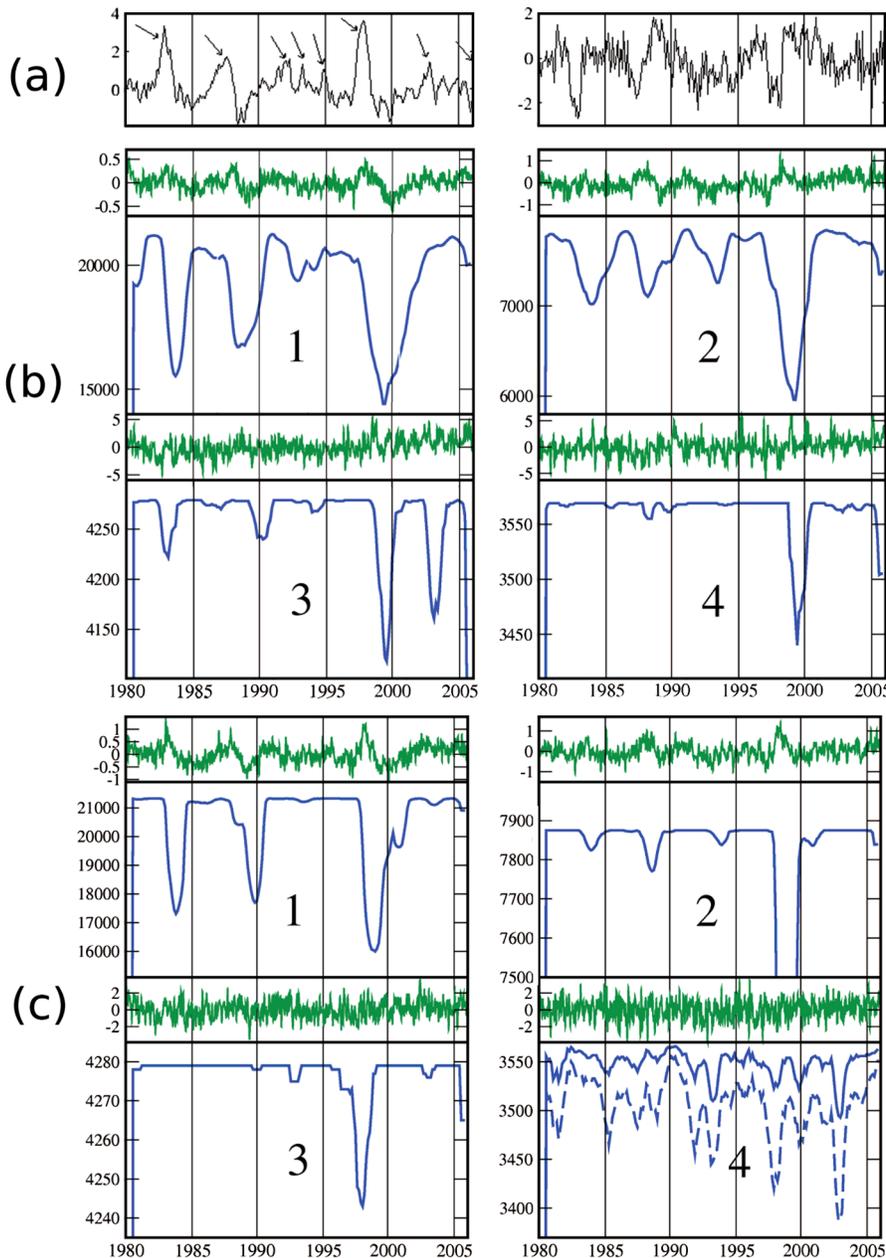


FIG. 2 (color online). (a) Mean sea surface temperature (left) in the standard basin shown in the rectangle inside A_1 in Fig. 1 (the NINO3 index), and the difference in sea level pressure (right) between Tahiti and Darwin (the SOI index), both are standard indices for El Niño (see, e.g., [16]). (b),(c) The upper curves represent the temperature anomaly series in zones (b) A_1, A_2, A_3, A_4 at sea level and (c) B_1, B_2, B_3, B_4 at 500 mb pressure level. The lower curves present $n_k(y)$, namely, the number of links that survive in the network as a function of time, for these same zones. In zone B_4 , the graph for $n_k(y)$ is completely flat, when $Q = 2$. For this zone we show the cases of $Q = 2.4$ (middle curve) and $Q = 2.5$ (lower curve) [17].

work. The number of links that exist in our network depends on y ,

$$n_k(y) = \sum_{l=0}^N \sum_{r=l+1}^N \Theta(M_{l,r}^y - k + 1). \quad (3)$$

Where k is the number of times a link has to survive in order to be included in the network [according to Eq. (2)], and N is the total number of links in the geographical zones. The summand in the right-hand side of Eq. (3) represents the network matrix. In the current work we chose the y resolution (the jumps between two subsequent dates represented by y) to be 50 days, $k = 5$ and the threshold $Q = 2$.

The results shown below are not sensitive to the choice of k . However, choosing too large k values reduces the number of surviving links significantly, and therefore eliminates much of the effect. Choosing too small values of k , on the other hand, does not enable the elimination of blinking links, and therefore causes $n_k(y)$ to be more noisy, but the significant effect of breaking links is still evident.

We chose four representative zones around the globe, as shown in Fig. 1. Our networks are built from measurements of temperatures close to sea level (networks A_j), and from measurements on a 500 mb pressure level (networks B_j), on a grid of 7.5° resolution. The measurements are taken for the years 1979–2006, for which eight known El Niño events have occurred.

In Fig. 2(a) we show the effect of El Niño as eight main extreme values on the two standard El Niño indices (based on temperature and pressure measurements), measured in the standard basin region inside zone 1 of Fig. 1 [11]. In the top of each of the eight panels in Figs. 2(b) and 2(c) we show the mean temperature anomaly over the whole corresponding zone defined in Fig. 1. It is clearly seen that compared to Fig. 2(a) the El Niño effect on mean temperature in all zones becomes very weak and almost cannot be detected except at zones A_1, B_1 (which include the standard basin), and A_2 . In most zones, El Niño effect on the temperatures are masked by noise of the same order. In marked contrast, when measuring the number of links $n_k(y)$ in the climate network we observe [in the bottom of Figs. 2(b) and 2(c)] a significant effect of El Niño in all four zones. This is represented by the sharp fall of $n_k(y)$ in most of the times of occurrence of El Niño. In zones A_1, A_2, A_3 between five and six out of the eight events can be observed, while in zone A_4 (in the north) only the strongest El Niño is seen clearly. Because of the close occurrence of the three events in the early 1990s it seems that two of the minima of $n_k(y)$ overlap. It is also notable that in the zone surrounding the El Niño basin (zone A_1) the minimum due to the 2002 event cannot be inferred. However, in the B_1 [Fig. 2(c)] network's $n_k(y)$ series the minimum caused by El Niño can be seen. In zone A_4 it is seen that even when the influence of El Niño on the mean temperature in the zone is not seen at all, the largest El Niño event in 1997 as

well as the event of 2005 can clearly be identified by a sharp minimum in $n_k(y)$.

In zone B_1 [Fig. 2(c)] the main events are also clearly seen, but the three events in the early 1990s overlap completely. In network B_2 all events, except the 2002 event, can be observed. In network B_3 only the 1997 event is observed reliably. In network B_4 the traces of El Niño can also be speculated only if one sets the threshold to a higher value.

The choice of the threshold $Q = 2$ is not arbitrary. When observing the probability density function of W (Fig. 3) it is clear that for non-El Niño time regimes $W \approx 2$ is actually the minimal value that exists. It therefore appears that choosing this threshold makes the network very sensitive to El Niño events while remaining insensitive to other changes in climate. The reason is that the distribution of $W_{l,r}^y$ tends to typical lower values of $W_{l,r}^y$ during El Niño, as can be clearly seen in Figs. 3(a)–3(e). A remarkable property of this softening is that the lower limit of the distribution drops from being close to two to some significantly lower value. Changes in climate around the world due to El Niño events thus share a unified property of the correlation pattern, which can be tracked in a reliable way by the number of surviving links $n_k(y)$ in the climate network.

How susceptible are the links that will break during El Niño? As can be seen in Figs. 3(f)–3(j), the links in the fully connected network that will later break have a distribution of correlation strengths very similar to that of

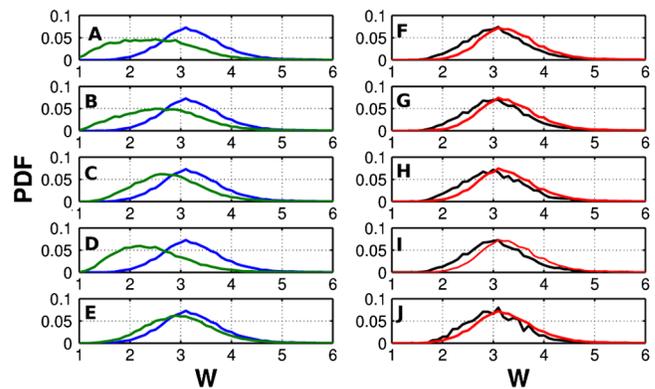


FIG. 3 (color online). (a)–(e) The distribution of $W_{l,r}^y$ in zone 1 (see Fig. 1). The five rows correspond to the five El Niño events which are the most noticeable on zone 1 (Fig. 2). The curves with a peak to the right (blue curve) describe the distribution in a reference time, where the influence of El Niño on the network is not seen. The curves with a peak to the left (green curve) describe the distribution for five El Niño events. (f)–(j) Two distributions of $W_{l,r}^y$ in the reference point [blue curves of graphs (a)–(e)]. The curves slightly shifted to the left (black) are the distributions of the correlation values of the links that later on will disappear due to one of the El Niño events, and the curves slightly shifted to the right (red) are the distribution of the ones that will remain connected in the considered event.

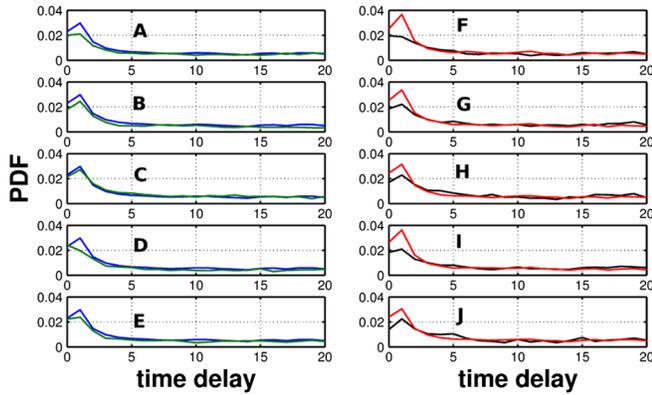


FIG. 4 (color online). Distribution of time delays. (a)–(e) Lower (green) curves: The distribution of time delays of all links in the reference time, with no signs of El Niño. Upper (blue) curves: Time delay distribution during five El Niño episodes. (f)–(j) Distribution of time delays of two groups of links during the reference time. Upper (red) curves: Distribution of time delays of links that remain during El Niño. Lower (black) curves: Distribution of time delays of links that break during El Niño.

the links that will survive. Only a slight tendency of weaker links to break can be observed. However, when looking at the distribution of the time delays (Fig. 4), there is a clear difference between links that survive and links that break. Links that collapse have a much broader distribution of time delays, and therefore usually have delays of more than a few days. Links with shorter time delays have higher probability to survive.

An alternative approach that yields a similar effect can be obtained by counting the number of elements of $\rho_{l,r}^y$ that during the periods $\{y-2, y-1, y\}$ (two subsequent dates $y, y+1$ are separated by 50 days) possess for $\rho_{l,r}^y$ the sequence $\{1, 0, 1\}$ or the sequence $\{0, 1, 0\}$. Such a treatment which tests directly the relation between El Niño and blinking of links yields results very similar to that given by $n_k(y)$. The blinking correlation events during El Niño may arise from a gradual breaking of indirect paths between two nodes l and r or from a sensitivity to the choice of Q . In either case these events are a direct and unified mark of an aggressive structural change that until now was described as various climate responses in various geographical zones. A more resolute theoretical problem of reconstructing an accurate network structure from experimental observations of its nodes' dynamics (in the current Letter—the temperature) remains largely open (see related discussions in [12–15]).

In summary, we have developed a method which enables one to follow large changes over time of an underlying network structure by observations of fluctuations in the correlations between nodes. The method tracks blinking links that appear and disappear in a short time, and assumes this behavior to be due to structural changes. Tracking the changes in the network of temperatures in several zones in

the world reveals a deep violent response to El Niño even in zones and heights where the mean temperature level is not affected. The links that break during El Niño are mostly links that have large time delays.

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Note added.—After the manuscript was submitted we learned that Tsonis and Swanson arrived at similar conclusions using a different approach [18].

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