Strong El Niño events and nonlinear dynamical heating

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[1] We present evidence showing that the nonlinear dynamic heating (NDH) in the tropical Pacific ocean heat budget is essential in the generation of intense El Niño events as well as the observed asymmetry between El Niño (warm) and La Niña (cold) events. The increase in NDH associated with the enhanced El Niño activity had an influence on the recent tropical Pacific warming trend and it might provide a positive feedback mechanism for climate change in the tropical Pacific. *INDEX TERMS:* 4522 Oceanography: Physical: El Niño; 4215 Oceanography: General: Climate and interannual variability (3309); 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 1620 Global Change: Climate dynamics (3309); 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology. **Citation:** Jin, F.-F., S.-I. An, A. Timmermann, and J. Zhao, Strong El Niño events and nonlinear dynamical heating, *Geophys. Res. Lett.*, *30*(3), 1120, doi:10.1029/2002GL016356, 2003.

1. Introduction

[2] The El Niño-Southern Oscillation phenomenon (ENSO) is the most important source of interannual climate variability. In the past two decades, two strong El Niño events (1982/83 and 1997/98) occurred. Over the same period, there is a pronounced asymmetry between El Niño and La Niña, the former being very strong (up to 4.5°C, as measured by the spatially averaged eastern equatorial Pacific temperature anomalies), the latter being relatively weak in amplitude (up to −3°C). Despite great progress in understanding [*Neelin et al.*, 1998] and predicting [*Latif et al.*, 1998] ENSO, it is still unclear why there is a warm/cold asymmetry in ENSO and what controls the strength of ENSO, and in particular, why these El Niño events attained such great intensities.

[3] There is some evidence [*An and Jin*, 2000; *Wang and An*, 2001] that ENSO underwent a dynamic change around the year 1976 from a stable to an unstable oscillating system. This change has been linked to the famous 1976 climate shift [*Trenberth*, 1990]. Before 1976, El Niño events propagated mainly westward, their amplitude was moderate, and their period was about 2–4 years. After the 1976 shift, El Niño events propagated mainly eastward, their amplitude was significantly larger, and their typical timescale was in the order of 3–7 years. If the changes in the interannual ENSO variability partly can be attributed to changing climate background conditions as speculated by *An and Jin* [2000], can the observed changes in ENSO variability such as the El Niño/La Niña asymmetry feed back onto the tropical climate mean state?

[4] We will address these questions using the ocean assimilation dataset from the National Center of Environment Prediction (NCEP) [*Ji et al.*, 1995] covering the period from 1980–2001. Despite the model and input data deficiencies this data product can be regarded as an approximate reconstruction of the real ocean state.

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2. Maximum Potential Intensity (MPI) for ENSO

[5] First, we will examine the strongest El Niño event ever recorded [*McPhaden*, 1999] instrumentally - the 1997/98 El Niño. During the mature stage of this event, the warm pool expanded so far to the east that the climatologic cold tongue (Figure 1a) vanished (Figure 1b). The mean tilt of the thermocline (representing the sharp vertical temperature gradient that separates the upper ocean from the abyssal deep ocean) (Figure 1c) was reversed (Figure 1d). Even the equatorial undercurrent (Figure 1c), a rather persistent ocean current, was strongly disrupted (Figure 1d). In fact, the 97/98 SST attained typical warm-pool temperatures (Figure 1e). Another similar strong event occurred in 1982/83.

[6] Motivated by these observations, here we propose a measure that characterizes the maximum potential intensity (MPI) for ENSO using the eastern equatorial Pacific SST. The upper bound of this SST, the MPI of El Nino events, corresponds to the radiative-convective equilibrium temperature of about 30°C. The warm pool SST attains values close this temperature. Similarly, the low bound of the equatorial SST in the eastern Pacific, the MPI for La Niña events, corresponds to a complete surface outcropping of the thermocline and is about 20°C. Since the average SST in the cold tongue region is about 25°C, the MPI of ENSO measured by SST anomalies averaged in the cold tongue region is about 5°C.

[7] The 1982/83 and 1997/98 El Niño events were so strong that they nearly reached the MPI, which is also clear from Figure 1e. The La Nina events, however have never reached MPI at least for the data shown in Figure 1e. For those warm events nearly reaching the MPI, the anomalies are too large to be viewed as small perturbations to the climate mean state. In other words, the nonlinear processes are important for these events.

[8] The above definition of MPI for ENSO is based on the current climate state of the tropical Pacific. The paleoclimate state of the tropical Pacific could be quite different. For a relative cold tropical Pacific, such as in the glacial times, the range of MPI could be reduced, which might also limit the ENSO intensity. On the contrary, in the warmer climate as simulated in the global warming simulations, the MPI may further increase to allow strong ENSO activity [*Timmermann et al.*, 1999].

3. Nonlinear Dynamical Heating and ENSO Asymmetry

[9] The fact that the strong 1982/83 and 1997/98 events reached the MPI for ENSO gives one measure of the ENSO nonlinearity. Another possible measure for the ENSO non-

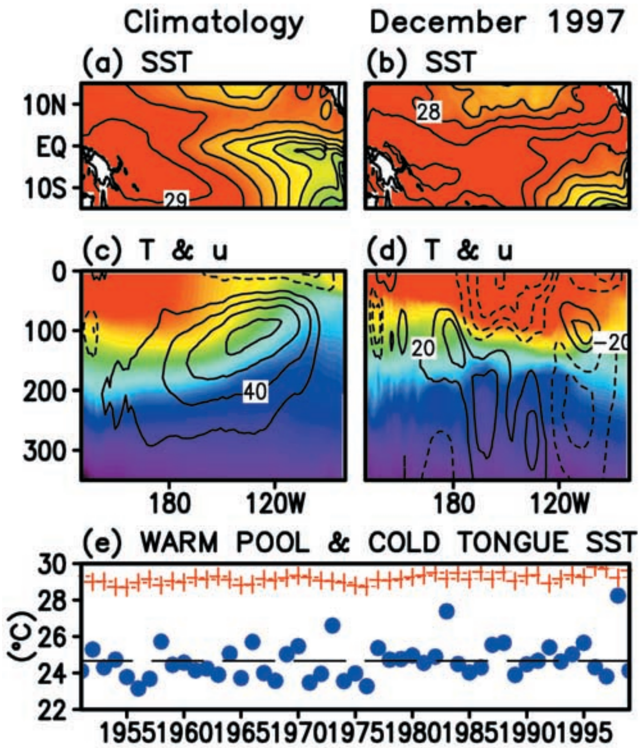

Figure 1. (a) Sea surface temperatures (SST) (°C); (c) upper ocean temperature (°C) (in color) and zonal currents (cm s^{-1}) (in contours). (a) and (c) are December means averaged from 1978–1998; (b) and (d) represent the 1997 December fields of (a) and (b); (e) Winter seasonal mean (November to January) SST in the warm pool (+) (averaged over the area 5°S to 5°N, 130° to 170°E) and in the cold tongue (averaged over the area 5°S to 5°N, 120° to 80°W). The large El Nino events of 1982/83 and 1997/98 are characterized by very small zonal temperature gradients.

linearity is the dominance of the NDH terms in the heat budget of the upper ocean. To quantify this second measure, we calculated the heat budget in the uppermost 50m of the tropical Pacific, using the NCEP ocean assimilation data.

[10] The heat budget of the ocean surface layer is calculated using the following SST equation:

$$\frac{\partial T'}{\partial t} = -(u'\partial x\bar{T} + v'\partial y\bar{T} + w'\partial z\bar{T} + \bar{u}\partial xT' + \bar{v}\partial yT' + \bar{w}\partial zT') - (u'\partial xT' + v'\partial yT' + w'\partial zT') + R' \quad (1)$$

Here, T, u, v, w are SST, zonal, meridional, and vertical velocities; overbar and prime denote the climatologic mean and anomalies. The contributions from heat fluxes and subgrid scale processes are denoted by the residual term R'. The term for NDH is in the bracket of the second line of the equation.

[11] As shown in Figure 2a the 1997/98 warm event is characterized by a large NDH anomaly of about 2°C/month that is located in the center of the El Niño SST anomaly. It is comparable in magnitude with the linear heat advection terms throughout much of the 1997/98 warm event. The subsequent La Niña event from 1998/99 was also characterized by a positive NDH anomaly of about 2°C/month. The overall effect of the strong NDH anomaly is to amplify El Niño events and to damp La Niña events. This leads to an asymmetry in the magnitude of El Niño and La Niña in consistency with the observations. The nonlinear advection of heat is negligible for moderate ENSO events such as the 1986/87 El Niño and the subsequent La Niña state (Figure 2c, d). In this case, El Niño and La Niña attained similar absolute magnitudes, also lending support to the assertion that NDH is responsible for the asymmetry.

4. Eastward Propagating El Nino and Its Strong Intensity

[12] The nonlinear advection of heating depends on particular temporal and spatial phase differences between the temperature and current fields. This is shown for the 1997/98 El Niño in Figure 3. During the mature phase, westerly zonal wind stress anomalies occur in the central to western equatorial Pacific, whereas easterly wind anomalies can be seen in the eastern Pacific (Figure 3a). This wind

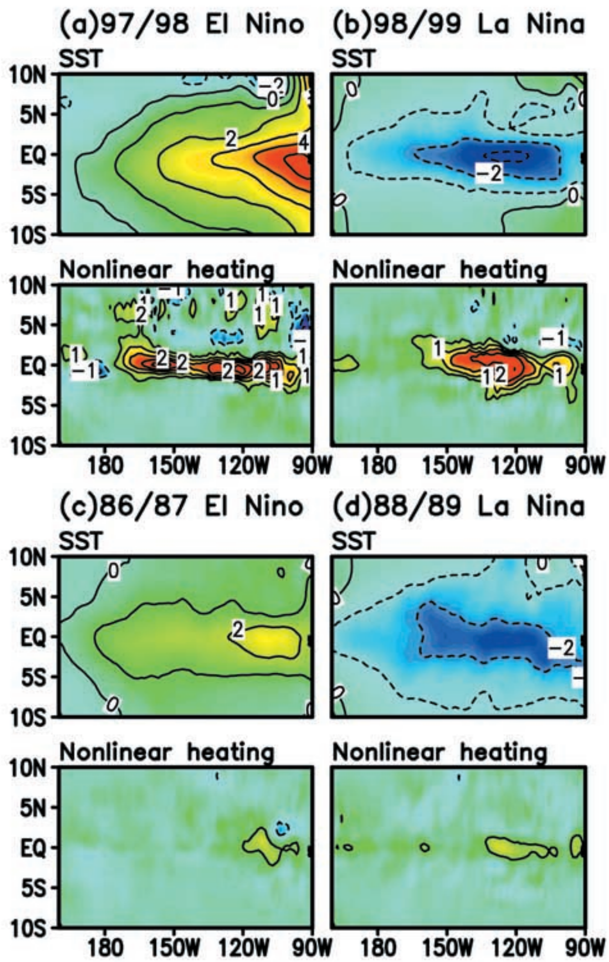

Figure 2. December SST anomaly (°C) and rate of change in SST (°C $month^{-1}$) due to the nonlinear dynamic heating terms computed for (a) the El Niño event in 1997 and (b) the La Niña event in 1998. (c) SST and nonlinear heating for the El Niño event in March 1987 and (d) the mature La Niña situation in December 1988. The data were prefiltered with 11-month running mean. The anomalies were obtained based on the climatology of 1970–1998.

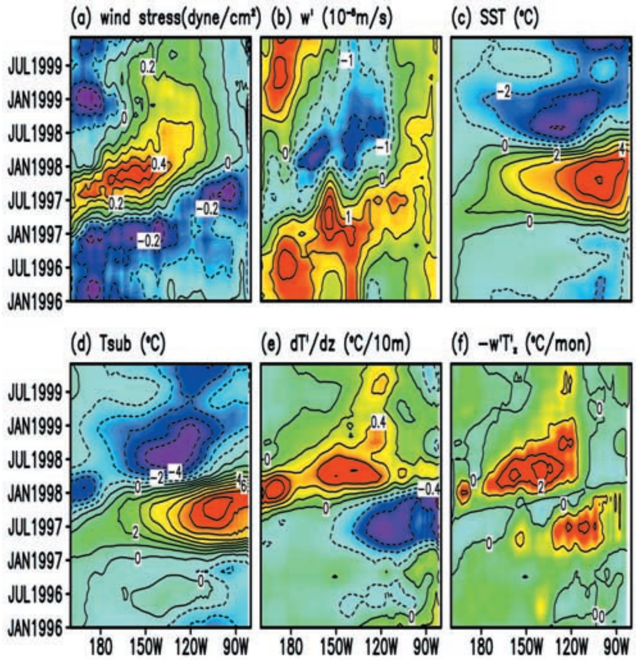

Figure 3. Time-longitude plots of (a) wind stress (dyne cm^{-2}), (b) upwelling velocity (10^{-5} m s^{-1}), (c) ocean temperature anomaly in the surface layer (°C), (d) subsurface ocean temperature (obtained at 65 m depth) (°C), (e) vertical temperature difference (between surface layer and the subsurface) (0.1 °C m^{-1}), and (f+) nonlinear vertical heat advection (°C $month^{-1}$) along the equator. Anomalies are computed with respect to the 1978–1998 climatology.

pattern is consistent with the linear atmospheric dynamic response to the SST anomalies [*Gill*, 1980] (Figure 3c). The westerly (easterly) wind stress anomalies near the equator induce anomalous downwelling (upwelling) (Figure 3b) due to the Coriolis effect. The reduction in the integrated zonal wind stress across the equatorial Pacific flattens the tilt of the equatorial thermocline. The deepening of the thermocline in the eastern equatorial Pacific leads to an adiabatic warming in the subsurface ocean (Figure 3d) that exceeds the surface warming (Figure 3c) throughout the development phase of the El Niño event (Figure 3e). At the same time, an enhanced upwelling (Figure 3b) due to easterly wind anomalies leads to an enhanced vertical advection of anomalously warm waters, thereby accelerating the surface warming.

[13] Similarly, the transition to the La Niña phase involves anomalous cooling in the subsurface ocean resulting in a positive vertical temperature gradient. At the same time, there is reduced upwelling in the eastern equatorial Pacific due to the westerly wind anomalies. The result is that upwelling of anomalously cold subsurface waters into the surface layer is prevented, thereby slowing down surface cooling. Therefore, the out-of-phase relationship between the vertical temperature gradient and the upwelling in the eastern equatorial Pacific gives rise to the positive NDH throughout the 1997 to 1999 ENSO cycle. The nonlinear warming serves as a strong positive feedback for the El Niño event and as a strong negative feedback for the following La Niña event. Similar results (not shown) were obtained for the 1982/83 El Niño and its subsequent La Niña phase. As illustrated above, a prerequisite for this type of nonlinear heating is an eastward movement of the anomalous wind stress patch. Before the 1976 climate shift, ENSO events were characterized by westward propagating anomalies. A heat budget analysis of another ocean assimilation data set [*Carton et al.*, 2000] covering the period from 1950–1999 (Figure 4) confirms that the pre-1976 era exhibited much less nonlinear heating during ENSO cycles and hence smaller amplitudes of El Niño events than that of the post-1976 era. Therefore, the direction into which ENSO events propagate may serve as a useful indicator to estimate the potential for nonlinear amplification and hence for the probability to generate strong El Niño events. Further studies are needed to show the linkage between the eastward propagation of an El Nino event and the preferred nonlinear dynamical amplification. Firmly establishing this linkage will help to predict the amplitudes of strong El Niño events, which so far have been very difficult to predict [*Landsea and Knaff*, 2000].

5. Nonlinear Dynamic Heating and Tropical Warming

[14] There has been an increase in the net warming starting from about 1976 with an average value of about 0.2°C/month, which was significantly higher than the average value of the pre-1976 period (Figure 4). Half of the increased warming after the 1976 climate shift may be attributable to an increased El Niño activity associated with 1982/83 and 1997/98 events. To estimate the response to this dynamical heating, we adopt the simple ENSO recharge-oscillator equation (equation 2.6) of *Jin* [1997] and add a NDH forcing term denoted as N' to the SST anomaly equation. For a rough estimation of the mean temperature changes generated by the term N', we consider the steady solution in a realistic parameter regime allowing a slightly damped oscillation. Following the choices of other parameters in *Jin* [1997] and setting the parameter b = 1.5 in the model (corresponding to relative coupling coefficient at 0.6), the system is slightly subcritical. In this case, the change in mean temperature is $\tau_c\overline{N'}$. Here $\overline{N'}$ is the time mean of heating term. The response time scale of the coupled model to steady forcing, τ_c, is about 4.5 months. With the excessive mean warming in the past two decades due to strong ENSO of about 0.1°C/month, the simple coupled model estimation for a steady response is thus about 0.45°C. This estimation is perhaps is a bit on the high side since the nonlinear heating term is not steady and the non-steady response will be less sensitive particularly for a 20-year mean. Yet, this estimation is not far from the observed tropical Pacific warming of about 0.3–0.4°C throughout the last decades. This implies that the mean warming can be attributed largely to an increased ENSO activity. Since the changes in ocean background conditions in the last few decades could have been responsible for the change in the ENSO activity [*An and Jin*, 2000; *Wang and An*, 2001], our result suggests a possible nonlinear positive feedback between mean climate change and ENSO variability.

6. Summary

[15] Summarizing, we found from analyses of the assimilated ocean data that the intense El Nino episodes in recent decades (1982/83 and 1997/98) were generated by nonlinear

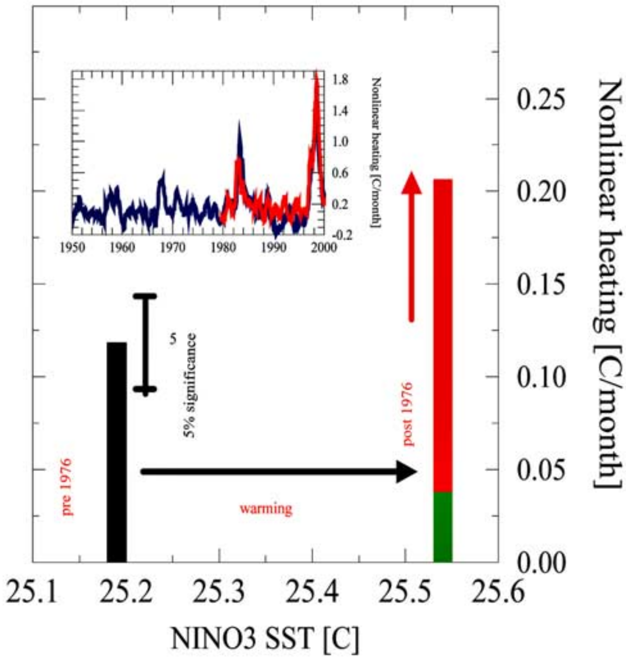

Figure 4. The inserted plot shows the time series of the nonlinear dynamic heating rates (°C month^{-1}) in the central-eastern equatorial Pacific (averaged over the area 2.5°S to 2.5°N, 150° to 100°W) based on NCEP (red) and SODA (black) data sets. The bar plot shows the mean nonlinear dynamic heating rates (°C month^{-1}) averaged from 1950 to 1976 (black bar) and from 1976 to 2000 (red and green bar, where red indicates the contribution from two strong ENSO events and the green is from the rest) together with the mean SST for these two periods in the same region. The 5% significance level for mean changes of the nonlinear heating is computed from a t-test using the variances of the pre-1976 and post-1976 period.

intensifications through the dynamical processes. These eastward propagating ENSO events had the temporal and spatial phase differences in the temperature and current fields to facilitate the dynamic heating effect in the equatorial upper ocean through nonlinear vertical and zonal advections. This nonlinear dynamic heating enhances the amplitudes of the warm phases, and it also reduces the amplitudes of cold phases of ENSO and thus results in the warm/cold asymmetry. This asymmetry has a nonlinear rectification effect on the climate mean state. Our study may provide useful knowledge for anticipating strong ENSO events.

[16] The changes in ENSO were attributed to the changes in the climate background state due to either inter-decadal climate variability or global warming. However, our evidence indicates that in recent decades the amount of nonlinear heating in the equatorial Pacific has changed significantly and the changing ENSO is also responsible for this occurrence of the nonlinear heating and thus the warming trend in the climate background state of the tropical Pacific. Following a business as usual greenhouse-warming scenario, one of model simulations [*Timmermann et al.*, 1999] exhibits an enhanced ENSO activity associated with a temperature increase in the eastern equatorial Pacific. These results were interpreted [*Jin et al.*, 2001] in terms of a local dynamical amplification of tropical Pacific climate change. The potential positive feedback between mean climate change and ENSO variability needs further studies.

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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.

Carton, J., G. Chepurin, X. Cao, and B. Giese, A Simple Ocean Data Assimilation analysis of the global upper ocean 1950–1995, Part 1: methodology, *J. Phys. Oceanogr.*, *30*, 294–309, 2000.

Gill, A., Some simple solutions for heat-induced tropical circulation, *Q. J. R. Meteorol. Soc.*, *106*, 447–462, 1980.

Ji, M., A. Leetmaa, and J. Derber, An ocean analysis system for seasonal to interannual climate studies, *Mon. Wea. Rev.*, *123*, 460–481, 1995.

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

Jin, F.-F., Z.-Z. Hu, M. Latif, L. Bengsson, and E. Roeckner, Dynamical and Cloud-Radiation Feedbacks in El Niño and Greenhouse warming, *Geophys. Res. Lett.*, *28*, 1539–1542, 2001.

Landsea, C. W., and J. A. Knaff, How much skill was there in forecasting the very strong 1997–98 El Niño?, *Bull. Am. Meteorol. Soc.*, *81*, 437, 2000.

Latif, M., D. Anderson, T. Barnett, M. Cane, R. Kleeman, A. Leetmaa, and J. O'Brien, A review of the predictability and prediction of ENSO, *J. Geophys. Res.*, *103*, 14,375–14,393, 1998.

McPhaden, M. J., The child prodigy of 1997–1998, *Nature*, *398*, 559–562, 1999.

Neelin, D., D. Battisti, A. Hirst, F.-F. Jin, Y. Wakata, T. Yamagata, and S. Zebiak, ENSO theory., *J. Geophys. Res.*, *104*, 14,262–14,290, 1998.

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*, *357*, 230, 1999.

Trenberth, K., Recent observed interdecadal climate changes in the Northern Hemisphere, *Bull. Am. Meteorol. Soc*, *71*, 988–993, 1990.

Wang, B., and S. I. An, Why the properties of El Niño changed during the late 1970s, *Geophys. Res. Lett.*, *28*, 3709–3712, 2001.

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