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Strong influence of westerly wind bursts on El Niño diversity

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Despite the tremendous progress in the theory, observation and prediction of El Niño over the past three decades, the classification of El Niño diversity and the genesis of such diversity are still debated. This uncertainty renders El Niño prediction a continuously challenging task, as manifested by the absence of the large warm event in 2014 that was expected by many. We propose a unified perspective on El Niño diversity as well as its causes, and support our view with a fuzzy clustering analysis and model experiments. Specifically, the interannual variability of sea surface temperatures in the tropical Pacific Ocean can generally be classified into three warm patterns and one cold pattern, which together constitute a canonical cycle of El Niño/La Niña and its different flavours. Although the genesis of the canonical cycle can be readily explained by classic theories, we suggest that the asymmetry, irregularity and extremes of El Niño result from westerly wind bursts, a type of state-dependent atmospheric perturbation in the equatorial Pacific. Westerly wind bursts strongly affect El Niño but not La Niña because of their unidirectional nature. We conclude that properly accounting for the interplay between the canonical cycle and westerly wind bursts may improve El Niño prediction.

Our understanding of El Niño dynamics started from the recognition that it is a coupled variability of the tropical Pacific ocean–atmosphere system[1]. Present theories can be generally grouped into two different frameworks, one considering El Niño/La Niña as a regular and self-sustaining oscillation with its timescale determined by the recharge and discharge of the equatorial upper-ocean heat content[2–5], and the other regarding it as a highly damped oscillation with each event triggered by atmospheric noise, especially the westerly wind bursts (WWBs) in the tropical western Pacific[6–9]. The former framework can be readily applied to the basic El Niño/La Niña cycle and is consistent with the high potential predictability of El Niño[10–12], whereas the latter seems to explain the irregularity of El Niño yet suggests that it is virtually unpredictable at long lead times. To better describe El Niño diversity and to provide a dynamically consistent interpretation for such diversity, we need a unified perspective that considers the different views on the classification of El Niño diversity, and reconciles the present theories to account for the interaction between the low-frequency recharge–discharge oscillation and the stochastic atmospheric forcing[13,14].

Classification of El Niño diversity

Every El Niño event is different from others, but it is often useful to classify different events into a few distinctive types according to the common manifestation, mechanism and impact of each type. In early years, El Niño was mostly studied in a composite form, such as the 'canonical El Niño' constructed by Rasmusson and Carpenter[15] based on seven events in the 1960–1970s, which has the largest variance in the central-eastern equatorial Pacific and remains the average pattern when all known events over the past 150 years are taken into account[10]. It was then suggested that El Niño could be classified into two or three basic types[16]. In the same spirit, a series of recent studies have emphasized the different flavours of El Niño, with particular attention to a type that consists of warm events centred in the central-western equatorial Pacific[17–21]. In contrast to the strong El Niño that occurs in the eastern Pacific cold tongue, weak warm events of this type have been named "El Niño Modoki"[18], "warm-pool El Niño"[19] or "central Pacific El Niño"[21]. It has been suggested that the spatial pattern of El Niño Modoki could be an artefact of the orthogonality requirement of empirical orthogonal function (EOF) analysis[22]. It was further argued that this mode is not distinctively different from the canonical El Niño, and that El Niño should instead be considered primarily as a broad central Pacific phenomenon plus a few extremely strong eastern Pacific events[23].

As an alternative to EOF and composite analyses, we apply the fuzzy clustering method[24] (see Methods) to the tropical Pacific sea surface temperature (SST) anomaly data from HadISST[25] over the past 50 years. This naturally and consistently reveals three warm patterns and essentially only one cold pattern (Fig. 1). The first warm pattern (Fig. 1a) consists of extremely strong El Niño events that had the largest warming near the South American coast. The second warm pattern (Fig. 1b) is a cluster of weak warm events centred near the dateline, very similar to the 'warm-pool El Niño' that has recently aroused a great deal of interest. The third (Fig. 1c) is basically the canonical El Niño with moderate warming in the central-eastern equatorial Pacific, which is quite symmetric to the only cold pattern identified (Fig. 1d–f). Thus, there seems to be a symmetric, canonical cycle in the central-eastern equatorial Pacific that represents a large portion of El Niño and La Niña events. Superimposed on this basic cycle are rare extreme El Niño events in the eastern Pacific and weak but more frequent warm events near the dateline, which collectively give El Niño its different flavours.

In principle, there should be a non-discrete continuum of SST patterns due to highly diversified El Niño flavours[26–28] and, depending on the specific clustering approach taken, there could be different

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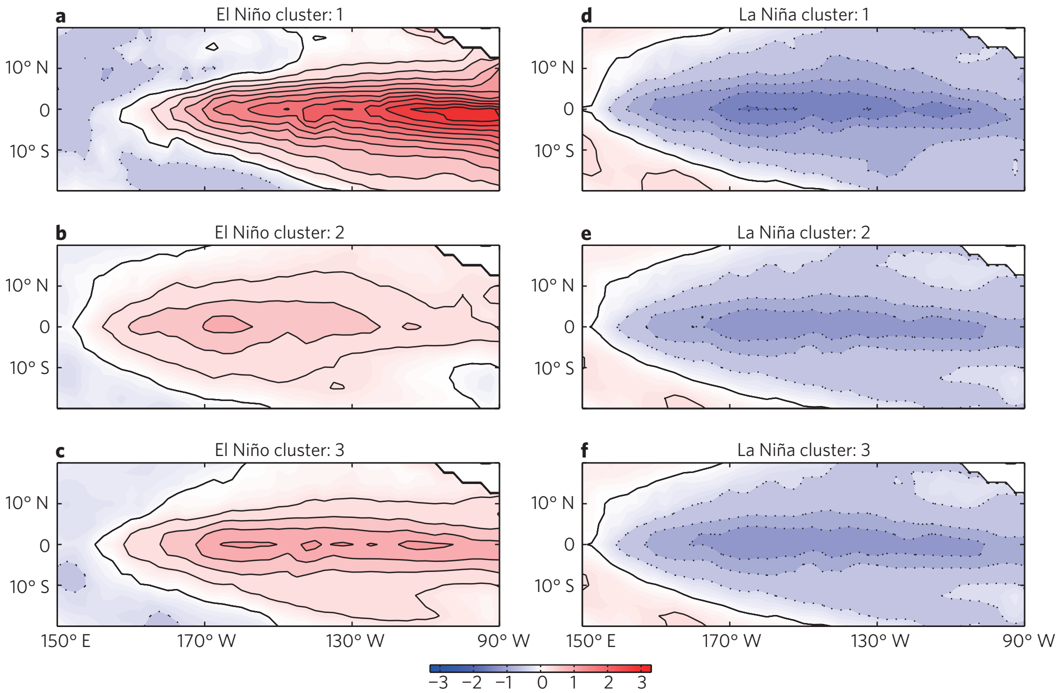

Figure 1 | The first three El Niño and La Niña clusters identified by the fuzzy clustering method. a–f, The identification of these warm (**a–c**) and cold (**d–f**) clusters of the tropical Pacific SST variability is based on 1961–2010 HadISST data. The contour interval is 0.3 °C, and negative contours are dotted. The three El Niño patterns are distinctively different, whereas the three La Niña patterns are essentially identical. The numbers of El Niño events dominated by patterns **a**,**b**,**c** are 3, 6, 8, respectively, while La Niña events are equally shared by patterns **d**,**e**,**f**.

classifications of El Niño and La Niña events. As mentioned earlier, there is a debate between two different classifications at present, both of which tend to classify El Niño events into two groups[27], consisting of either the cold-tongue and warm-pool events[19], or the canonical and extreme events[23]. The picture presented in Fig. 1, although still simplified, goes one step beyond the previous classifications and reconciles the debate between those two different views. Another point worth noting is the apparent lack of La Niña diversity in this fuzzy clustering analysis, whereas other studies revealed various La Niña patterns and their different regional and global impacts[29,30]. At present there is a general agreement that the distinction among La Niña events is much subtler than for El Niño, and thus the different flavours of the El Niño/La Niña cycle arise primarily from different types of El Niño rather than La Niña. One has to be mindful that any classification, including the one presented here, is to some extent subjective, and is often chosen based on practical convenience rather than rigorous mathematics. A minimal criterion for a valid classification is its consistency with the physical picture from our current understanding of El Niño dynamics.

Genesis of El Niño diversity

Now the question is what physical processes are responsible for the genesis of the diversified El Niño behaviour, including the canonical cycle as well as the extreme El Niño events to the east and the weak El Niño events to the west. As evident in Fig. 2 and also in previous studies[31,32], every El Niño event during the past 50 years was accompanied by WWB activity. Moreover, these wind bursts tended to be stronger and more frequent during large warm events, suggesting that WWB is not purely stochastic — there is a deterministic part of it that strongly depends on and in turn affects the low-frequency development of El Niño[31,32]. Basically, WWBs have two distinct effects on equatorial ocean dynamics: first, they cause surface water convergence and push down the equatorial thermocline, thus exciting eastward downwelling equatorial Kelvin waves that produce surface warming in the eastern equatorial Pacific[33]; and second, they generate strong equatorial surface currents, which advect warm water equatorwards and eastwards, extending the eastern edge of the warm pool[34]. Therefore, it is reasonable to hypothesize that, acting on top of a regular El Niño/La Niña cycle, WWBs may produce extreme El Niño events in the eastern equatorial Pacific through the combined effects of equatorial wave dynamics and surface warm-water advection, and they may also generate warm-pool El Niño near the dateline by advection alone when the phase of the basic recharge–discharge oscillation is unfavourable for a strong event to occur.

To test this hypothesis, we add SST-modulated WWB-like perturbation[35] to an intermediate ocean–atmosphere coupled model[3] (see Methods). The model by itself does not contain noise and is tuned to produce a regular oscillation with SST anomalies confined to the central-eastern Pacific (Fig. 3, leftmost column), in strong resemblance to the canonical El Niño/La Niña cycle. When WWBs are included, the interannual oscillation becomes highly irregular and the model reproduces different flavours of El Niño (Fig. 3). Strong warm events occasionally occur in the eastern Pacific, accompanied by congregated, cross-dateline WWBs. There are also relatively weak but more frequent warm events occurring in the vicinity of the dateline, with corresponding WWBs confined to the western Pacific. The model behaviour under WWB forcing is similar to the observations shown in Fig. 2, indicating that WWBs could be responsible for the genesis of both extreme El Niño and warm-pool El Niño, and thus for El Niño irregularity and diversity. Similar experiments have been executed in other studies[8,13,35,36], and it has been shown that whether these bursts give rise to one type of El Niño or the other depends on the timing of their occurrence relative to the phase of the recharge–discharge cycle of the equatorial upper-ocean heat content. This offers a renewed focus for monitoring and prediction of the state-dependent atmospheric perturbation, especially when combined with the recent finding that the fundamental aspects of the discharge onset may be independent of the particular flavour of El Niño[37].

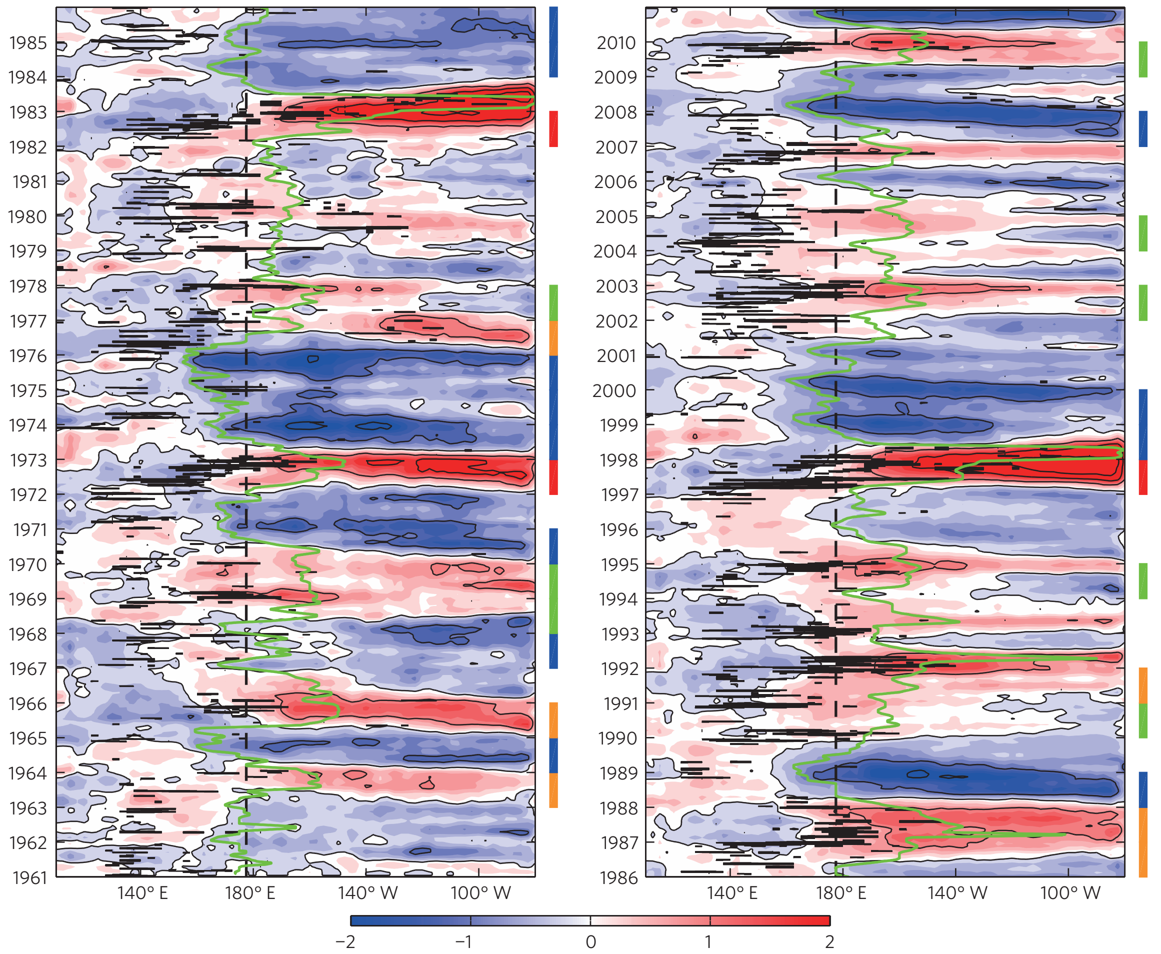

Figure 2 | Evolution of observed SST anomaly and WWB along the Equator from January 1961 to December 2010. The colours and contours are for SST anomaly and the horizontal black lines are for WWB. The contour interval is 1 °C and the thick green curve is the 28.5 °C SST isotherm, denoting the eastern edge of the warm pool. Red, green, orange and blue bars on the right mark the events dominated by extreme El Niño, warm-pool El Niño, canonical El Niño and La Niña, respectively.

The same fuzzy clustering method is applied to SST anomalies of the WWB-forced model run to examine the leading patterns of model variability (Fig. 4a–d). Similar to the observation-based classification shown in Fig. 2, the model SST variability can be classified into three distinctively different El Niño patterns and one La Niña pattern. These patterns together describe a symmetric, canonical cycle (Fig. 4c,d), on which are superimposed relatively rare extreme El Niño (Fig. 4a) and more frequent warm-pool El Niño events (Fig. 4b). Note that the effects of WWBs are unidirectional, in the sense that they generate additional types of El Niño but not La Niña, thus contributing significantly to the asymmetry of the El Niño/La Niña cycle[38]. To elucidate the physical processes involved in the genesis of different warm and cold events, Fig. 4e–h displays the average surface-layer heat budget during the growing phase of these events. Similar budget analysis has been performed by other investigators with somewhat different focus[19,20]. For extreme El Niños (Fig. 4e), the vertical advection (largely due to thermocline deepening) is clearly the dominant player, although horizontal advection also contributes. For warm-pool El Niños (Fig. 4f), however, the zonal and meridional advection are most important, with the vertical advection playing a negligible role. For the canonical cycle (Fig. 4g,h), the budgets of warm and cold phases are essentially symmetric, with all advection terms making significant contributions. These results are consistent with the dynamical reasoning that we have put forward.

Implications for El Niño predictability

El Niño has been the poster child for seasonal-to-interannual climate prediction, because it is by far the most energetic and influential short-term variability in the Earth's climate system. The potential predictability of El Niño is likely to be on the order of years (ref. 10), but real-time El Niño forecasting remains an elusive and formidable goal[39–41]. This is probably because predictability estimates were mainly based on models dominated by a single mode of El Niño variability or on hindcast skills of relatively large El Niño events[12], whereas in reality El Niño has a variety of flavours[17,27], especially in the past decade[21,42]. Our perspective on El Niño diversity has several implications for predictability. First, properly accounting for the effects of WWBs may be necessary for climate models to improve their El Niño simulation and prediction[43,44]. The fact that many models tend to produce a regular interannual oscillation centred in the central-eastern equatorial Pacific[45] suggests that they are only capable of generating a canonical cycle and thus would have limited predictive skill. Second, even if state-dependent WWBs are simulated or parameterized, the strong warm events in the eastern equatorial Pacific would be intrinsically more predictable than the weak warm events near the dateline, as WWBs are more strongly modulated and thus more deterministic during large warm episodes[32]. Finally, a measure of the basic El Niño/La Niña cycle (such as the equatorial Pacific upper-ocean heat content)[4,5] and its interplay with WWBs may serve as a precursor for event development[14,35].

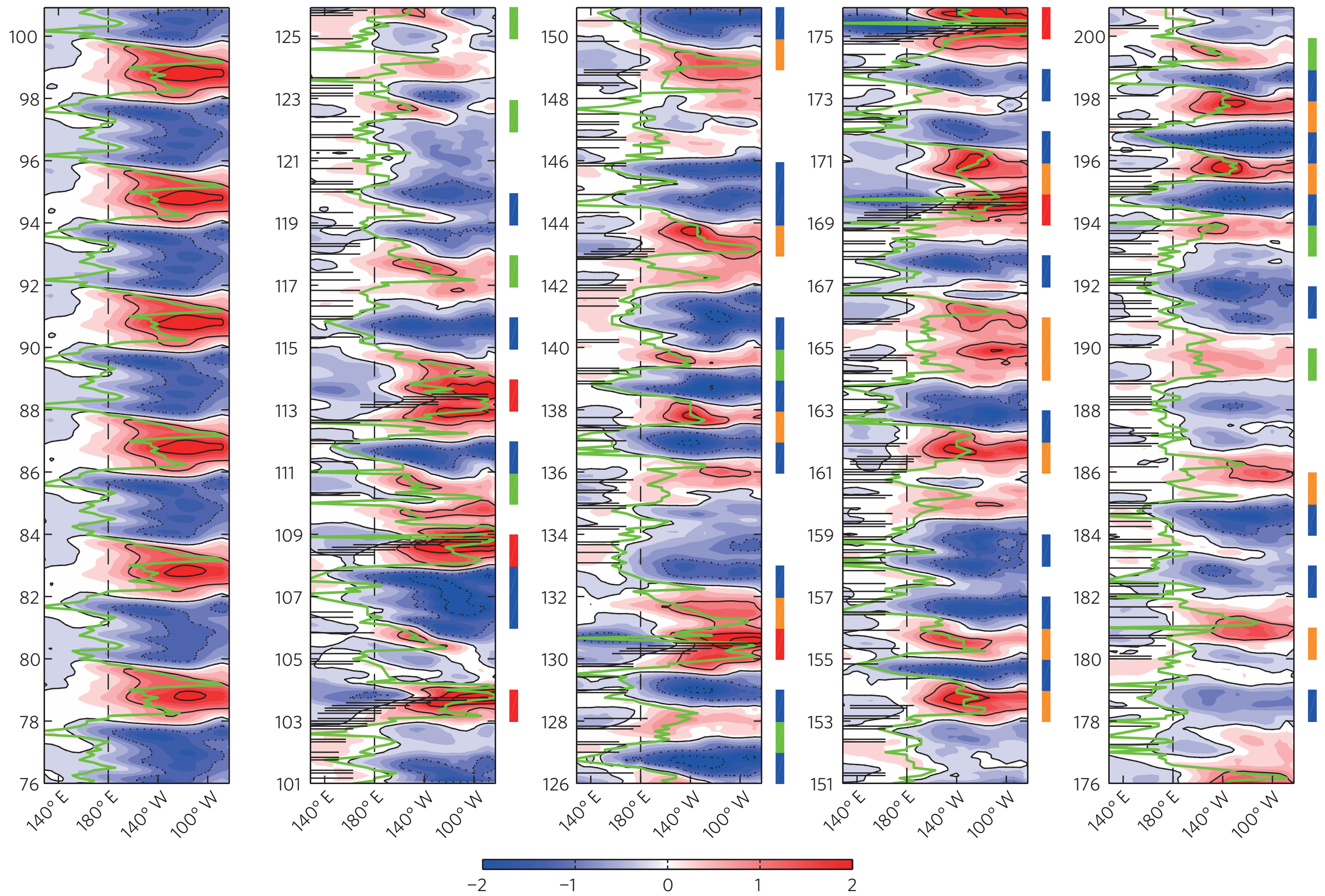

Figure 3 | Evolution of SST anomaly and WWB along the Equator for the last 125 years of a 200-year model runs. The colours and contours are for SST anomaly and the horizontal black lines are for WWB. Semi-random WWB forcing is started at the beginning of the 101st year. The contour interval is 1 °C and the thick green curve denotes the 28.5 °C SST isotherm. Red, green, orange and blue bars on the right mark the events of extreme El Niño, warm-pool El Niño, canonical El Niño and La Niña, respectively.

For instance, in spite of the media frenzy about a super El Niño to occur in 2014, the spring conditions of the equatorial heat content and WWBs correctly suggested that such an event was unlikely to take place. Figure 5 shows the integrated forcing from WWBs[46] and equatorial upper-ocean warm-water volume[5] preceding every El Niño event since 1982. It is clear that the 1997 and 1982 super El Niño events were preceded by very large build-up of heat content and strong (1997) or medium (1982) WWBs; the warm-pool El Niño events in 1994 and over the past decade were preceded by negative or small equatorial upper-ocean warm-water volume and weak to medium WWBs; and the moderate El Niño events such as those in 1986 and 1991 were preceded by medium equatorial upper-ocean warm-water volume and WWBs. These observations are generally consistent with our current understanding of the combined effects of WWBs and build-up of heat content. For 2014, warm-water volume was relatively large in March and April but not so for the months before and after; WWB peaked in January–February but decreased sharply afterwards. If the equatorial upper-ocean warm-water volume and WWB activity in winter and spring seasons were actually taken as precursors of the subsequent El Niño, the conditions of 2014 shown in Fig. 5 would suggest a weak to moderate event rather than a super El Niño.

To further examine the similarities and differences between the 2014 spring conditions and those preceding the 1997 super El Niño, Fig. 6 compares the evolutions of the equatorial SST and zonal wind anomalies from January to May between 2014 and 1997. The SST evolution patterns of the two years are similar, with warm anomalies developing in the western as well as the far eastern equatorial Pacific, apparently caused by WWB-induced warm-water advection and by downwelling Kelvin waves, respectively. The most notable difference is the strong westerly winds in May of 1997 extending from the western to central equatorial Pacific, whereas no such winds were observed at the same time in 2014, as also noticed by other investigators[14]. This is probably because of the much stronger warming centred near the dateline in the spring of 2014, which, according to the classic theory of tropical wind response to heating anomalies[47], would limit the development of westerly winds in the central equatorial Pacific. This difference may partly explain the absence of a super El Niño in 2014, because the development of strong westerly winds in the central equatorial Pacific in association with the warming to its east is an indication of positive ocean–atmosphere feedback[1], an essential element of large El Niño events.

In summary, the analyses presented here support the notion that El Niño is likely to be a result of the interplay between a self-sustaining symmetric oscillation dictated by classic theories, and the WWB-type perturbations that are partially modulated by El Niño itself. The former provides a basic dynamical framework, whereas the latter gives rise to different flavours of El Niño. Such a scenario is appealing because it reconciles hotly debated issues related to the classification and genesis of various El Niño events, by killing three birds — diversity, asymmetry and extremes — with one stone. But one must not dwell on the simplicity of the picture painted here. Our intention is to emphasize the strong influence of WWBs on

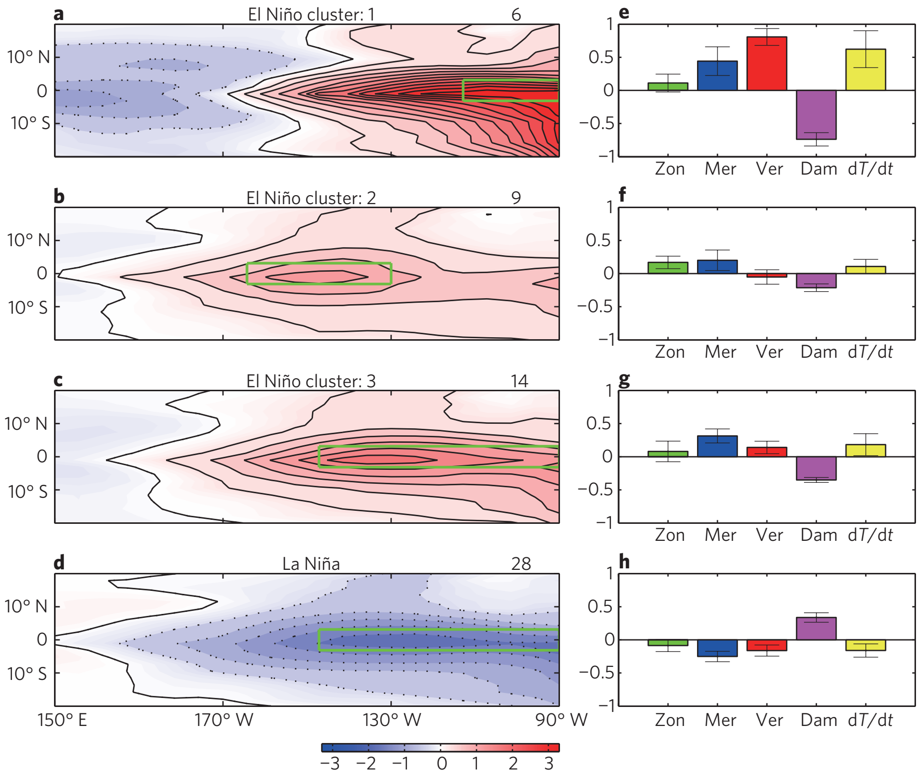

Figure 4 | El Niño and La Niña patterns (left column) and surface-layer heat budgets (right column) from WWB-forced model run. a–d, Three El Niño patterns and one La Niña pattern identified by the fuzzy clustering method. The contour interval is 0.3 °C and negative contours are dashed. The green box in each panel denotes the area of maximum SST variability. **e–h**, Surface-layer heat budgets in the green boxes of the corresponding left panels (**a–d**). Green, blue and red bars denote zonal, meridional and vertical advection, respectively. Yellow and purple bars are for the total tendency and damping term (negatively proportional to SST anomaly), respectively. Unit of all terms is °C per month. The budget is averaged over all events of the given pattern and over 12 months before an event reaches its maximum. Error bars show one standard deviation.

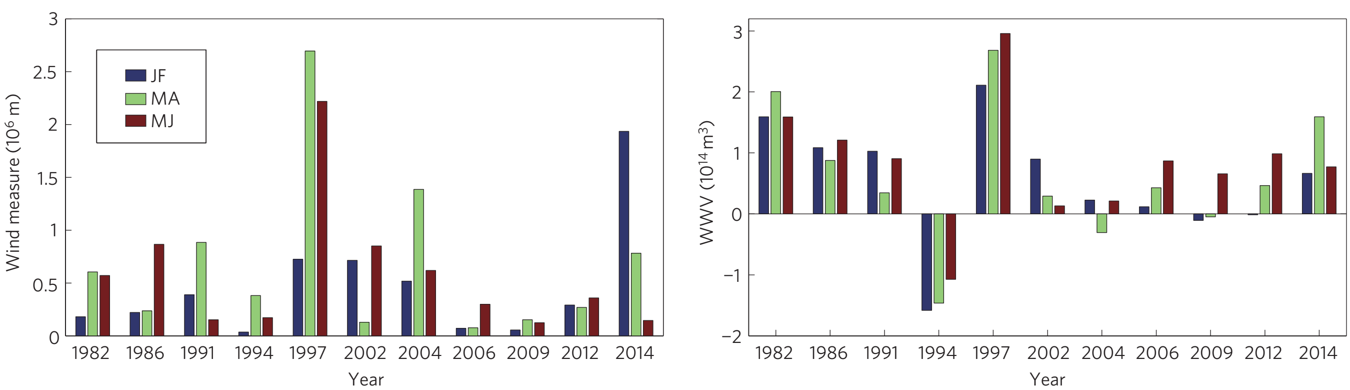

Figure 5 | WWB and warm-water volume anomalies in 11 El Niño years since 1982. Here WWB (left) is represented by wind measure[46], the time integral of WWBs over specified months, and WWV (right) is a measure of the equatorial heat content represented by the warm-water volume above the 20 °C isotherm[5]. These variables are integrated over the equatorial Pacific (5° S to 5° N, 110° E to 80° W) based on the NCEP and GODAS datasets, respectively. Blue, green and brown bars denote mean values in January–February, March–April and May–June, respectively.

El Niño diversity, but not to downplay other processes that may play significant roles in El Niño dynamics and thus contribute to the complexity of its diversity. For example, there are other precursors, from both the northern and southern Pacific extratropics, that seem to be important triggers in the excitation of El Niño events[48,49]. Moreover, aside from WWBs, there are also easterly wind surges in the equatorial Pacific, which may excite cold events[50]. The relative importance of all these processes and the possible interactions among them should be further explored to achieve a comprehensive understanding of El Niño diversity.

Methods

The fuzzy clustering method used in this study is an effective pattern-classification technique suitable for climate research[24]. It groups a set of given members into specified categories according to their degree of membership, which is defined as the root-mean-squared Euclidean distance to the cluster centre. The members analysed here are a subset of the monthly SST anomalies in the tropical Pacific (150° E to 90° W, 20° S to 20° N) during El Niño and La Niña events, with each type of event considered separately. These members have to meet two criteria: first, the average SST anomaly in at least one 40° longitude × 10° latitude box along the Equator has a magnitude greater than the local standard deviation and also greater than 0.5 °C; and second, such a condition lasts for at least five successive months.

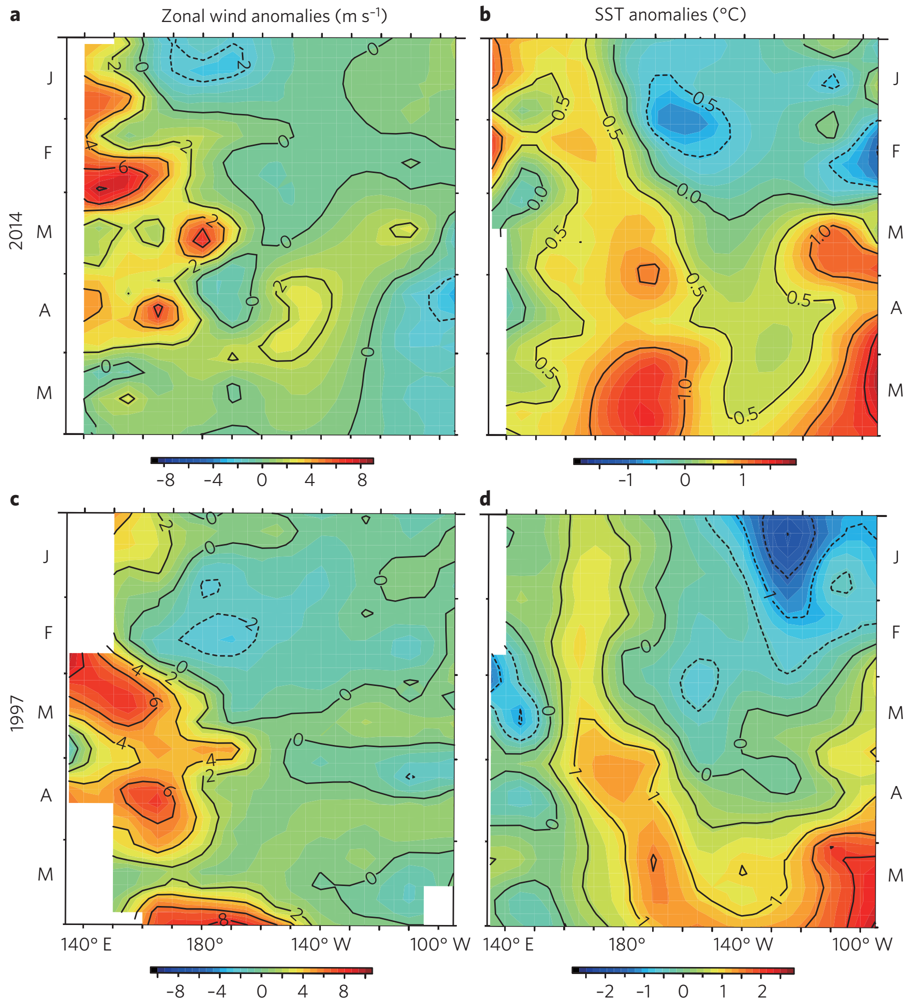

Figure 6 | Comparison of evolutions of zonal wind and SST anomaly during the first five months of 2014 and 1997. a–d, The zonal wind (**a**,**c**) and SST (**b**,**d**) anomalies for both 2014 (**a**,**b**) and 1997 (**c**,**d**) are from the TAO/TRITON observations provided by the TAO Project Office of PMEL. Positive values in **a** and **c** are for westerly wind anomalies.

Once the members are chosen, they are grouped into clusters in an iterative manner: first, a certain number of cluster centres are randomly chosen in the set of all members; second, the degree of membership of every member to each of the cluster centres is examined and grouped accordingly; and third, the cluster centres are updated with the average of the members in the groups. The second and third steps are looped until the target function, which scales the degree of membership of all members to all cluster centres, is smaller than a given tolerance. The optimal number of clusters is usually decided if the overlapping, separation and compactness of the cluster centres, which are scaled by statistical criteria such as partition coefficient and partition index, are optimal[24]. To meet such criteria, and to unify the previous classifications that group El Niño events into either cold-tongue and warm-pool types, or canonical and extreme types, we chose three to be the optimal number of clusters for our analysis.

The SST data used in this study is the Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST) version 1.1 from 1961 to 2010 with a resolution of 1° × 1° (http://www.metoffice.gov.uk/hadobs/hadisst/data/download.html). The daily surface wind speed is from the National Centres for Environmental Prediction (NCEP) reanalysis from 1961 to 2010 with a resolution of 2.5° × 2.5° (http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surface.html). The warm-water volume, which is defined as the integral of water above the 20 °C isotherm over the equatorial Pacific (120° E to 80° W, 5° S to 5° N)[5], is derived from the potential temperature and salinity datasets from the NCEP Global Ocean Data Assimilation System (GODAS) reanalysis from 1980 to 2014 (http://www.esrl.noaa.gov/psd/data/gridded/data.godas.html). The climatological seasonal cycle is removed to obtain anomalies. A WWB event is defined[35] as a westerly wind gust with a maximum speed of at least 7.0 m s^{-1}, a duration of 5 to 30 days and an anomalous speed exceeding 2.0 m s^{-1}.

The model used in this study is a slightly modified version of an intermediate ocean–atmosphere coupled model[3] widely applied to El Niño research and prediction. It differs from the original model in its improved parameterization of subsurface temperature anomaly based on newer observational data. The idealized WWBs added to the model preserve a Gaussian shape at the Equator, and their initial longitude is set to 135° E, with a magnitude of 0.25 N m^{-2}. In order to account for the low-frequency modulation of WWBs by SST, a simplified scheme of coupled SST–WWB relationship[35] is applied. The initial triggering of a WWB is purely random, but it is allowed to actually occur only when local SST exceeds 28.5 °C. Once this condition is met, the WWB moves eastward at a speed of 0.25° per day, which is representative of the observed propagation speed. When the scheme produces no WWBs for 40 consecutive days, the centre of the next WWB is set back to the initial longitude. The surface mixed layer of the model is fixed to 50 m, and the mixed-layer heat budget (Fig. 4), including all components of anomalous advection and a linear damping, is a standard output of the model.

Code availability. The code for the fuzzy clustering analysis and the numerical model are available on request from T.L. (liantao@sio.org.cn).

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Author contributions

D.C. conceived the work and wrote the paper. T.L. carried out data analyses and model experiments. C.F., M.A.C., Y.T., R.M., X.S., Q.W. and L.Z. contributed to the interpretation of the analysis and model results, and to the improvement of the manuscript.

Additional information

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Competing financial interests

The authors declare no competing financial interests.