Ensemble-mean dynamics of the ENSO recharge oscillator under state-dependent stochastic forcing

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[1] In this paper, the conceptual recharge oscillator model for the El Niño-Southern Oscillation phenomenon (ENSO) is utilized to study the influence of fast variability such as that associated with westerly wind bursts (WWB) on dynamics of ENSO and predictability. The ENSO-WWB interaction is simply represented by stochastic forcing modulated by ENSO-related sea surface temperature (SST) anomalies. An analytical framework is developed to describe the ensemble-mean dynamics of ENSO under the stochastic forcing. Numerical ensemble simulations verify the main results derived from the analytical ensemble-mean theory: the state-dependent stochastic forcing enhances the instability of ENSO and its ensemble spread, generates asymmetry in the predictability of the onsets of cold and warm phases of ENSO, and leads to an ensemble-mean bias that may eventually contribute to a climate mean state bias.
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1. Introduction

[2] The slow deterministic dynamics of the El Niño-Southern Oscillation (ENSO) phenomenon have been extensively explored using conceptual and intermediate models [e.g., *Anderson and McCreary*, 1985; *Cane and Zebiak*, 1985; *Suarez and Schopf*, 1988; *Battisti and Hirst*, 1989; *Philander*, 1990; *Jin*, 1997]. These studies consistently suggested that deterministic ENSO dynamics are governed by the leading coupled oscillatory modes in the tropical Pacific. However, a number of studies suggested that the Madden-Julian Oscillation (MJO), westerly wind bursts (WWB), and North-Pacific Oscillation (NPO), may all have significant impacts on ENSO variability and predictability [e.g., *Kessler et al.*, 1995; *Kleeman and Moore*, 1997; *Moore and Kleeman*, 1999; *Perigaud and Cassou*, 2000; *Zhang et al.*, 2001; *Zhang and Gottschalck*, 2002; *Yu et al.*, 2003; *Lengaigne et al.*, 2004; *McPhaden*, 2004; *Vimont et al.*, 2001; *Zavala-Garay et al.*, 2005]. Moreover, not only is ENSO dependent on fast atmospheric variability, but MJO and WWB activity is modulated by temperature anomalies in the central equatorial Pacific [*Keen*, 1982; *Luther et al.*, 1983; *Gutzler*, 1991; *Kessler et al.*, 1995; *Kessler and Kleeman*, 2000; *Vecchi and Harrison*, 2000; *Yu et al.*, 2003; *Eisenman et al.*, 2005; *Perez et al.*, 2005]. As conjectured by *Keen* [1982], *Lukas* [1988] and *Lengaigne et al.* [2004], an individual MJO/WWB can shift the warm pool eastward, making it more likely for more MJO/WWB events to be generated and thus further extensions of the warm water front and developments of Kelvin pulses, which may contribute to the generation of a mature El Niño event. This type of fast and coupled interaction, which can be parameterized in terms of a multiplicative noise source, may have an important influence on ENSO predictability [*Lengaigne et al.*, 2004], the instability of ENSO [*Eisenman et al.*, 2005], and the statistical probability distribution of ENSO [*Perez et al.*, 2005]. The aim of our study is to develop a new theoretical framework that captures and synthesizes these effects and illustrates the main qualitative differences between the additive [e.g., *Penland and Sardeshmukh*, 1995; *Thompson and Battisti*, 2000; *Zavala-Garay et al.*, 2005] and state-dependent (multiplicative) stochastic forcing on the dynamics of ENSO.

2. ENSO Recharge Oscillator Forced By Additive and Multiplicative Noise

[3] As exemplified by numerous studies, the fast atmospheric fluctuations associated with the MJO/WWB activity alter the tropical thermocline depth and SST by triggering oceanic Kelvin waves and affecting the ocean currents and heat fluxes. The slow variations of the ocean thermal conditions also modulate the atmospheric fast variability. These type of interactions can be mathematically described in terms of state-dependent noise forcing – the so-called multiplicative noise [*Blauboer et al.*, 1982; *Timmermann and Lohmann*, 1999]. Conceptually, similar approaches were adopted recently by *Jin et al.* [2006] such as to capture the feedbacks between synoptic eddies and the low-frequency flows in the extratropical atmospheric circulation.

[4] Here, we adopt the same conceptual approach and a highly idealized model to study the interaction between fast MJO/WWB variations and the slow dynamics of ENSO. Let us consider the following simple recharge oscillator model of ENSO with an ad hoc stochastic multiplicative forcing term:

$$\begin{aligned}\frac{dT}{dt} &= -\lambda T + \omega h + \sigma \xi(t) G,\\ \frac{dh}{dt} &= -\omega T - a\sigma\xi(t)G, \quad \frac{d\xi}{dt} = -r\xi + w(t).\end{aligned} \tag{1}$$

This form of the equations can be justified following *Jin* [1997] and *Burgers et al.* [2005]. Here T and h represent the

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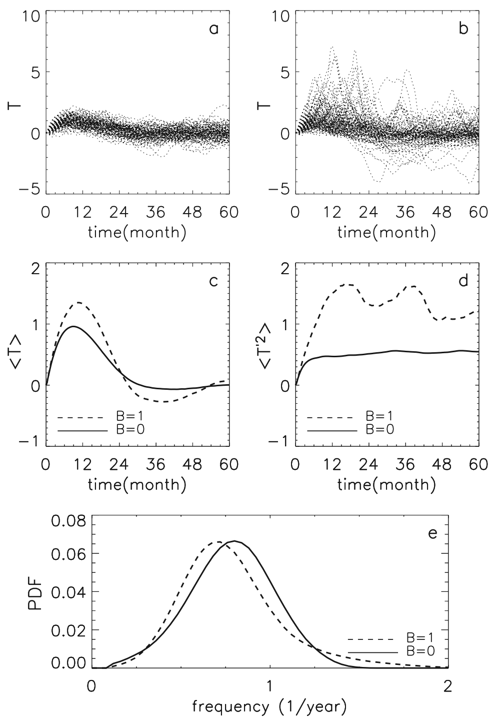

Figure 1. Fifty randomly chosen realizations out of 5000-member ensemble simulations for (a) $B = 0$ and (b) $B = 1$. (c, d) Ensemble-mean evolutions of $\langle T \rangle$ and ensemble spread $\sqrt{\langle T'^2 \rangle}$ based on the 5000-member simulations and for both B = 0 (solid curve) and $B = 1$ (dashed curve). (e) PDF of SST anomalies from 1000-year simulations for both $B = 0$ (solid curve) and $B = 1$ (dashed curve).

eastern equatorial Pacific SST and the zonally averaged equatorial heat-content anomalies, respectively; $w(t)$ is a white noise forcing term which drives an Ornstein-Uhlenbeck process $\xi(t)$ that is normalized to be of a unit variance and a decay timescale of $1/r$; σ is the amplitude of the multiplicative noise forcing. For simplicity, we have normalized T and h, for instance by their typical amplitudes, respectively. The stochastic forcing terms $\sigma\xi(t)G$ and $a\sigma\xi(t)G$ represent the effects of fast atmospheric wind anomalies (short de-correlation timescales) on the eastern equatorial SST anomalies and the equatorial heat content variations, respectively. The proportionality coefficient a reflects the fact that the same stochastic wind stress can serve as the forcing for SST and also for the recharge and discharge of the equatorial heat-content anomalies. For the sake of simplicity, a is set to zero hereafter.

[5] We use the function G to characterize the modulation of the atmospheric noise by the interannual SST anomalies. When $G = 1$, the system is forced by additive noise (see also discussion by *Jin* [1997], whereas the case $G = 1 + BT$ represents the state-dependent noise forcing due to the interannual modulation of WWB/MJO activity via SST anomalies. Another interpretation of this term is that it captures a randomly fluctuating growth rate $(-\lambda + \sigma B\xi(t))/2$ of the ENSO recharge oscillator. A similar state-dependent noise forcing has been described by *Perez et al.* [2005], who found qualitative changes of the stationary PDF in an intermediate ENSO model driven by multiplicative noise forcing.

3. Impacts of Temperature-Dependent Noise on ENSO

[6] To illustrate the impacts of the state-dependent noise forcing on ENSO dynamics, we consider some idealized cases. Here, we set $\lambda = 1/6$ month^{-1}, $r = 1/1.5$ month^{-1}, $\sigma = 1/\sqrt{24}$ month^{-1}, $\omega = 2\pi/48$ month^{-1} and the initial values are chosen as $T = 0$, $h = 2$. The initial conditions are chosen near a transition from a neutral into a warm phase. The given values for λ and ω correspond to a stable ENSO oscillator with a negative growth rate.

[7] In the case of $B = 0$, the ensemble-mean solution of our linear model does not depend on the noise forcing. The numerical ensemble-mean solution obtained from a 5000-member ensemble is indeed almost indistinguishable from the deterministic solution solved with the same initial conditions without noise forcing (not shown). The warm events in the ensemble simulations mostly have relative weak amplitudes (Figure 1a and the ensemble spread is modest (Figure 1d). The ensemble-mean event dies out without even going into a significant cold phase (Figure 1c) because the ENSO mode in this case is heavily damped.

[8] On the contrary, when $B = 1$, a significant number of warm events in the ensemble simulations attain very large amplitudes (Figure 1b). The ensemble-mean ENSO cycle is stronger and a weak cold phase follows the strong warm phase (Figure 1c). The ensemble spread is clearly amplified due to the modulated noise forcing (Figure 1d). For a lead time over 12 months, the signal-to-noise ratio is higher in the additive forcing case than that for the case $B = 1$, which suggests WWB-ENSO interactions might have a crucial influence on the predictability of ENSO, as pointed out by *Lengaigne et al.* [2004].

[9] Furthermore, the PDFs (probability distribution function) of SST anomalies for the cases with $B = 0$ and $B = 1$ (Figure 1e) are clearly different, and the later has a skewness towards rear and large warm SST anomaly events. Thus, linearly modulated stochastic forcing in (1) has an equivalent effect to the nonlinearity in terms of the generation of the ENSO warm skewness.

[10] Although the different roles of additive and multiplicative noise on dynamical systems have been documented extensively in the literature, it is still elusive how this type of noise-induced destabilization may influence ENSO stability and predictability in coupled ENSO models. We propose a conceptual ensemble-mean framework to address this issue in the next section.

4. Ensemble-Mean Dynamics Under Stochastic Closures

[11] From the simple examples in Figure 1, it becomes evident that modulated noise has a crucial impact on the amplitudes of ENSO in the ensemble mean sense. In this section, we propose an analytical closure approach to study the ensemble-mean dynamics of ENSO. Separating the variables into ensemble mean and departure, i.e.:

$$T = \langle T \rangle + T', h = \langle h \rangle + h',$$

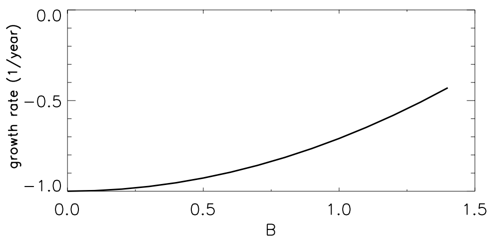

Figure 2. Dependence of growth rate ($-\lambda_E/2$) of the ensemble-mean ENSO oscillator (4) on the parameter B.

where $\langle T\rangle$, $\langle h\rangle$ denote the ensemble means for T and h, respectively, and using the approach proposed by *Jin et al.* [2006], we can obtain the following equations:

$$\begin{aligned}
\frac{d\langle T\rangle}{dt} &= -\lambda\langle T\rangle + \omega\langle h\rangle + \sigma B\langle \xi T'\rangle,\\
\frac{d\langle h\rangle}{dt} &= -\omega\langle T\rangle,\\
\frac{d\langle \xi T'\rangle}{dt} &= -(\lambda + r)\langle \xi T'\rangle + \omega\langle \xi h'\rangle + \sigma(1 + B\langle T\rangle) + \sigma B T_3,\\
\frac{d\langle \xi h'\rangle}{dt} &= -r\langle \xi h'\rangle - \omega\langle \xi T'\rangle.
\end{aligned} \tag{2}$$

Here, $T_3 = \langle \xi^2 T'\rangle$. By adopting a second order closure (letting $T_3 = 0$), the system of equations (2) is closed for the ensemble-mean evolution.

[12] Typically $r \gg \lambda$, we thus can apply the quasi-equilibrium assumption [*Jin et al.*, 2006] by further omitting the time tendency terms in (2). Then, the approximate ensemble-mean equations for the ENSO recharge oscillator read as follows:

$$\begin{aligned}
\frac{d\langle T\rangle}{dt} &= -\lambda_E\langle T\rangle + \omega\langle h\rangle + \sigma^2 B/\left(r + \lambda + \omega^2/r\right),\\
\frac{d\langle h\rangle}{dt} &= -\omega\langle T\rangle
\end{aligned} \quad . \tag{3}$$

[13] Here $\lambda_E \approx \lambda - \sigma^2 B^2/(r + \lambda + \omega^2/r)$ gives a reduced damping rate for the ensemble mean ENSO oscillator (3). This expression clearly shows that the ensemble-mean ENSO oscillator is less stable in the presence of multiplicative noise forcing (Figure 2). For instance, the negative growth rate is reduced by nearly 25% when $B = 1$ and reduced by half when $B = 1.4$, as seen from Figure 2. It is this noise-induced destabilization that is responsible for the difference in amplitudes of the ensemble-mean ENSO cycles for the same deterministic initial conditions as shown in Figure 1d. In other words, the modulated noise forcing, representing the ENSO-WWB/MJO interaction, tends to enhance the instability of the slow ENSO oscillator. This kind of destabilization can be inferred from the well-known mathematical properties of stochastic dynamical systems [*Gardiner*, 1990]. We here refer to this new instability as the noise-induced ensemble-mean instability of ENSO. *Eisenman et al.* [2005] reported a similar result from the parameterized ENSO-WWB interaction in their numerical study of an intermediate ENSO model. The analytical result from the ensemble-mean dynamical framework (3) clearly reveals that this destabilization depends on the variance as well as on the damping timescale of the modulated noise forcing.

[14] Furthermore, there is a constant forcing term in the ensemble-mean equations (3). This term comes from equation (2) for $\langle \xi T'\rangle$ and represents a rectification effect of modulated noise forcing. It leads to a non-zero ensemble-mean steady solution (not shown). Thus, modulated noise forcing has a rectification effect on the mean state, which may contribute to a climate mean state bias in the coupled models.

[15] To test the accuracy of the closure approximation used in ensemble-mean dynamical system, we further compare the ensemble-mean solutions obtained from this second-order closure to those computed statistically after numerically integrating equations (1) using a 5000-member ensemble. The good agreement depicted in Figure 3a indeed confirms the validity of our approach.

[16] We also derived the ensemble-mean dynamic system for the covariance matrix:

$$\begin{aligned}
\frac{1}{2}\frac{d\langle T'^2\rangle}{dt} &= -\lambda\langle T'^2\rangle + \omega\langle h'T'\rangle + \sigma(1 + B\langle T\rangle)\langle \xi T'\rangle\\
&\quad + \sigma B\langle \xi T'^2\rangle\\
\frac{1}{2}\frac{d\langle h'^2\rangle}{dt} &= -\omega\langle h'T'\rangle\\
\frac{d\langle h'T'\rangle}{dt} &= -\lambda\langle h'T'\rangle + \omega\left(\langle h'^2\rangle - \langle T'^2\rangle\right)\\
&\quad + \sigma(1 + B\langle T\rangle)\langle \xi h'\rangle + \sigma B\langle \xi h'T'\rangle
\end{aligned} \tag{4}$$

Combining equations (4) with equations (2) yields an equation for the ensemble-mean dynamics of the spread $\langle T'^2\rangle$. In case of multiplicative noise $B \neq 0$, closures for the third moments are needed to solve equations (4). Using the equations for the third moments (not shown here) and the fourth-order closure approximations [cf. *Jin and Lin*,

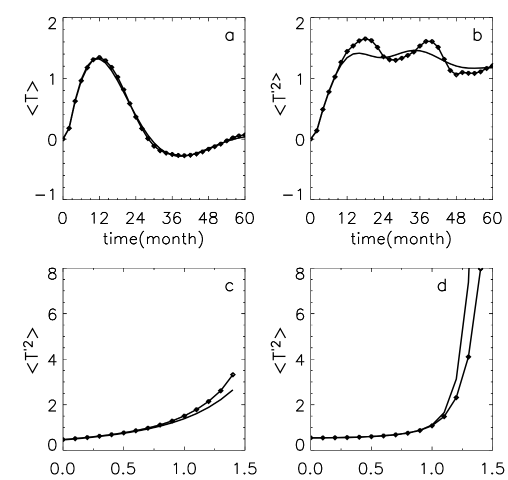

Figure 3. Evolutions of (a) $\langle T\rangle$ and (b) $\sqrt{\langle T'^2\rangle}$ as well as the dependences of $\sqrt{\langle T'^2\rangle}$ at (c) year 1 and (d) year 9 on the parameter B. The results simulated by the ensemble-mean dynamics are in solid curves and those simulated by a 5000-member numerical ensemble are depicted by curves with squares.

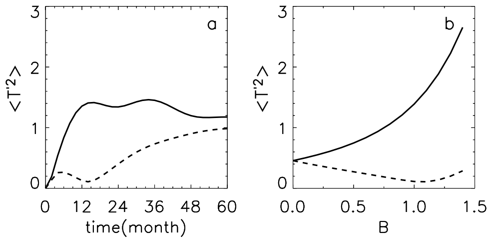

Figure 4. (a) Evolutions of $\sqrt{\langle T'^2 \rangle}$ for El Niño (solid line) and La Niña (dashed line) onsets obtained from two different initial conditions as specified in the text. (b) Dependences of $\sqrt{\langle T'^2 \rangle}$ at year 1 on the parameter B under the two different initial conditions.

2007], we can obtain the closed dynamical equations for the ensemble-mean spread. The details for the fourth-order closure will be reported elsewhere.

[17] The ensemble spread was obtained statistically by numerically integrating equations (1) 5000 times using different noise realizations as well as by solving the ensemble-spread equations (4) under the 4th order closure approximation (Figure 3b). The agreement between results from the two different approaches for the ensemble spread or the second moment is not as close as ensemble-mean evolution or the first moment. Nevertheless, the results in both Figure 3a and Figure 3b basically validate our closure assumptions and the ensemble dynamics framework.

[18] Our results suggest that on the one hand, modulated noise can effectively enhance the instability of ENSO in the ensemble-mean sense and thus help to amplify the ensemble-mean amplitude of the ENSO cycles; on the other hand, it also enhances the spread of ENSO forecasts. In other words, when MJO and WWB activities are modulated by ENSO-related SST anomalies and feedback to the generation of SST anomalies in the eastern equatorial Pacific, ENSO cycles are likely to become stronger than without this mutual interaction. But, predicting the ENSO cycles can become more difficult because of the enhanced error growth and ensemble spread and hence the reduced signal-to-noise ratio. This dilemma was in fact noted recently using a coupled general circulation model (CGCM) which simulates large-amplitude, quasi-periodic ENSO events, but exhibits a very large-ensemble spread in a series of ensemble forecasts [*Lengaigne et al.*, 2004].

[19] The influences of the modulation factor B on the noise-induced destabilization of ENSO as well as on the ensemble spread are further illustrated in Figures 3c and 3d. Not only is there a significant amplification during the first stages of an ENSO forecast (lead time $\sim$12 months) but also when reaching long-term saturation after several years (Figure 3d). It is expected that when the multiplicative noise tends to bring the system near to the noise-induced criticality such that the system becomes unstable, then nonlinearities have to be taken into account to damp the amplitude growth. In that case, we anticipate that Figure 3d will look quite different if nonlinearities are included in equations (1). A discussion of the nonlinear ensemble dynamics of the ENSO recharge oscillator driven with multiplicative stochastic forcing will be presented elsewhere.

[20] In case of multiplicative noise, the initial condition of the ensemble-mean SST will have an impact on the evolution of the ensemble spread, as illustrated in Figure 4. The onset of warm events from a recharged state (T = 0, h = 2, a state with positive equatorial heat content) is much less predictable than that of cold events from a discharged state (T = 0, h = -2, a state with negative equatorial heat content). This is consistent with the findings of *Kessler* [2002] who found that the onset of large El Niño events prior to any major eastern equatorial SST perturbation has a very low predictability, thus challenging the concept of ENSO being an oscillatory mode. Rather than questioning the concept of ENSO cycles, we can attribute this feature to the properties of the state-dependent noise. It should also be pointed out that for a linear system under additive noise forcing (B = 0), the noise-induced spread is independent of the deterministic initial conditions.

5. Conclusions

[21] Using a conceptual recharge-oscillator model for ENSO, we studied the interaction between the fast varying atmospheric variability, represented by a state-dependent stochastic process with a short de-correlation time scale, and the relatively slow-evolving ENSO mode. Unlike for linear additive noise forcing, state-dependent multiplicative noise not only alters the ensemble-mean evolution of ENSO, but also amplifies the ensemble spread during an ensemble forecast.

[22] We demonstrated that multiplicative noise may destabilize the ENSO oscillator through the so-called noised-induced instability. This finding challenges the view of ENSO being an additive-noise driven stable oscillator because noise itself can generate instability. Moreover, for our particular ENSO model, the modulated noise can greatly amplify the ensemble spread and make it initial-condition dependent. It may also induce a systematic drift in the ensemble-mean solutions.

[23] We proposed approximation closures for studying the ensemble-mean dynamics of ENSO under modulated stochastic forcing. We demonstrated that the second-order closure (the fourth-order closure) is accurate to describe the ensemble-mean evolution (spread) of ENSO. The amplifications of both signal and spread can be captured by the approximate ensemble-mean dynamics system.

[24] The simple ensemble-mean dynamics concepts and approaches illustrated here for the ENSO recharge oscillator model need to be extended to more comprehensive coupled model frameworks. This may open a venue for understanding not only the interaction between the fast varying variability and slow ENSO modes, but also for refining the ensemble approach for ENSO predictions.

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References

Anderson, D. L. T., and J. P. McCreary (1985), Slowly propagating disturbance in a coupled ocean-atmosphere model, *J. Atmos. Sci.*, *42*, 615–629.

Battisti, D. S., and A. C. Hirst (1989), Interannual variability in the tropical atmosphere/ocean system: Influence of the basic state and ocean geometry, *J. Atmos. Sci.*, *46*, 1687–1712.

Blauboer, D. G., G. J. Komen, and J. Reiff (1982), The behavior of the sea surface temperature (SST) anomaly response to stochastic latent- and sensible heat forcing, *Tellus*, *23*, 17–28.

Burgers, G., F.-F. Jin, and G. J. Oldenborgh (2005), The simplest ENSO recharge oscillator, *Geophys. Res. Lett.*, *32*, L13706, doi:10.1029/2005GL022951.

Cane, M. A., and S. E. Zebiak (1985), A theory for El Niño and the Southern Oscillation, *Science*, *228*, 1084–1087.

Eisenman, I., L. Yu, and E. Tziperman (2005), Westerly wind bursts: ENSO's tail rather than the dog?, *J. Clim.*, *18*, 5224–5238.

Gardiner, C. W. (1990), *Handbook of Stochastic Methods for Physics, Chemistry, and the Natural Sciences*, 2nd ed., 441 pp., Springer, New York.

Gutzler, D. S. (1991), Interannual fluctuations of intraseasonal variance of near-equatorial winds, *J. Geophys. Res.*, *96*, 3173–3185.

Jin, F.-F. (1997), An equatorial ocean recharge paradigm for ENSO. Part I: Conceptual model, *J. Atmos. Sci.*, *54*, 811–829.

Jin, F.-F., and L. Lin (2007), Closure for ensemble-mean linear model with a stochastic basic flow, *J. Atmos. Sci.*, *64*, 497–514.

Jin, F.-F., L.-L. Pan, and M. Watanabe (2006), Dynamics of synoptic eddy and low-frequency flow feedback. Part I: A dynamic closure, *J. Atmos. Sci.*, *63*, 1677–1694.

Keen, R. (1982), The role of cross-equatorial cyclone pairs in the Southern Oscillation, *Mon. Weather Rev.*, *110*, 1405–1416.

Kessler, W. S. (2002), Is ENSO a cycle or a series of events?, *Geophys. Res. Lett.*, *29*(23), 2125, doi:10.1029/2002GL015924.

Kessler, W. S., and R. Kleeman (2000), Rectification of the Madden-Julian Oscillation into the ENSO cycle, *J. Clim.*, *13*, 3560–3575.

Kessler, W. S., M. J. McPhaden, and K. M. Weickmann (1995), Forcing of intraseasonal Kelvin waves in the equatorial Pacific, *J. Geophys. Res.*, *100*, 10,613–10,631.

Kleeman, R., and A. M. Moore (1997), A theory for the limitation of ENSO predictability due to stochastic atmospheric transients, *J. Atmos. Sci.*, *54*, 753–767.

Lengaigne, M., E. Guilyardi, J. P. Boulanger, C. Menkes, P. Delecluse, P. Inness, J. Cole, and J. Slingo (2004), Triggering of El Niño by westerly wind events in a coupled general circulation model, *Clim. Dyn.*, *23*, 601–620.

Lukas, R. (1988), On the role of western Pacific air-sea interaction in the El Niño/Southern Oscillation phenomenon, in *Proceedings of the U.S. TOGA Western Pacific Air-Sea Interaction Workshop, Honolulu*, pp. 43–69, Univ. Corp. for Atmos. Res., Boulder, Colo.

Luther, D. S., D. E. Harrison, and R. A. Knox (1983), Zonal winds in the central equatorial Pacific and El Niño, *Science*, *222*, 327–330.

McPhaden, M. J. (2004), Evolution of the 2002/03 El Niño, *Bull. Am. Meteorol. Soc.*, *85*, 677–695.

Moore, A. M., and R. Kleeman (1999), Stochastic forcing of ENSO by the intraseasonal oscillation, *J. Clim.*, *12*, 1199–1220.

Penland, C., and P. D. Sardeshmukh (1995), The optimal growth of tropical sea surface temperature anomalies, *J. Clim.*, *8*, 1999–2024.

Perez, C. L., A. M. Moore, J. Zavaly-Garay, and R. Kleeman (2005), A comparison of the influence of additive and multiplicative stochastic forcing on a coupled model of ENSO, *J. Clim.*, *18*, 5066–5085.

Perigaud, C. M., and C. Cassou (2000), Importance of oceanic decadal trends and westerly wind bursts for forecasting El Niño, *Geophys. Res. Lett.*, *27*, 389–392.

Philander, S. G. H. (1990), *El Niño, La Niña, and the Southern Oscillation*, 293 pp., Elsevier, New York.

Suarez, M. J., and P. S. Schopf (1988), A delayed action oscillator for ENSO, *J. Atmos. Sci.*, *45*, 3283–3287.

Thompson, C. J., and D. Battisti (2000), A linear stochastic dynamical model of ENSO. Part I: Mode development, *J. Clim.*, *13*, 2818–2832.

Timmermann, A., and G. Lohmann (1999), Noise-induced transitions in a simplified model of the thermohaline circulation, *J. Phys. Oceanogr.*, *30*, 1891–1900.

Vecchi, G. A., and D. E. Harrison (2000), Tropical Pacific sea surface temperature anomalies, El Niño and equatorial westerly events, *J. Clim.*, *13*, 1814–1830.

Vimont, D. J., D. S. Battisti, and A. C. Hirst (2001), Footprinting: A seasonal link between the mid-latitudes and tropics, *Geophys. Res. Lett.*, *28*(20), 3923–3926.

Yu, L., R. A. Weller, and T. W. Liu (2003), Case analysis of a role of ENSO in regulating the generation of westerly wind bursts in the western equatorial Pacific, *J. Geophys. Res.*, *108*(C4), 3128, doi:10.1029/2002JC001498.

Zavala-Garay, J., C. Zhang, A. Moore, and R. Kleeman (2005), The linear response of ENSO to the Madden–Julian oscillation, *J. Clim.*, *18*, 2441–2459.

Zhang, C., H. H. Hendon, W. S. Kessler, and A. J. Rosati (2001), Meeting summary: A workshop on the MJO and ENSO, *Bull. Am. Meteorol. Soc.*, *82*, 971–976.

Zhang, Q., and J. Gottschalck (2002), SST anomalies of ENSO and the Madden-Julian Oscillation in the equatorial Pacific, *J. Clim.*, *15*, 2429–2445.

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