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Mechanisms of the 2014-2016 Delayed Super El Niño Captured by Simple Dynamical Models

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Abstract Recent studies suggest that atmospheric wind bursts in the tropical Pacific have played a major role during the 2014-2016 period marked by a failed El Niño favoring a subsequent super El Niño with dramatic worldwide impacts. Here we show that this new type of major event or so-called delayed super El Niño is realistically and easily captured by simple dynamical models with emphasis on the role of state-dependent stochastic wind bursts, both easterly and westerly. We analyze in particular 1) qualitative model surrogates for this event compared and contrasted with the 1997-1998 super El Niño, 2) their formation mechanisms and 3) statistical occurrence as generated by random wind bursts. Despite favorable ocean conditions atmospheric wind bursts differentiate the failure or development as well as the delay of El Niño events in the simple model. In particular, the early El Niño stalling by easterly wind bursts and subsequent development by westerly wind bursts observed during 2014-2016 is consistently retrieved along with a realistic spatial structure and chronology. The simple model further allows one to analyze El Niño ensemble statistics that reveals a significant occurrence of the delayed super El Niño

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type in addition to super events like the one of 1997-1998 and moderate events. The present theoretical findings therefore suggest that delayed super El Niño events are not necessarily unusual in the tropical Pacific despite not appearing in the recent observational record and could reoccur in the future.

Keywords delayed super El Niño · simple dynamical models · stochastic wind bursts

1 Introduction

The El Niño-Southern Oscillation (ENSO) is the largest global climate signal on interannual time scales with dramatic worldwide impacts. It consists of alternating periods of anomalously warm El Niño conditions and cold La Niña conditions every 2 to 7 years, with considerable irregularity in strength, duration and structure of these events (Neelin et al, 1998; Clarke, 2008). The recent period was quite remarkable with the occurrence of a failed El Niño in 2014-2015 favoring a subsequent super El Niño in 2015-2016. Due to its unique chronology we refer hereafter to this event (or sequence of events) as the delayed super El Niño of 2014-2016. A brief illustration of the 2014-2016 period in observations is provided in Fig. 1 and discussed hereafter in Section 2. At the beginning of 2014, a recharged heat content and a series of westerly wind bursts (WWBs) indicated an emerging El Niño (McPhaden, 2015). The event progression however quickly stalled, due in particular to the occurrence of a historically strong easterly wind burst (EWB) in the middle of the year and a weakening of WWBs (Menkes et al, 2014; Hu and Fedorov, 2015; Chiodi and Harrison, 2017). Subsequently, the tropical Pacific remained in the recharged state with again favorable starting conditions for another event the following year (Levine and McPhaden, 2016; Hu and Fedorov, 2017). In contrast, the wind bursts were predominantly westerly in 2015 which favored the development of a major El Niño event at the end of the year similar in strength to the 1982-1983 or 1997-1998 events from the recent record (Paek et al, 2016). In particular, this unique chronology of events was most unanticipated by the scientific community. Most real-time forecasts predicted a strong event in 2015 that did not occur and further showed a great range in predicted intensity for the 2016 event (L'Heureux et al, 2017). The mechanisms and prediction of rare and extreme El Niño events such as the one of 2014-2016 still remain elusive, notably because in the relatively short observational record each of them shows unique and distinctive features (Cai et al, 2014; Takahashi and Dewitte, 2015).

During the 2014-2016 period, the most significant and unexpected feature was the evolution of wind burst activity in the tropical Pacific. A broad range of atmospheric disturbances in the tropics may be considered as possible triggers or inhibitors for ENSO variability, including WWBs (Harrison and Vecchi, 1997; Vecchi and Harrison, 2000; Lengaigne et al, 2004; Puy et al, 2016), EWBs (Hu and Fedorov, 2015, 2017) as well as the convective envelope of the Madden-Julian Oscillation (MJO) ((Moore and Kleeman, 1999); (Hendon et al, 2007);

(Majda and Stechmann, 2009)). The role of those atmospheric disturbances on the dynamics and irregularity of ENSO is still under debate. Most current state-of-the art Coupled General Circulation Models (CGCMS) are still struggling to capture the variability associated with wind bursts and organized tropical convection in general despite its dominant role in setting the ENSO characteristics ((Lin et al, 2006); (Seiki et al, 2011)). Recent improvements have been made in those models with the development of stochastic parameterizations schemes for the atmosphere, including state-dependent stochastic forcing (e.g. (Weisheimer et al, 2014); (Deng et al, 2015); (Deng et al, 2016); (Goswani et al, 2017); (Christensen et al, 2017)). Meanwhile, wind bursts are often parameterized in simpler models according to different recipes (e.g. (Fedorov, 2002); (Eisenman et al, 2005); (Jin et al, 2007); (Chen et al, 2015)). This may include sometimes ad-hoc prescriptions of wind burst thresholds and propagations, or even the complete omission of EWBs. Most studies however agree that the wind bursts characteristics are state-dependent on the Pacific system, with for example warmer sea surface temperatures (SSTs) favoring increased wind bursts activity ((Perez et al, 2005); (Tziperman and Yu., 2007); (Gebbie et al, 2007)). In addition, different dynamical scenarios can be envisioned for a stable equatorial Pacific system where the ENSO is a direct response to atmospheric disturbances in comparison to an unstable system where the ENSO is maintained by other internal processes ((Kessler, 2002); (Philander and Fedorov, 2003); (Kleeman, 2008)). Given the major role played by wind bursts on ENSO genesis and most particularly during the recent 2014-2016 period, it is crucial to include them in the theoretical framework ((Lian and Chen, 2017)).

Recently, a simple ENSO model was developed that emphasizes the role of wind bursts and realistically captures the ENSO diversity, including the eastern Pacific moderate and occasional super El Niño as well as the central Pacific El Niño (Thual et al, 2016; Chen and Majda, 2016, 2017; Chen et al, 2017). The model dynamics, amenable to detailed analysis, consist of stochastic wind bursts coupled to simple ocean-atmosphere processes that are otherwise deterministic, linear and stable. Such a coupled model where the external wind bursts play the role of maintaining the ENSO is fundamentally different from the Cane-Zebiak (Zebiak and Cane, 1987) and other nonlinear models that rely instead on internal instability. The wind burst stochastic parameterization retains both WWBs and EWBs and differs from the one of other simple models in several ways (e.g. (Eisenman et al, 2005; Jin et al, 2007; Chen et al, 2015)). First, as a null hypothesis the interactions between ENSO and WWBs are the same as those between ENSO and EWBs on a short time scale though they have different cumulating effects at interannual timescale. Second, there is a stochastic dependence of both types of wind bursts on the western Pacific warm pool strength instead of the eastern Pacific conditions. Third, there are no ad-hoc prescriptions of wind burst thresholds and propagations but instead intermittent and random transitions between different levels of wind burst activity.

Given its emphasis on wind bursts dynamics the above simple ENSO model is likely a useful theoretical framework to understand the mechanisms of the 2014-2016 delayed super El Niño. In this study, such an ENSO model is used to analyze 1) qualitative model surrogates for the 2014-2016 delayed super El Niño, 2) their formation mechanisms and 3) statistical occurrence as generated by random wind bursts. A few modeling studies have focused specifically on the role of wind bursts during the 2014-2016 period, though in different settings with either CGCMs of increased complexity (Hu and Fedorov, 2015, 2017), forced Ocean General Circulation Models (OGCMs, (Menkes et al, 2014; Chiodi and Harrison, 2017)) or simpler conceptual models with ordinary differential equations (Levine and McPhaden, 2016).In contrast with CGCMs and OGCMs, simple dynamical models such as the present one reveal the ENSO mechanisms in a more straightforward way and are usually computationally efficient which allows detailed studies. In addition, although conceptual models with ordinary differential equations capture the basic ENSO oscillation, the spatial structures and dependencies including the wave propagations are not explicit. Here we show that the present simple ENSO model can realistically and easily capture the overall structure and chronology of the 2014-2016 delayed super El Niño as well as its distinctive features from the 1997-1998 El Niño, including an early stalling and development the following year as in nature. In addition to this, we demonstrate in systematic fashion that such a delayed and intensified El Niño development results from an initial stalling by EWBs and subsequent triggering by WWBs, which confirms findings from the above recent studies. Finally, the simple model further allows one to analyze El Niño ensemble statistics. Results from ensemble runs experiments with identical initial conditions show that random wind bursts dramatically affect the timing and strength of El Niño events in the model leading to either delayed super El Niño events as well as super events, moderate events or no events at all. We find in particular that starting from favorable recharged conditions around 75% of events develop immediately while around 20% of events are delayed to the following year. Those results suggest that delayed super El Niño events are statistically significant in the tropical Pacific system despite not appearing in the recent observational record and could reoccur in the future.

The article is organized as follows. In Section 2 we first provide a brief illustration of the 2014-2016 delayed super El Niño in observations. In Section 3 we briefly present the ENSO model used in this study. In Section 4 we analyze qualitative model surrogates for the 2014-2016 delayed super El Niño, their formation mechanisms and statistical occurrence as generated by random wind bursts. Section 5 is a discussion with concluding remarks. Finally, extensive additional information is provided in the supplementary material including details on the model formulation as well as additional experiments.

2 The Delayed Super El Niño in Observations

This section provides a brief illustration of the 2014-2016 delayed super El Niño as well as the 1997-1998 super El Niño in observations. The following three observational datasets are used: daily zonal winds at 850hPa from the NCEP/NCAR reanalysis (Kalnay et al, 1996), daily sea surface temperatures from the OISST reanalysis ((Reynolds and al, 2007)), and monthly thermocline depth from the NCEP/GODAS reanalysis (Behringer et al, 1998). Reanalysis data is provided by NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (http://www.esrl.noaa.gov/psd/). All fields are averaged within 5N-5S and applied a 90-days running mean, while wind bursts are computed as the residual of the zonal winds running mean. This separation is however artificial to some extent because wind bursts in nature also have a low-frequency component (Puy et al, 2016). The sum of zonal winds and wind bursts is referred to as total zonal winds anomalies.

Fig. 1 (top) shows the chronology of the 2014-2016 delayed super El Niño in observations. The delayed super El Niño in Fig. 1 starts in early 2014 with gradually increasing SST, zonal winds and thermocline depth in the western Pacific, as well as a sequence of WWBs. The development of this event is first stalled due notably to a historically strong EWB in June 2014 and subsequent weak WWBs in 2014. The strong EWB of June 2014 can be seen to some extent in Fig. 1(a) however due to its large zonal fetch it would be best measured by the zonal average of wind bursts over the entire Pacific (Hu and Fedorov, 2015). After the event stalling in 2014 the equatorial Pacific is again in favorable buildup conditions at the start of 2015. During 2015 a series of strong WWBs leads to the development of the delayed super El Niño peaking in late 2015 and early 2016.

For comparison, Fig. 1 (bottom) also shows the evolution of the 1997-1998 super El Niño. The super El Niño in Fig. 1 starts with gradually increasing SST, zonal winds and thermocline depth in the western Pacific in 1997. In contrast to the 2014-2016 period, wind bursts are predominantly westerly during the entire year of 1997 leading to a peaking of the super El Niño in late 1997 and early 1998 followed by a reversal towards La Niña conditions in the spring of 1998.

3 Model and Methods

Here we briefly present the ENSO model used in this study with an emphasis on its wind bursts parameterization while a complete formulation is provided in the supplementary material. We analyze here the earlier model version from Thual et al. (Thual et al, 2016) that captures the eastern Pacific moderate and occasional super El Niño while additional nonlinear dynamical elements from Chen and Majda (Chen and Majda, 2016, 2017) that facilitate the central Pacific El Niño are omitted. In particular, in the absence of stochastic wind bursts such a coupled system is linear, deterministic and stable. This simplification allows us to focus on the role of wind bursts during the 2014-2016 period in nature, even though results shown hereafter are qualitatively similar in the more complete model from Chen and Majda (Chen and Majda, 2016, 2017) (see supplementary material, Fig. S8).

The starting model consists of a non-dissipative atmosphere coupled to a simple shallow-water ocean and SST budget. All variables are anomalies including zonal winds u, zonal currents U, thermocline depth H and SST T. Note that the atmosphere is consistent with the skeleton model for the MJO (Majda and Stechmann, 2009; Thual et al, 2014), valid here on the interannual timescale and suitable to describe the dynamics of the Walker circulation (Majda and Klein, 2003; Stechmann and Ogrosky, 2014).

A key element in the model is the addition of stochastic wind bursts perturbations that represent several important ENSO triggers found in nature such as WWBs, EWBs as well as the convective envelope of the MJO. The wind bursts perturbations have a fixed spatial structure centered in the western Pacific (see Fig. S1) and an amplitude a_p (positive for WWBs and negative for EWBs) that evolves as follows:

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$$\frac{da_p}{d\tau} = -d_p a_p + \sigma_p \dot{W}(\tau), \qquad (1)$$

where τ is time, d_p is dissipation and $\dot{W}$ is a white noise source of intensity σ_p. In particular, σ_p depends on the western Pacific warm pool strength. For instance, wind bursts of increased intensity are usually favored in nature by warmer SSTs in the western Pacific or when the warm pool extends eastwards. To account for this, we allow the equatorial Pacific system to switch back and forth between two Markov states (Lawler, 2006; Majda and Harlim, 2012):

$$\sigma_p = \begin{cases} \sigma_{p0} & \text{for the quiescent state 0} \\ \sigma_{p1} & \text{for the active state 1,} \end{cases} \qquad (2)$$

where increased wind burst activity $\sigma_{p1} > \sigma_{p0}$ in the active state 1. The probabilities of transiting from one state at time τ to the other at a time $\tau + \Delta\tau$ read:

$$\begin{aligned} P(\sigma_p(\tau+\Delta\tau) = \sigma_{p1} | \sigma_p(\tau) = \sigma_{p0}) = \mu_{01}\Delta\tau + o(\Delta\tau) \\ P(\sigma_p(\tau+\Delta\tau) = \sigma_{p0} | \sigma_p(\tau) = \sigma_{p1}) = \mu_{10}\Delta\tau + o(\Delta\tau), \end{aligned} \qquad (3)$$

where the transition rates μ_{01} and μ_{10} depend on T_W the average of SST anomalies in the western half of the equatorial Pacific as:

$$\begin{aligned} \mu_{01} &= (1 + \tanh(2T_W))/21 \\ \mu_{10} &= (1 - \tanh(2T_W))/4.4. \end{aligned} \qquad (4)$$

In particular, a stronger warm pool ($T_W \geq 0$) favors the transition to the active state with increased wind burst activity, and conversely a weaker warm pool ($T_W \leq 0$) favors the transition to the quiescent state. Note that the interactions between ENSO and WWBs are the same as those between ENSO and EWBs on a short time scale but have different cumulating effects at interannual timescale.

4 Analysis and Results

Here we use the ENSO model presented above to analyze 1) qualitative model surrogates for the 2014-2016 delayed super El Niño compared and contrasted with the 1997-1998 super El Niño, 2) their formation mechanisms and 3) statistical occurrence as generated by random wind bursts. Fig. 2 shows model long-term solutions from a numerical experiment. The model simulates a realistic intermittent and irregular ENSO cycle with occasional delayed and super El Niño events (at years 206 and 234, respectively) as well as many moderate events (e.g. at years 212, 226, 229) (see also Fig. S3, S4, S5 in the supplementary material for additional examples). In particular, during those events the increased warm pool strength (T_W) switches the system to the active Markov state 1 with increased wind burst activity a_p (cf Eq. 2-4). However, increased wind burst activity is a necessary but nonsufficient condition for El Niño development in the model as shown by several examples of weak or failed events (e.g. at years 215, 240, 244).

We now propose 1) qualitative model surrogates for the 2014-2016 period in nature. Fig. 3 (top) shows a zoom on the event from Fig. 2 around years 204 to 206. The chronology of this event realistically resembles the one of the 2014-2016 delayed super El Niño (see Fig. 1 for comparison). The event in Fig. 3 starts around year 204 with a recharged state favorable to El Niño development consisting of increased SST and thermocline depth in the western Pacific. At the middle of year 204, those anomalies propagate towards the eastern Pacific as indicative of an emerging El Niño but quickly stall. Subsequently, the western Pacific conditions persist until the development of a super El Niño peaking around year 206. Wind burst activity plays a key role during this event, as in nature. To highlight this, the 90-days running mean of a_p in Fig. 3 (black line) measures whether sequences of wind bursts are dominantly westerly (when positive) or easterly (when negative). We show in addition the propagation and reflection of the oceanic Kelvin and first Rossby waves that are forced by zonal winds and wind bursts in the model (see supplementary material for their derivation). The wind bursts around years 204 to 205 are both westerly and easterly resulting in overall weak changes in SSTs. In particular, the eastern Pacific warming at the middle of year 204 is initiated by strong WWBs and associated downwelling Kelvin wave but immediately stalled by a subsequent strong EWB and associated upwelling Kelvin wave. In contrast, the wind bursts become dominantly westerly during year 205 resulting in a steady increase of SST in the eastern Pacific and the development of the super El Niño. Finally, wind burst activity shutdowns at year 206 initiating a relaxation of conditions towards La Niña. For comparison, Fig. 3 (bottom) shows a zoom on the event from Fig. 2 around years 233 to 234 as a qualitative surrogate for the 1997-1998 super El Niño in nature. Despite similar starting conditions the wind bursts are dominantly westerly during the development of this event resulting in a steady increase of SST in the eastern Pacific.

We now discuss 2) the overall formation mechanisms of the delayed super El Niño in the model. In particular, we demonstrate that the initial stalling by EWBs along with subsequent WWBs (Fig. 3) favors a delayed development the following year, in agreement with recent studies (Hu and Fedorov, 2015, 2017; Levine and McPhaden, 2016; Chiodi and Harrison, 2017) though with a different method. Fig. 4 shows lagged correlations between T_E the average of SST anomalies in the eastern Pacific and other fields. This highlights an "ideal scenario" with conditions and chronology that are on average favorable to El Niño genesis in the model. Wind bursts that are dominantly easterly first favor the buildup of SST and thermocline depth in the western Pacific around -2 to -1 years prior to the event peak (cf negative correlation with a_p). Next, dominant WWBs around -1 to 0 years initiate and intensify the propagation of those anomalies towards the eastern Pacific. Finally, wind bursts shutdown around the event peak (cf null correlation after +0 years) initiating a relaxation of conditions towards La Niña. Note that lagged correlations are increased for the 90-days running mean of a_p (black line) because the low-frequency component of wind bursts is more efficient at forcing the ocean-atmosphere system.

We now analyze 3) the statistical occurrence of the delayed super El Niño in the model. Wind bursts are shown to dramatically affect the timing and strength of El Niño events with a significant occurrence of delayed super events. To assess this, we consider ensemble run experiments (5000 members) all initiated from favorable initial conditions qualitatively similar to the ones of early 2014 in nature. Those initial conditions (taken at year 204.3 in Fig. 3) consist of a recharged state established for around 6 months with increased SST and thermocline depth in the western Pacific in the active state of wind burst activity. Fig. 5 shows examples of ensemble members including a delayed super El Niño event (A), a super event (B) and a moderate event (C). Despite identical initial conditions those events differ dramatically due to the random wind bursts. The delayed super event A is first stalled by EWBs then triggered the following year by strong WWBs, in agreement with Fig. 3 and the genesis scenario from Fig. 4. There are in contrast strong and sustained WWBs at the onset of the super event B in Fig. 5 and unsustained WWBs at the onset of the moderate event C. See also Fig. S6 in the supplementary material for the evolution of ensemble mean and standard deviation.

Fig. 6 shows statistics for the ensemble run experiments, where in order to differentiate all types of events we look at the timing and amplitude of the El Niño SST peak in the eastern Pacific. The scatterplot in Fig. 6(a) shows that a large diversity of events is generated by random wind bursts covering all above scenarios (A,B,C). Delayed super events (A) peak later than super events (B) and both have a stronger peak amplitude than moderate events (C). Interestingly, delayed events are slightly stronger on average due to their increased buildup time as shown by the positive correlation between peak timing and amplitude (cf regression curves in Fig. 6a). Fig. 6(b) shows the probability density function (PDF) of peak amplitude, that is realistically skewed with a fat tail indicative of rare super events in the model (Thual et al, 2016; Chen and Majda, 2016, 2017; Chen et al, 2017). Finally, Fig. 6(c) shows the PDF of peak timing, indicating that around 75% of events peak around the first year following favorable starting conditions, while around 20% of events are delayed to the second year. This suggests that delayed super El Niño events are not unusual, at least in the present model. Finally, a remaining 5% of events peak around the third year and beyond that are related to subsequent evolution of the ENSO cycle. Note that slightly different initial conditions lead to qualitatively similar results overall with still a significant occurrence of delayed super events (not shown). However, a slightly stronger initial recharged state that has been established for a longer period increases the likelihood of delayed events by construction and conversely. As another proof of the significance of super delayed El Niño events, those are found to be prominent in the long-term solutions of the model (see e.g. Fig. 2 as well as Fig. S3 in the supplementary material).

5 Discussion

In this study, a simple ENSO model has been used to analyze 1) qualitative model surrogates for the 2014-2016 delayed super El Niño, 2) their formation mechanisms and 3) statistical occurrence as generated by random wind bursts. The model realistically captures the overall structure and chronology of such an event as well as its distinctive features from the 1997-1998 El Niño, including the early stalling by EWBs and subsequent WWBs favoring a delayed and intensified development as in nature. In addition, random wind bursts are shown to dramatically affect the timing and strength of El Niño events in the model with a significant occurrence of delayed super events.

Given the major role played by wind bursts on ENSO genesis and most particularly during the recent 2014-2016 period, it is crucial to reconsider their dynamics and mechanisms in the theoretical framework ((Lian and Chen, 2017)). Most CGCMs still struggle to capture the ENSO variability but have shown recent improvements notably with the development of stochastic parameterizations schemes for the atmosphere, including state-dependent stochastic forcing (e.g. (Weisheimer et al, 2014; Deng et al, 2015, 2016; Goswani et al, 2017; Christensen et al, 2017)). In contrast with CGCMs, simple dynamical models such as the present one reveal the ENSO mechanisms in a more straightforward way and are usually computationally efficient which allows for more detailed studies and insight on suitable parameterizations. Although many wind bursts parameterizations are used in simple ENSO models (e.g. (Eisenman et al, 2005; Jin et al, 2007; Chen et al, 2015)), the present model for example emphasizes the role of both WWBs and EWBs and their stochastic state-dependence on the western Pacific warm pool strength. EWBs in particular have been given much less emphasis than WWBs in theoretical studies prior to the 2014-2016 delayed super El Niño despite playing a major role during the evolution of such an event. More detailed representations of wind bursts may include in addition varying fetch and localization depending on the underlying SST conditions (Gebbie et al, 2007; Thual et al, 2014). Finally, it is important to discuss different theoretical scenarios in light of the recent period where the ENSO is either triggered by external wind bursts or instead by internal instability (Philander and Fedorov, 2003; Kleeman, 2008).

Despite providing theoretical insight, simple models lack a large diversity of processes found in nature that are necessary for a complete description of the 2014-2016 El Niño and other super events in general. The mechanisms and prediction of those rare events still remain elusive, because in the relatively short observational record each of them shows unique and distinctive features (Paek et al, 2016; L'Heureux et al, 2017). For example, it is still unclear whether the El Niño stalling by EWBs in 2014 and subsequent development (McPhaden, 2015; Hu and Fedorov, 2015, 2017; Chiodi and Harrison, 2017) was statistically speaking exceptional. In the present study we find that starting from favorable recharged conditions around 75% of events develop immediately while around 20% of events are delayed to the following year. Those results suggests, at least in the present model, that delayed super El Niño events are statistically significant in the tropical Pacific despite not appearing in the recent observational record and could reoccur in the future. Assessing this requires further understanding of the underlying ENSO dynamics as well as decadal variability and anthropogenic climate change that keeps modifying the background conditions of the equatorial Pacific and the statistics for the occurrence of different types of El Niño events (Cai et al, 2014; Takahashi and Dewitte, 2015).

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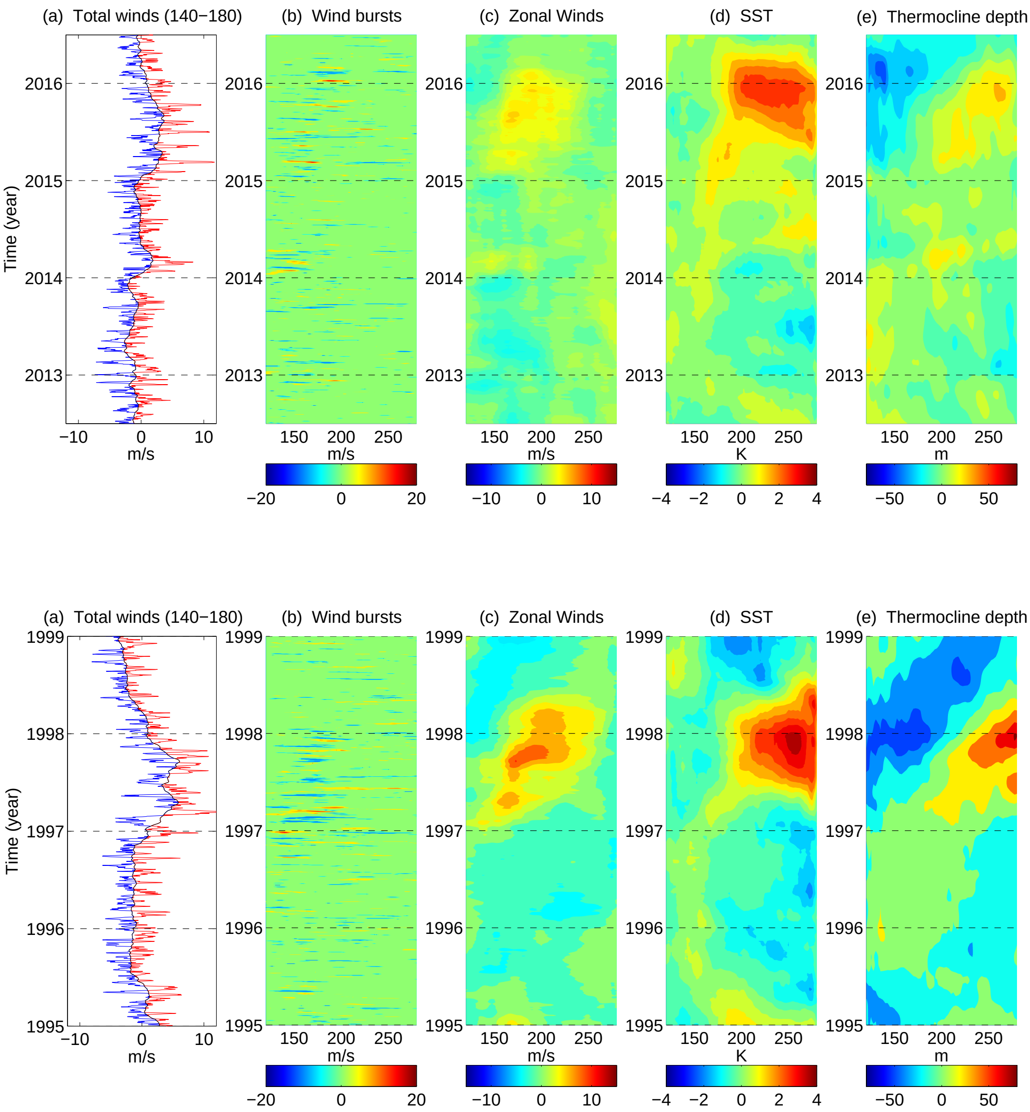

Fig. 1 Chronology of the 2014-2016 delayed super El Niño (top) and 1997-1998 super El Niño in observations (bottom). (a) Total zonal winds anomalies in the western Pacific ($m.s^{-1}$, average 140E-180E) including a 90-days running mean (black, with values above/below the running mean in red/blue respectively). Hovmollers of (b) wind bursts ($m.s^{-1}$, computed as residual from a 90-days running mean), (c) zonal winds anomalies ($m.s^{-1}$), (d) SST anomalies (KK), and (e) thermocline depth anomalies (m).

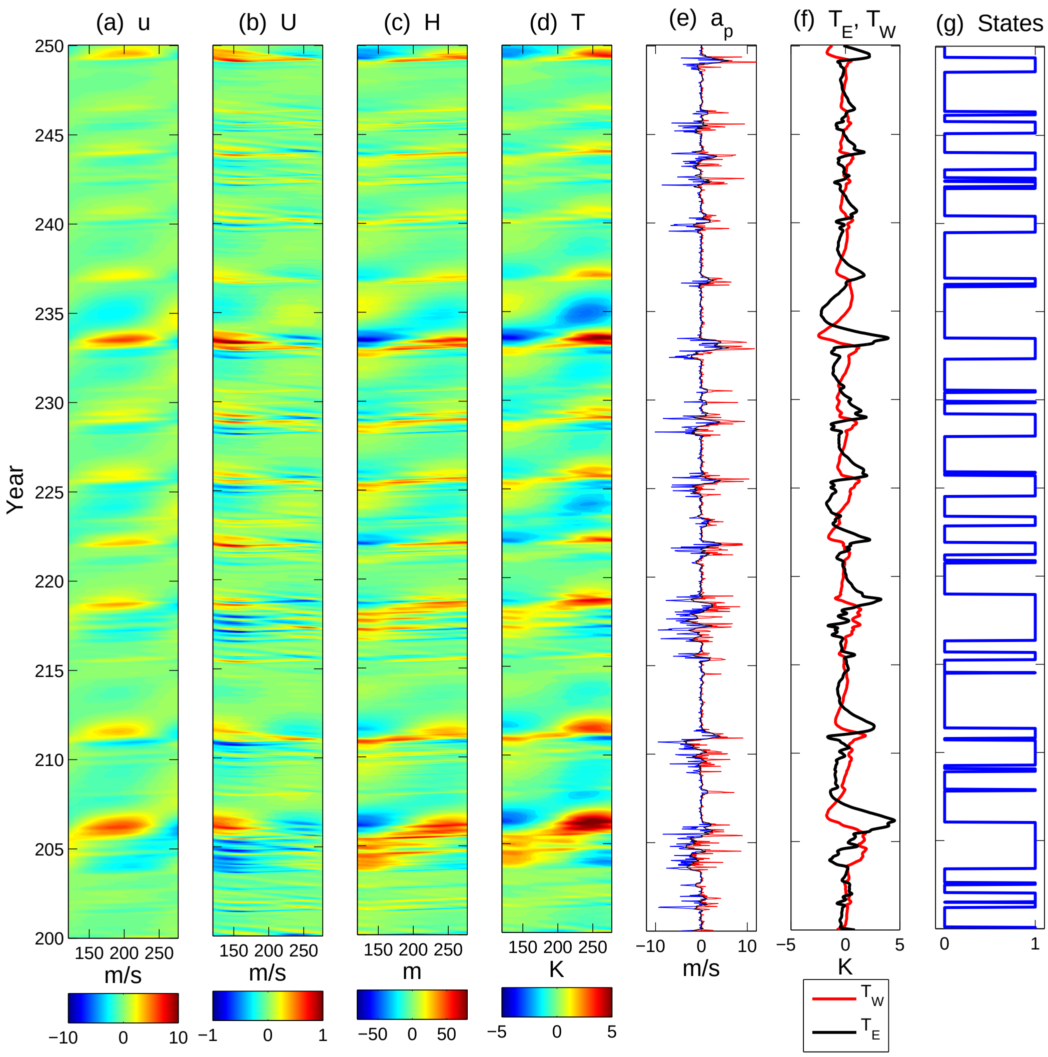

Fig. 2 Model solutions with examples of super, delayed, moderate and failed El Niño events. Hovmollers at equator for anomalies of (a) zonal winds u ($m.s^{-1}$), (b) zonal currents U ($m.s^{-1}$), (c) thermocline depth H (m), and (d) SST T (K), as a function of longitude (deg E) and time (years). Timeseries of (e) wind bursts amplitude a_p ($m.s^{-1}$, including a 90-days running mean in black and values above/below the running mean in red/blue respectively). (f) Averages T_E (K, black) and T_W (K, red) of SST T in the eastern and western half of the equatorial Pacific, respectively. (g) the Markov state of the model.

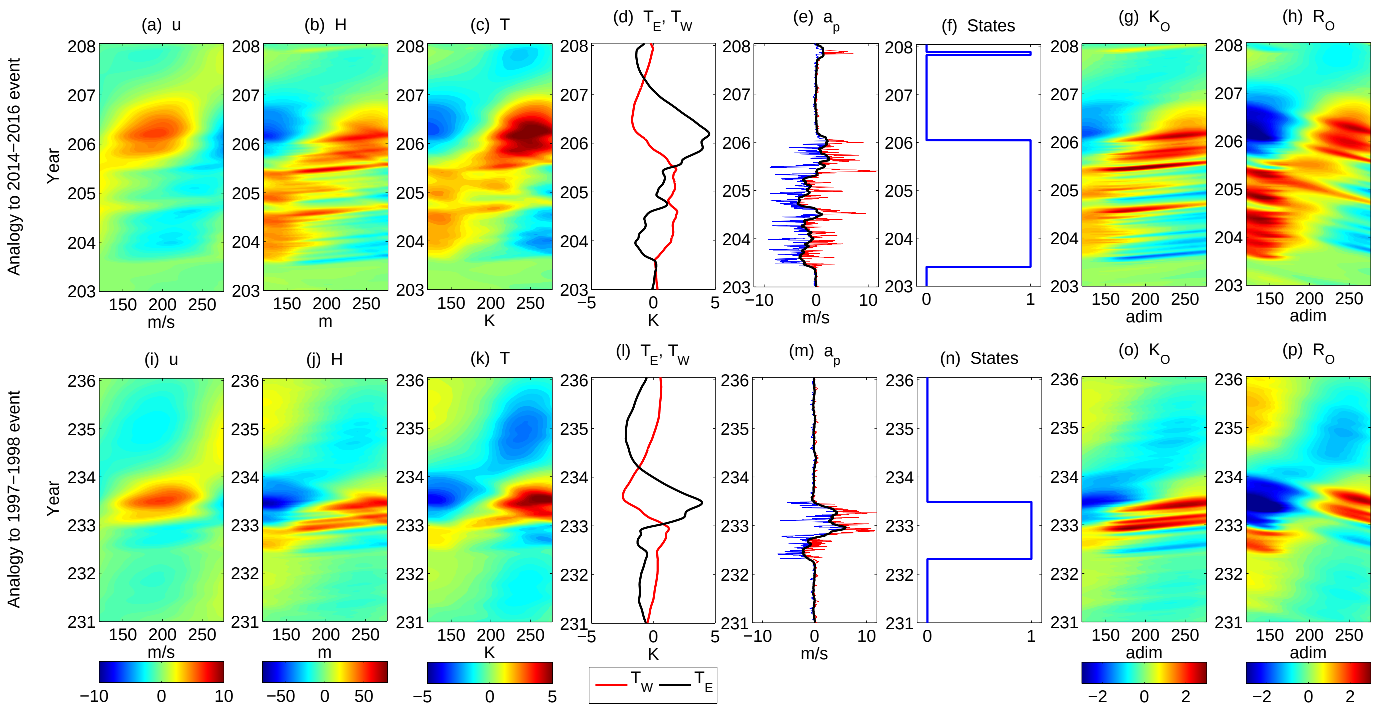

Fig. 3 Model surrogates for the 2014-2016 delayed super El Niño (top) and 1997-1998 super El Niño (bottom), obtained from zooms in Fig. 2. (g,h) Amplitude of oceanic (g) Kelvin and (h) first Rossby waves.

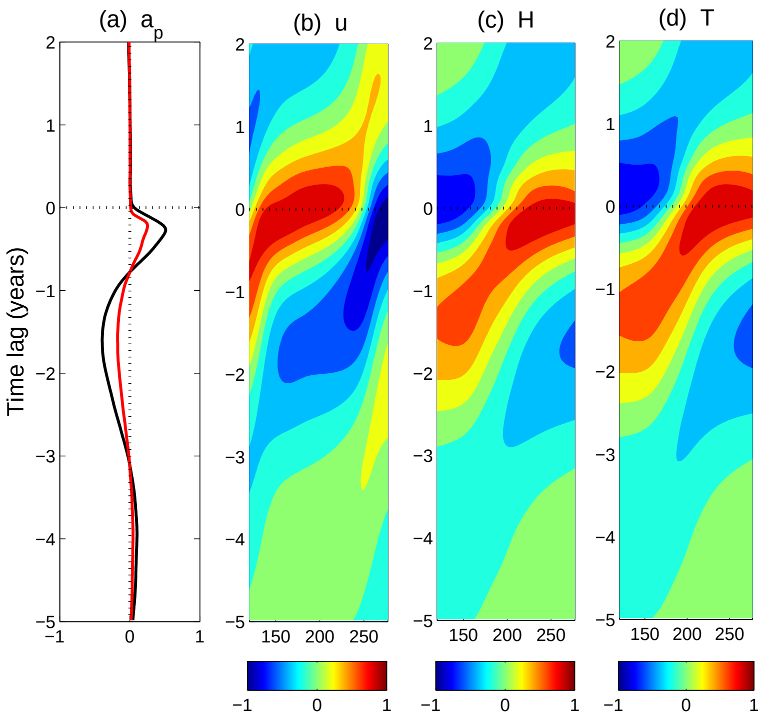

Fig. 4 El Niño formation mechanisms. Lagged correlations between eastern Pacific SST T_E in the model and anomalies of (a) wind bursts amplitude a_p (red, including its 90-days running mean in black), (b) zonal winds u, (c) thermocline depth H and (d) SST T.

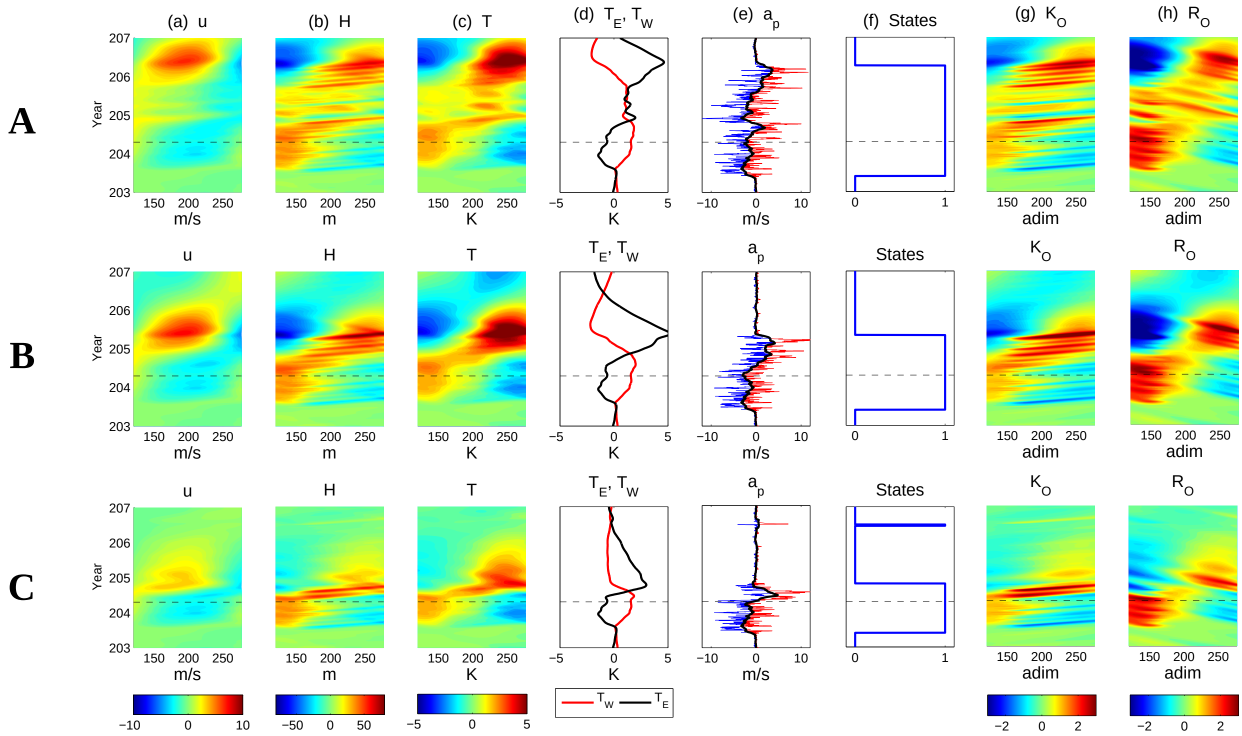

Fig. 5 Examples of ensemble run members, including a (A) delayed super El Niño event, (B) super event and (C) moderate event. All events are initiated from identical initial conditions at year 204.3 (dashed line) and differ due to random wind bursts.

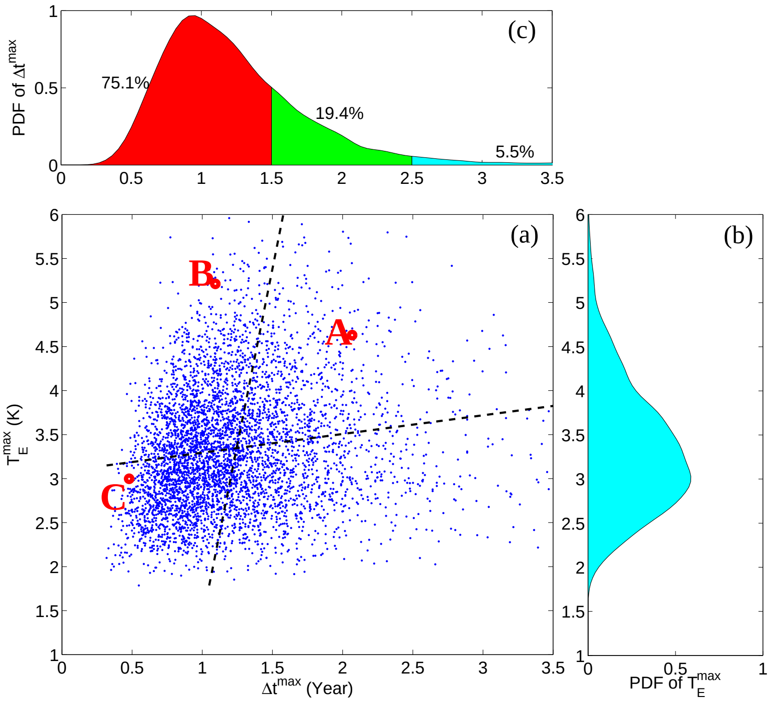

Fig. 6 Statistics of ensemble runs with identical initial conditions. (a) Scatterplot of El Niño peak time since initial conditions Δt^{max} (years) and peak amplitude T_E^{max} (K) as computed from SST indice T_E, with overplot of regression curves (black dashed lines) and individual events A, B, C from Fig. 5 (red). (b) PDF of T_E^{max} (K). (c) PDF of Δt^{max}, with separation between occurrence within 0 to 1.5 yr (75.1% of events), 1.5 to 2.5 years (19.4%) and beyond (5.5%).