A Nonlinear Mechanism for Decadal El Niño Amplitude Changes

Axel Timmermann
IPRC, SOEST, Honolulu, Hawaii 96822, USA

Fei-Fei Jin
Department of Meteorology, SOEST, Honolulu, Hawaii 96822, USA

Received 24 April 2001; revised 12 July 2001; accepted 26 September 2001; published 3 January 2002.

[1] Based on the analysis of a low-order tropical atmosphere-ocean model we propose a nonlinear mechanism explaining several features of the observed El Niño-Southern Oscillation (ENSO) phenomenon: ENSO irregularity, ENSO Amplitude Modulations and decadal tropical climate variability. The mechanism suggested here is based on the idea of homoclinic/heteroclinic orbits, an inherently nonlinear concept. It turns out that this mechanism operates even in the presence of wind noise and is consistent with results from intermediate ENSO model simulations. *INDEX TERMS:* 4522 Oceanography: Physical: El Niño, 1620 Global Change: climate dynamics (3309), 4215 Oceanography: General: Climate and interannual variability (3309), 3240 Mathematical Geophysics: Chaos

1. The Problem

[2] Climate variability in the tropical Pacific is characterized by an irregular interannual oscillation with a typical period of 2–7 years, the El Niño-Southern Oscillation phenomenon [*Neelin et al.*, 1998] (ENSO). This oscillation impacts weather and climate globally. Furthermore, decadal-scale variability is observed which modifies ENSO activity [*Gu and Philander*, 1995, *Torrence and Webster*, 1998, *Urban et al.*, 2000] as well as the tropical climate mean state [e.g. *Graham*, 1994, *Zhang et al.*, 1997]. Different hypothesis have been put forward to explain the origin of ENSO irregularity [*Jin et al.*, 1994, *Tziperman et al.*, 1994, *Chang et al.*, 1996] and decadal-scale variability in the tropical Pacific [*Gu and Philander*, 1997, *Pierce et al.*, 1999, *Schneider*, 2000, *Knutson et al.*, 1997, *Timmermann et al.*, 1999, *Weaver* 1999]. The interannual timescale of ENSO is produced by tropical ocean-atmosphere interactions, whereas the decadal time scale is largely considered to be the result of extratropical processes or noise. Our letter aims at explaining how decadal timescales in the tropical Pacific can be generated without invoking extratropical processes. Using a low order ENSO model we find that irregular ENSO dynamics as well as longterm changes in ENSO activity can be generated by the nonlinear advection terms in the temperature equation. The resulting dynamics can be explained in terms of homoclinic/heteroclinic chaos [*Glenndinning and Sparrow*, 1984, *Nicolis*, 1987, *Meacham*, 2000], a concept of dynamical system theory. It is has been suggested that decadal variability can be generated in the tropics[1]. Our goal is to illustrate a nonlinear concept which explains these findings.

[1]This has been shown already in a number of papers e.g. *Kirtman and Schopf* [1998.]

0094-8276/02/2001GL013369

2. The Model

[3] The low-order ENSO model [*Jin* 1996, 1998; *Sun*, 2000] consists of three prognostic equations for western T_1 and eastern T_2 equatorial sea surface temperatures (SST) and thermocline depth h_1 anomalies. Wind stress anomalies τ, generated by the zonal temperature contrast, drive equatorial upwelling w in the eastern equatorial Pacific as well as zonal advection u. The dynamical equations read

$$\frac{dT_1}{dt} = -\alpha(T_1 - T_r) - u(T_2 - T_1)/(L/2) \quad (1)$$

$$\frac{dT_2}{dt} = -\alpha(T_2 - T_r) - w(T_2 - T_{sub})/H_m, \quad (2)$$

$$u/(L/2) = \epsilon\beta\tau \quad (3)$$

$$w/H_m = -\beta\tau \quad (4)$$

[4] The fraction parameter ϵ attains values in the order of 0.01–0.1 as shown by *Jin* [1998]. It measures the strength of the zonal advection and will be used as a sensitivity parameter lateron. Neglecting the external sources for wind stress anomalies, the wind stress related to the Walker circulation can be expressed as

$$\tau = \mu(T_1 - T_2)[\sigma\xi_t - 1]/\beta, \quad (5)$$

where $\sigma\xi_t$ represents Gaussian white noise of variance σ^2. Unless otherwise stated, the experiments described below neglect noise (i.e. $\sigma = 0$). The subsurface temperature T_{sub} depends strongly on the thermocline depth. Following *Jin* [1996] it can be parametrized as

$$T_{sub} = T_r - \frac{T_r - T_{r0}}{2}[1 - \tanh(H + h_2 - z_0)/h^*]. \quad (6)$$

Here h_2 is the depth departure of the eastern equatorial thermocline from its reference depth H. z_0 is the depth at which w takes its characteristic value. h^* measures the sharpness of the thermocline.

[5] The east-west contrast of thermocline depth $h_2 - h_1$ is determined by the Sverdrup balance between the pressure gradient and equatorial wind stress. We assume an instantanous adjustment of the thermocline gradient to wind stress changes. Changes of the western equatorial thermocline depth h_1 are governed by the zonally integrated Sverdrup meridional mass transport resulting from wind forced Rossby waves. This process is characterized by the dynamical adjustment timescale $1/r$. The dynamical equations

for the thermocline depth anomalies in the eastern and western equatorial Pacific read

$$h_2 = h_1 + bL\tau, \quad (7)$$

$$\frac{dh_1}{dt} = r(-h_1 - bL\tau/2), \quad (8)$$

respectively. b captures the effeciency of wind stress τ in driving thermocline tilt.[2]

[6] Without the zonal advection of SST the model is known to generate regular ENSO cycles which can be interpreted in terms of the recharge oscillator paradigm [*Jin*, 1997]. The inclusion of nonlinear zonal advection is responsible for the generation of two new features: longterm modulations of ENSO activity and chaos. This is illustrated in Figure 1.

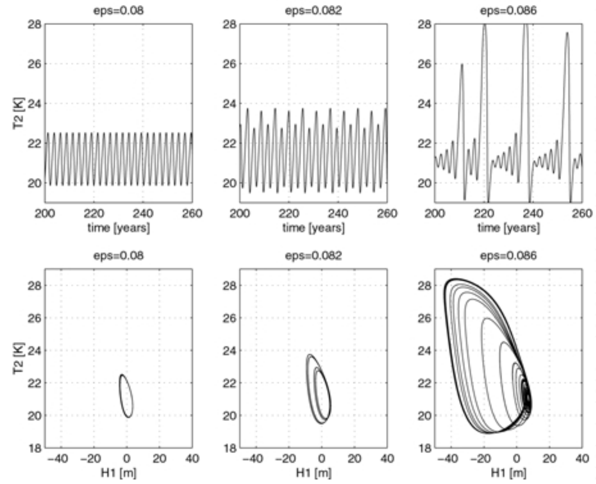

Figure 1. Upper panels: Eastern equatorial SST anomalies simulated by the low-order ENSO model (upper panels) for different values of ϵ. Lower panels: Corresponding phase-space views in the T_1-T_2 plane.

3. The Dynamics

[7] The simulated eastern equatorial temperature anomalies are shown for four different realistic values of a parameter ϵ = 0.08, 0.082, 0.086, 0.12 which controls the relative strength of zonal and vertical advection in the model. For small ϵ we observe a periodic oscillation with a period of about 2.5 years and an amplitude of about 1 K. This oscillation goes along with a limit cycle in phase space, as illustrated in the lower left panel of Figure 1.

[8] Increasing ϵ slightly to 0.082 leads to a qualitative change of the dynamics. We observe an oscillation in which large and moderate amplitude ENSO events alternate. This is a clear indication that a period doubling bifurcation occured between ϵ = 0.08 and ϵ = 0.082. The phase space diagram resemles a double-loop. Further enhancement of ϵ to values of about 0.086 leads to irregular oscillations. Furthermore, it can be seen that ENSO undergoes long term amplitude changes with typical timescales of 10–20 years. The timescale of these modulations is determined by a nonlinear combination of the advective timescales and the basin-wide dynamic adjustment rates. For $\epsilon \sim 0.086$ one observes a chaotic phase-space trajectory chracterized by a spiraling motion around a point which can be identified as a fixed point of saddle focus type (one negative real eigenvalue and a complex conjugated pair of eigenvalues with a positive real part). The fixed point represents the tropical climate mean state in this model, whereas the motion spiraling outwards corresponds to a linearly unstable ENSO and its increasing amplitude.

[9] A further increase of ϵ to values of about 0.12 and higher pushes the ENSO system into another limit cycle which is characterized by large amplitude events and a period of 4–5 years (not shown).

[10] In addition we have performed a set of experiments in which stochastic wind stress variations are included.[3] The noise amplitude σ is varied from 0.1 to 1.4. Figure 2 shows T_1-T_2 phase space plots for two different noise values. The strength of the zonal advection in these simulations is set to ϵ = 0.086.

[11] One observes that large noise amplitudes do not affect the trajectory qualitatively. The phase space trajectory shown in Figure 2 resembles a situation close to a homoclinic bifurcation even for unreaslitically large noise variances.

[12] Clearly in a rather realistic parameter regime, nonlinear tropical ocean-atmosphere interactions as described with the low order ENSO model can generate irregular ENSO oscillations as well as large amplitude modulations on decadal timescales. Our findings provide an alternative to previous hypothesis [*Gu and Philander*, 1997, *Timmermann et al.*, 1999, *Weaver*, 1999, *An and Jin*, 2000] which are based on the idea that changes in ENSO activity are caused by externally generated decadal changes of the background state.

4. The Interpretation

[13] Here we would like to discuss briefly how the findings described above can be understood in terms of the theory of dynamical systems. Our analysis of the low order ENSO model revealed three main features: ENSO undergoes longterm amplitude modulations as well as period doubling bifurcations. Furthermore, the dynamical system (equations (1)–(8)) exhibits chaotic dynamics. These features are consistent with the *homoclinic/heteroclinic chaos scenario*. In this scenario the interaction between one or two unstable stationary equilibrium points and periodic orbits is considered, respectively. For simplicity we will focus here only on the homoclinic case. A detailed presentation of heteroclinic ENSO chaos will be presented elsewhere. As illustrated in Figure 3 it becomes apparent that a homoclinic orbit associated with a saddle focus is characterized by an oscillation which grows in amplitude until a critical value is attained. Eventually the orbit grows strongly in the z direction in Figure 3, whereas the amplitude of the original oscillation decreases. The excursions in the z direction are also limited due to nonlinearities and the orbit returns back to the saddle focus. Hence, a homoclinic orbit in three dimensions exhibits amplitude modulated behaviour. Realistically one deals with systems which operate close to a homoclinic orbit in parameter space. In the vicinity of this idealized situation one observes similar dynamics, such as amplitude modulations with arbitrarily long timescales.

[14] The spiraling motion in Figure 3 is just an example of what might happen when unstable fixed point and periodic orbit approach one another. For $\mu = 0$ the period of the orbit becomes infinite, since the stationary point is a trap for the dynamics. The orbit for $\mu = 0$ is called a *homoclinic orbit*. As μ becomes sufficiently small the periodic orbit disappears and the unstable steady state remains. This sequence of dynamical stages is called a *homoclinic bifurcation* [*Shil'nikov*, 1965; *Glenndinning and Spar-*

[2] The parameter values used in our study are: T_{r0} = 16°C, T_r = 29.5°C, α = 1/180 d^{-1}, r = 1/400 d^{-1}, H_m = 50m, H = 100m, z_0 = 75m, h^* = 62m, μ = 0.0026 $K^{-1}d^{-1}$, $\mu bL\beta$ = 22m/K and L = 15 10^6m.

[3] It should be noted here that stochastic wind stress perturbations are only included in the temperature equations (1) and (2). The reason is that the thermocline equations (7) and (8) are already filtered equations. In order to account for the effect of noise on thermocline dynamics one would have to use a model which resolves waves.

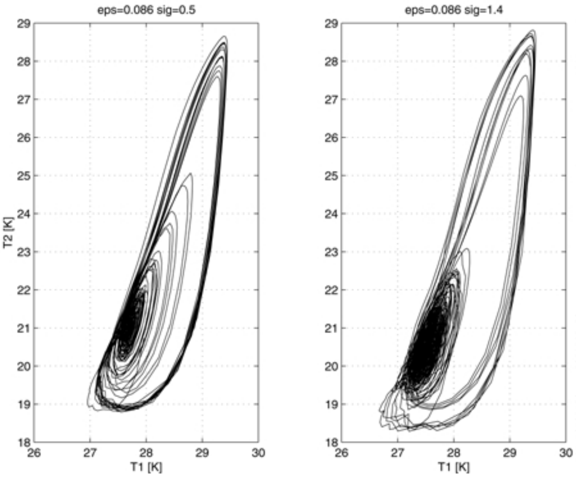

Figure 2. Phase-space views in the $T_1 - T_2$ plane for different values of σ = 0.5,1.4. The zonal advection parameter is set to 0.086.

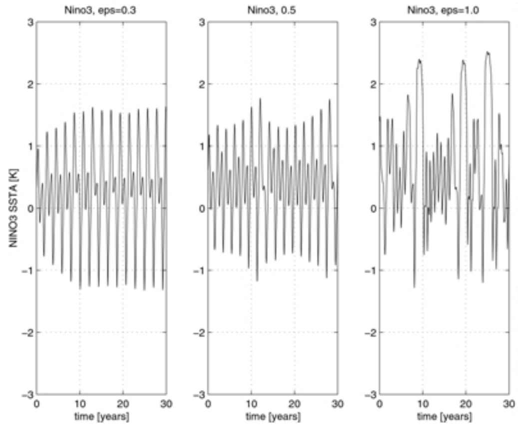

Figure 4. Niño 3 SST anomalies simulated by the ZC model for different effectivities $\tilde{\epsilon}$ of the anomalous zonal advection $\tilde{\epsilon} u' \nabla T$.

row, 1984; *Nicolis*, 1987; *Meacham*, 2000]. It should be noted here that the arrows in Figure 3 can also be reversed. A homoclinic bifurcation affects the system's dynamics globally.

[15] In three and higher dimensions the presence of homoclinic orbits can induce very complicated chaotic dynamics. The emergence of chaos depends strongly on the eigenvalue ratio of the real eigenvalues corresponding to the stationary state and the periodic orbit. Without proof we will mention that inverse period doubling bifurcations can play an important role in generating chaos in the parameter vicinity of homoclinic/heteroclinic orbits.

[16] We also performed a more thorough analysis using bifurcation techniques [*Doedel*, 1981]. The results of this rather technical analysis exceed the scope of this letter and will be presented elsewhere. Except for some minor modifications they confirm our idea that decadal ENSO amplitude modulations in the low order ENSO model (equations (1)–(8)) are generated by global homoclinic/heteroclinic bifurcations. The bifurcation parameter chosen in our analysis is the strength of zonal advection. It should be noted here that also other parameter choices might reveal similar dynamical stages as shown in Figure 1.

5. Intermediate Model Results

[17] In order to show that similar dynamics can be simulated using more complex models we performed some experiments with the *Zebiak and Cane* (ZC) [1987] intermediate coupled atmosphere-ocean model.

[18] A new mean state is constructed from the average of the ZC model mean state and the annual mean state of the ECHAM4/OPYC3 Coupled General Circulation Model [*Roeckner et al.*, 1996; *Timmermann et al.*, 1999a]. Annual cycle forcing is neglected. Furthermore, we reduced the baroclinic wave speed from 2.9 m/s to 2.7 m/s. In our experiments we modified the strength of the anomalous zonal temperature advection by multiplying it with a factor ranging from $\tilde{\epsilon}$ = 0.3 to 1.0 (a value of 1 corresponds to the standard value used in the ZC model) such as to mimic the experiments performed with our low order model described in section 2. The resulting Niño 3 SST anomaly time series are depicted in Figure 4.

[19] We observe very similar features as in Figure 1. For reduced values of the anomalous zonal advection efficiency we observe a biannual regular ENSO oscillation. For $\tilde{\epsilon}$=0.5 the biannual ENSO signal becomes distorted by irregular low frequency behaviour. A further increase of $\tilde{\epsilon}$ to values of about 1.0 reveals a similar, but less regular, bursting behaviour of ENSO as seen in the low order recharge ENSO model. The mean time between strong El Niño events is in the order of a decade and more. Due to the complexity of the ZC model we do not expect a straightforward detection of the homoclinic orbit, but the crucial characteristics of the homoclinic chaos scenario can be seen in Figure 4. For large values of $\tilde{\epsilon}$ the ENSO oscillation becomes more regular (not shown) and exhibits a period of about 3.5 years.

[20] These changes of the dynamical regimes are consistent with the low order model change induced by strengthening the zonal advection term. Hence, we conjecture that also the ZC model follows a similar path in parameter space and that the decadal ENSO amplitude modulations in the modified ZC model can be interpreted in terms of the homoclinic chaos concept.

[21] It is very important to note that one can approach a homoclinic orbit in parameter space from many directions. Changes in the zonal advection are one effective way of probing the existence of a homoclinic bifurcation. Changes in the strength of vertical advection give rather similar results. This is typical of dynamical system analysis. Unfortunately this makes the intuitive understanding of the underlying nonlinear mechanisms more difficult.

6. The Implications

[22] Our understanding of the generation of decadal tropical variability, particularly the nature of decadal changes in ENSO variability and the emergence of ENSO irregularity, can be unified by the nonlinear concept discussed above and known under the term homoclinic chaos.

[23] Applied to our low order ENSO model the fundamental idea can be scetched as follows: the tropical climate mean state becomes unstable, giving rise to ENSO-like oscillations. The eigenvalues corresponding to this interannual ENSO-like mode

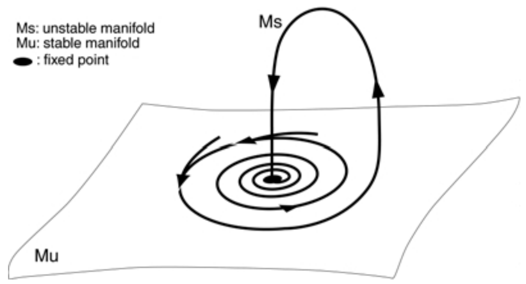

Figure 3. Schematic illustration of a homoclinic orbit of saddle node type in three dimensions.

characterize a growing oscillation in one direction and a stable non-oscillatory mode in a transversal phase-space direction. This damped mode is largely associated with the warm pool dynamics. Hence, the climate mean state represents a saddle node of the system. If the nonlinearities of the model are strong enough to bring the system trajectory back into the vicinity of the unstable climate mean state a scenario as the one described above is very likely. Hence, the nonlinearities control how strong the trajectory is reinjected into the neighborhood of the climate mean state. This process determines also the degree of irregularity and the number of interannual oscillations before a major ENSO event is simulated.

[24] This unique scenario allows for the nonlinear selection of decadal timescales in tropical dynamics. We also believe that this nonlinear scenario is superior to previously suggested ENSO irregularity scenarios [*Jin et al.*, 1994, *Tziperman et al.*, 1994, *Chang et al.*, 1996] because none of them is suited to generate decadal amplitude vacillations of sufficient magnitude.

[25] Further analysis is required to relate these new ideas to more complex ENSO models and observations.

References

An, S.-I., and F.-F. Jin, An eigen analysis of the interdecadal changes in the structure and frequency of ENSO mode, *Geophys. Res. Lett.*, *27*, 2573–2576, 2000.

Chang, P., Link, L. Ji, L. Hong, and M. Flügel, Chaotic Dynamics versus Stochastic Process in El Niño-Southern Oscillation in Coupled Ocean-Atmosphere Models, *Physica D*, *98*, 301–320, 1996.

Doedel, E. J., AUTO, a program for the automatic bifurcation analysis of autonomous systems, *Cong. Numer.*, *30*, 265–384, 1981.

Glenndinning, O., and C. Sparrow, Local and Global Behaviour near Homoclinic Orbits, *J. Stat. Phys.*, *35*, 645–697, 1984.

Graham, N. E., Decadal-scale climate variability in the 1970s and 1980s: observations and model results, *Clim. Dyn.*, *10*, 135–159, 1994.

Gu, D.-F., and S. G. H. Philander, Secular changes of annual and interannual variability in the tropics during the past century, *J. Clim.*, *8*, 864–876, 1995.

Gu, D.-F., and S. G. H. Philander, Interdecadal climate fluctuations that depend on exchanges between the tropics and extratropics, *Science*, *275*, 805–807, 1997.

Jin, F.-F., J. D. Neelin, and M. Ghil, El Niño on the Devil's Staircase: Annual subharmonic steps to chaos, *Science*, *264*, 70–72, 1994.

Jin, F.-F., Tropical-ocean interaction, Pacific cold tongue, and El Niño-Southern oscillation, *Science*, *274*, 76–78, 1996.

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

Jin, F.-F., A Simple Model for the Pacific Cold Tongue and ENSO. *J. Atmos. Sciences*, 2458–2469, 1998.

Kirtman, B. P., and P. S. Schopf, Decadal variability in ENSO predictability and prediction, *J. Climate*, *11*, 2804–2822, 1998.

Knutson, T. R., S. Manabe, and D.-F. Gu, Simulated ENSO in a global coupled ocean-atmosphere mode: multi-decadal amplitude modulation and CO_2 sensitivity, *J. Clim.*, *10*, 138–161, 1997.

Meacham, S. P., Low-frequency variability in the wind-driven circulation, *J. Phys. Oceanogr.*, *30*, 269–293, 2000.

Neelin, J. D., D. S. Battisti, A. S. Hirst, F.-F. Jin, Y. Wakata, T. Yamagata, and S. E. Zebiak, ENSO Theory, *J. Geophys. Res.*, *103*(C7), 14,261–14,290, 1998.

Nicolis, C., Long-term climatic variability and chaotic dynamics, *Tellus, A*, *39*(1), 1–9, 1987.

Pierce, D. W., T. P. Barnett, and M. Latif, Connections between the Pacific Ocean tropics and midlatitudes on decadal timescales, *J. Clim.*, *13*, 1173–1194, 1999.

Roeckner, E., J. M. Oberhuber, A. Bacher, M. Christoph, and I. Kirchner, ENSO variability and atmospheric response in a global atmosphere-ocean GCM, *Clim. Dyn.*, *12*, 737–754, 1996.

Schneider, N., A decadal spiciness mode in the tropics, *Geophys. Res. Lett.*, *27*, 257–261, 2000.

Sun, D. Z., in *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation, Multiscale variability and Global and Regional Impacts*, Diaz, H. F., V. Markgraf, Eds. (Cambridge University Press, 2000) pp. 443–463.

Timmermann, A., M. Latif, and R. Voss, Modes of Climate Variability as simulated by the coupled atmosphere-ocean model ECHAM3/LSG, Part I: ENSO-like climate variability and its low-frequency modulation, *Clim. Dyn.*, *15*, 605–618, 1999.

Timmermann, A., J. Oberhuber, A. Bacher, M. Esch, M. Latif, and E. Roeckner, Increased El Niño frequency in a climate model forced by future greenhouse warming, *Nature*, *398*, 694–697, 1999.

Torrence, C., and P. J. Webster, Interdecadal changes in the ENSO-Monsoon System, *J. Clim.*, *12*, 2679–2690, 1998.

Tziperman, E., L. Stone, M. A. Cane, and H. Jarosh, El Niño Chaos: Overlapping of resonances between the seasonal cycle and the Pacific Ocean-Atmosphere oscillator, *Science*, *264*, 72–74, 1994.

Urban, F. E., J. E. Cole, and J. Overpeck, Influence of mean climate change on climate variability from a 155-year tropical Pacific coral record, *Nature*, *407*, 989–993, 2000.

Weaver, A. J., Extratropical subduction and decadal modulation of El Niño, *Geophys. Res. Lett.*, *26*, 743–746, 1999.

Zebiak, S. E., and M. A. Cane, A model El Niño Southern Oscillation, *Mon. Wea. Rev.*, *115*, 2262–2278, 1987.

Zhang, Y., J. M. Wallace, and D. S. Battisti, ENSO-like Interdecadal Variability: 1900-93, *J. Clim.*, *10*, 1004–1020, 1997.

Axel Timmermann, Institut für Meereskunde, Düsternbrooker Weg 20, D-24105 Kiel, Germany. (atimmermann@ifm.uni-kiel.de)

Fei-Fei Jin, Department of Meteorology, University of Hawaii at Manoa, 2525 Correa Road, Honolulu HI 96822-2291, USA. (jff@soest.hawaii.edu)