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LINKAGES BETWEEN EL NIÑO AND RECENT TROPICAL WARMING

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The El Niño-Southern Oscillation phenomenon (ENSO) is the most important source for interannual climate variability. It originates from tropical coupled air-sea interactions in the Pacific but encompasses weather patterns globally with severe impacts [Cane, 1983; Rasmusson and Wallace, 1983] for both societies and ecological systems**.** Recently the possibility has been discussed [Collins, 2000; IPCC, Climate Change 2001; Knutson et al., 1997; Timmermann, 2001; Timmermann et al., 1999] that an anticipated anthropogenic greenhouse warming might have an influence not only on the climate mean state of the tropical Pacific, but also on its variability. The linkages between ENSO and global warming [Trenberth and Hoar,] is still unclear despite the great progress made in understanding [Neelin et al., 1998] and predicting [Latif et al., 1998] ENSO.

Theories based on the linear dynamics of the coupled ocean-atmospheric system have provided fundamental insights into the mechanisms that are responsible for its oscillatory nature [Philander, 1983] and its periodicity of about 3-5 years: Small positive (negative) perturbations can be amplified into an El Niño (La Niña) event [Bjerknes, 1969] due to the presence of a positive air-sea feedback that involves large-scale mass and heat redistributions in the atmosphere and the ocean. The phase transition from an El Niño event to a La Niña event is through a delayed negative feedback that originates from ocean dynamical adjustments [Cane and Zebiak, 1985; Schopf and Suarez, 1988; Battisti and Hirst, 1989; Jin and Neelin, 1993]. That is, the equatorial ocean heat content is slowly draining out (building up) during a warm (cold) ENSO phase as the result of the dynamic mass exchange between the equatorial belt and off-equatorial regions, thereby leading to a phase reversal [Wyrtki, 1986; Jin, 1997]. The typical interannual timescales originates from a combination of a timescale that characterizes the positive dynamical feedback and a timescale that characterizes the delayed negative ocean feedback.

This linear deterministic theory does not provide much insight into what governs the amplitude of ENSO. The physical processes that determine the amplitude of ENSO depend crucially on the dynamical regime in which ENSO operates. If ENSO operates in a self-sustained regime, neglecting the role of weather noise, nonlinear terms control the amplitude of ENSO [Jin, 1997]. If ENSO is a stable oscillation [Penland and Sardeshmukh, 1995] that has to be kicked off by stochastic weather perturbations such as westerly wind-bursts, the amplitude is strongly determined by the level of these short-term weather fluctuations. There is some evidence [An and Jin, 2000; Wang and An, 2001] that ENSO has undergone a dynamic shift around the year 1976 from a stable to an unstable oscillating system. This shift has been linked to changes in the background state, associated with the famous 1976 climate shift [Trenberth, 1990]. This climate shift also changed the propagation characteristics of ENSO and its amplitude. 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. At the same time, there is a pronounced asymmetry between El Niño and La Niña, the former being very strong (up to 4.5^{o}C, as measured by the spatially averaged eastern equatorial Pacific temperature anomalies), the latter being relatively weak in amplitude (up to -3^{o}C).

These changes in the interannual ENSO variability have been attributed to changing climate background conditions [An and Jin, 2000; Wang and An, 2001]. A question that has not been answered yet using existing observational data is whether the observed changes in ENSO variability such as the El Niño/La Niña asymmetry feed back onto the tropical climate mean state. Furthermore one might ask, is there a positive feedback between changes in climate background conditions and ENSO variability with the potential to accelerate tropical climate change? These questions will be addressed using the ocean assimilation dataset from the National Center of Environment Prediction [Ji et al., 1995] (NCEP) covering the period from 1980-2001. Despite of the model and input data deficiencies this data product can be regarded as an approximate reconstruction of the real ocean state.

In order to determine which processes are responsible for generating large El-Niño events we analyzed 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 much to the east that the climatologic cold tongue (Fig.1a) vanished (Fig.1b). The mean tilt of the thermocline (representing the layer of sharp vertical temperature gradient that separates the upper ocean from the abyssal deep ocean) (Fig.1c) was reversed (Fig.1d). Even the equatorial undercurrent (Fig.1c), a rather persistent ocean current was strongly disrupted (Fig.1d). Therefore, the anomalies in sea surface temperature

(SST), thermocline depth and ocean currents are possibly too large to be viewed as small linear perturbations of the tropical Pacific climate mean state. In fact the 97/98 SST attained typical warm-pool temperatures (Fig.1f), thereby reaching the maximum amplitude* for an El Niño event. Another similar event occurred in 1982/83. It is expected that for such extreme events nonlinear dynamic heating terms become important. In order to quantify their role in generating ENSO events we calculated the heat budget** in the layer of the uppermost 50 meters of the tropical Pacific, using the NCEP ocean data assimilation product. As shown in Figure 2a the 1997/98 event is characterized by a large nonlinear advective heating anomaly of about 2^{o}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 El-Niño event. The subsequent La Niña state from 1998/99 was also characterized by a positive nonlinear heat advection of about 2^{o}C/month. The overall effect of nonlinear heat advection is to amplify strong El Niño events and to damp strong La Niña events. This leads to an asymmetry in the magnitude of El Niño and La Niña in consistency with the observations [Burgers and Stephenson, 1999]. The nonlinear advection of heat is negligible for modest ENSO events such as the 1986/87 El Niño and the subsequent La Niña state (Fig.2b). In this case El-Niño and La Niña attained similar absolute magnitudes.

Further analysis of the heat budget reveals that nonlinear advective heating originates from 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 (Fig.3a). This wind pattern is consistent with the linear atmospheric dynamic response to the SST anomalies [Gill, 1980] *(*Fig. 3c*).* The westerly (easterly) wind stress anomalies near the equator induce anomalous downwelling (upwelling) (Fig.3b) due to Coriolis force 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 (Fig.3d) that exceeds the surface warming (Fig. 3c) throughout the development phase of the El Niño event (Fig.3e). At the same time, an enhanced upwelling (Fig. 4b) due to easterly wind anomalies leads to an anomalous vertical advection of anomalously warm waters, thereby accelerating the surface warming.

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 prevailing 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 nonlinear dynamic warming throughout the 1997 to 1999 ENSO cycle. The nonlinear warming serves as a strong positive feedback for the El Niño event and 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 can serve as a useful indicator to estimate the potential for nonlinear amplification and hence for the probability to generate strong El Niño events. This knowledge might help to predict the amplitudes of large El Niño events that so far have been a very difficult to predict [Landsea and Knaff, 2000].

In Fig. 4 we show the nonlinear dynamic heating for the last 2 and 5 decades from two ocean data assimilation sets (NCEP [Ji et al., 1995] and SODA [Carton et al., 2000]). It can be seen that there has been a net warming starting from about 1976 with an average value of about 0.2^{o}C/month that was significantly higher than the average value of the pre-1976 period (Fig.4). Much of the increased warming after the 1976 climate shift can be directly attributed to an increased El Niño activity associated with 1982/83 and 1997/98 events. It can be estimated from dynamical considerations*** that this the increased nonlinear heating results in a 0.2-0.3^{o}C temperature increase in the eastern equatorial Pacific, given a typical timescale of about 3 to 4 months. From these considerations it can be concluded that the observed tropical Pacific warming of about 0.3 ^{o}C throughout the last decades can be attributed largely to an increased ENSO activity. Moreover, as has been shown previously [An and Jin, 2000; Timmermann, 2001; Wang and An, 2001], changes in ocean background conditions as the ones experienced in the last few decades had the potential to change also ENSO activity. Hence, we are dealing with a positive feedback between mean climate change and ENSO variability that might lead to an accelerated future tropical warming response in response to anthropogenic climate change.

Summarizing, we found from analyses of the assimilated ocean data that in recent decades the amount of nonlinear heating in the equatorial Pacific has changed significantly. Nonlinear tropical heating originates from a specific spatio-temporal phase relationship between surface and subsurface temperatures of ENSO. It has been responsible for the observed asymmetry between El Niño and La Niña as well as for an overall temperature rise of about 0.3^{o}C since the late 1970s. This accelerating effect for climate change can be further studied by using climate simulation data obtained from state-of-the-art coupled atmosphere-ocean models experiments. Following a business as usual greenhouse-warming scenario, one of these model simulations [Knutson and Manabe, 1997] 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, in disagreement with previously suggested thermostat effects [Sun and Liu, 1996]. Simulating the observed nonlinear rectification effect of the tropical climate mean state due to increased ENSO activity might serve as a valuable test for climate models and might help to narrow climate model uncertainties [IPCC, Climate Change 2001].

[*] Here we propose a measure that characterizes the maximum potential intensity (MPI) for an El Niño event as measured by the eastern equatorial Pacific SST. This MPI corresponds to the radiative-convective equilibrium temperature (temperature of the equatorial Pacific without ocean dynamics). The warm pool temperature attains values close to the MPI. Similarly, the lowest temperature bound for a La Niña event is associated with a complete surface outcropping of the thermocline. It amounts to about 20^{o}C. Since the average SST in the cold tongue region is about 25^{o}C, the maximum MPI measured in terms of SST anomalies in the cold region is about 5^{o}C.

[**] The heat budget of the upper most 50m of the ocean surface layer is calculated using the following SST equation:

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

Here, T, u, v, w are SST, zonal, meridional and vertical velocities, overbar and prime denote the climatologic mean and anomalies. Heat flux and subgrid scale contributions are accounted for by the residual term R. The nonlinear advective heating term is represented by the bracket in the second line of the equation.

[***] The relevant response timescale to steady forcing can be estimated from a simple ENSO delayed-oscillator equation [Jin and Neelin, 1993; Wyrtki, 1986] that includes a nonlinear heating term N' :

$$\frac{\partial T'}{\partial t} = -\varepsilon T' + bT'(t) - dT'(t-\tau) + N' \; .$$

T' represents the temperature anomalies in the eastern equatorial Pacific. b is a positive rate for SST changes due to the Bjerknes feedback. d represents the delayed negative rate from the ocean dynamic feedback and ε denotes a collective damping rate capturing heat flux feedbacks as well as the effect of climatological Ekman upwelling. In order to estimate mean temperature changes that are generated by the nonlinear heating term N', we consider the stationary solution of the upper equation. The inverse characteristic timescale is then given by $\varepsilon - b + d$ and changes in mean temperature can be computed from $\overline{N'}/(\varepsilon - b + d)$. Typical values of $1/\varepsilon$ are in the order of about 2 months. It follows that $1/(\varepsilon - b + d)$ is larger than $1/\varepsilon$ due to the coupled dynamic feedbacks, represented by b-d. The typical timescale for the response to steady heating amounts to about 3 to 4 months.

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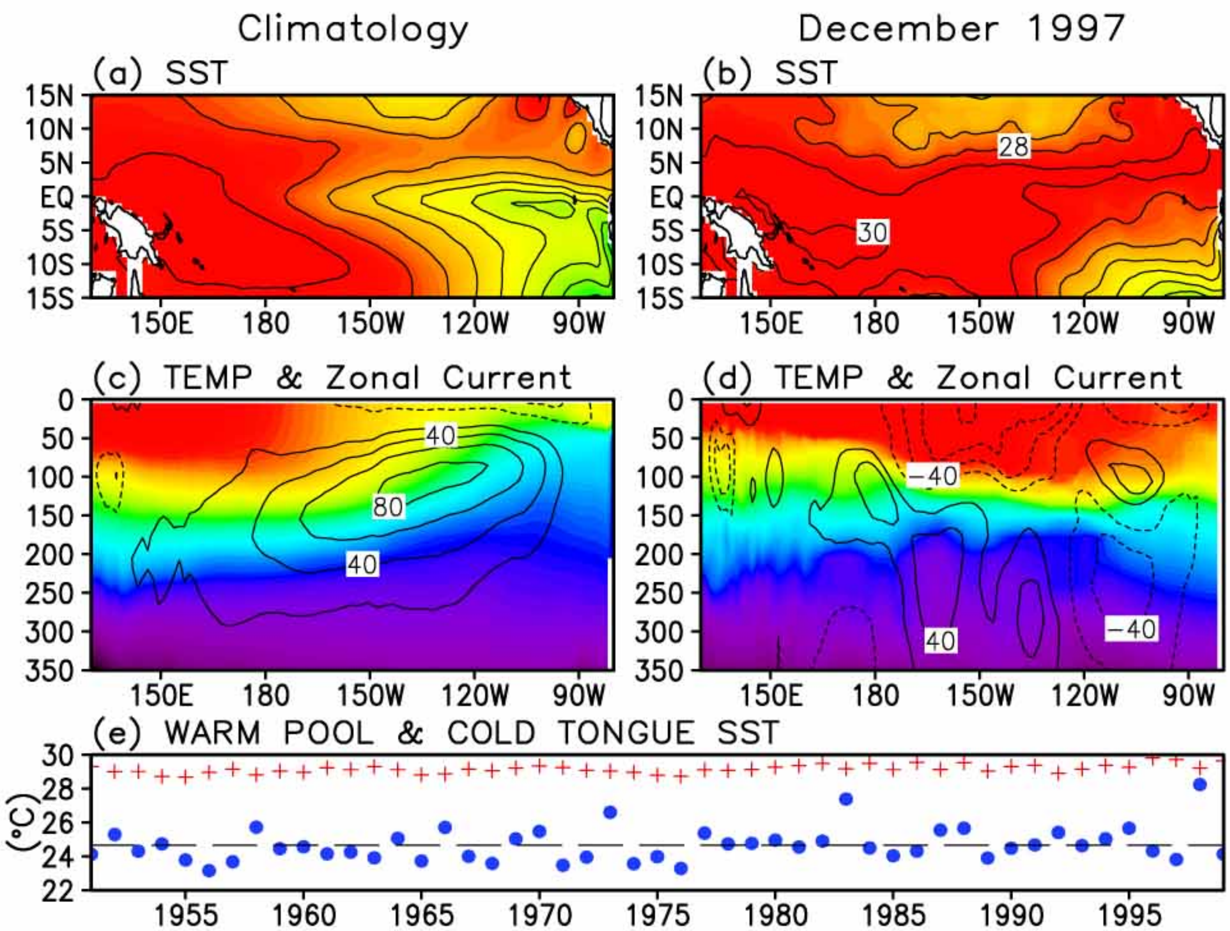

Fig. 1. (a) Sea surface temperatures (SST) (oC); (c) upper ocean temperature (oC) (in color) and zonal currents (cm s-1) (in contours). (a) and (c) are December means averaged from 1978-1998; (b) and (d) represent the 1997 December fields of (a) and (b); (e) Winter seasonal mean (November to January) SST in the warm pool (+) (averaged over the area 5oS to 5oN, 130o to 170oE) and in the cold tongue (averaged over the area 5oS to 5oN, 120o to 80oW). The large El Nino events 1982/83 and 1997/98 are characterized by very small zonal temperature gradients

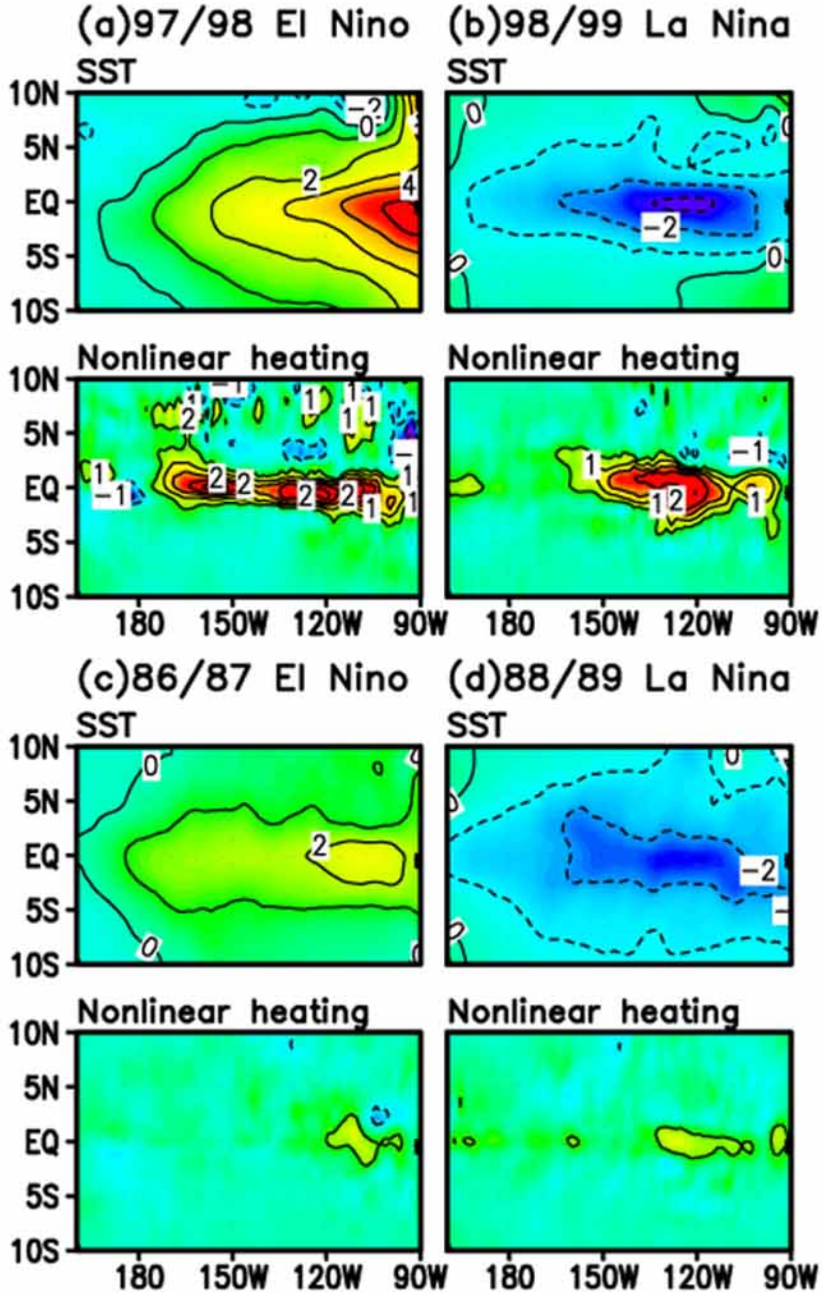

Fig. 2. December SST anomaly (oC) and rate of change in SST (oC month-1) due to the nonlinear dynamic heating terms computed for (a): the El Niño event in 1997 and (b): the La Niña event in 1998. (c) SST and nonlinear heating for the El Niño event in March 1987 and the mature La Niña situation in December 1988 (d). The data were prefiltered with 11-month running mean. The anomalies were obtained based on the climatology of 1978-1998.

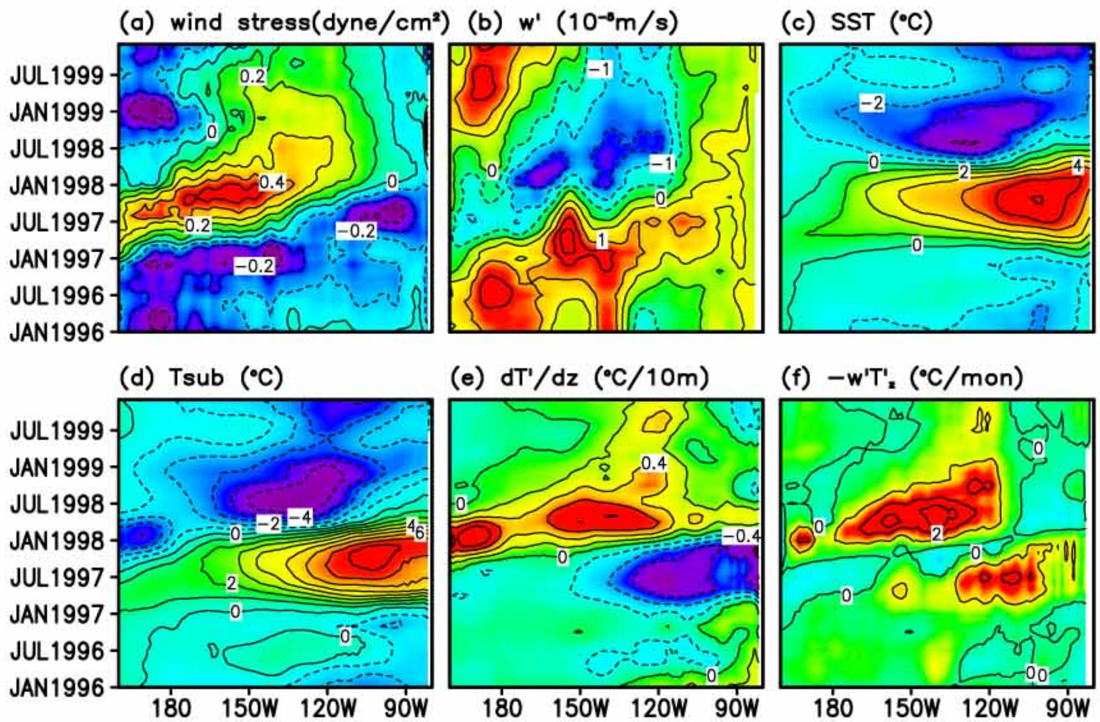

Fig. 3. Time-longitude plots of (a) Wind stress (dyne cm-2), (b) upwelling velocity (10-5 m s-1), (c) ocean temperature anomaly in the surface layer (oC), (d) subsurface ocean temperature (obtained at 65 m depth) (oC), (e) vertical temperature difference (between surface layer and the subsurface) (0.1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

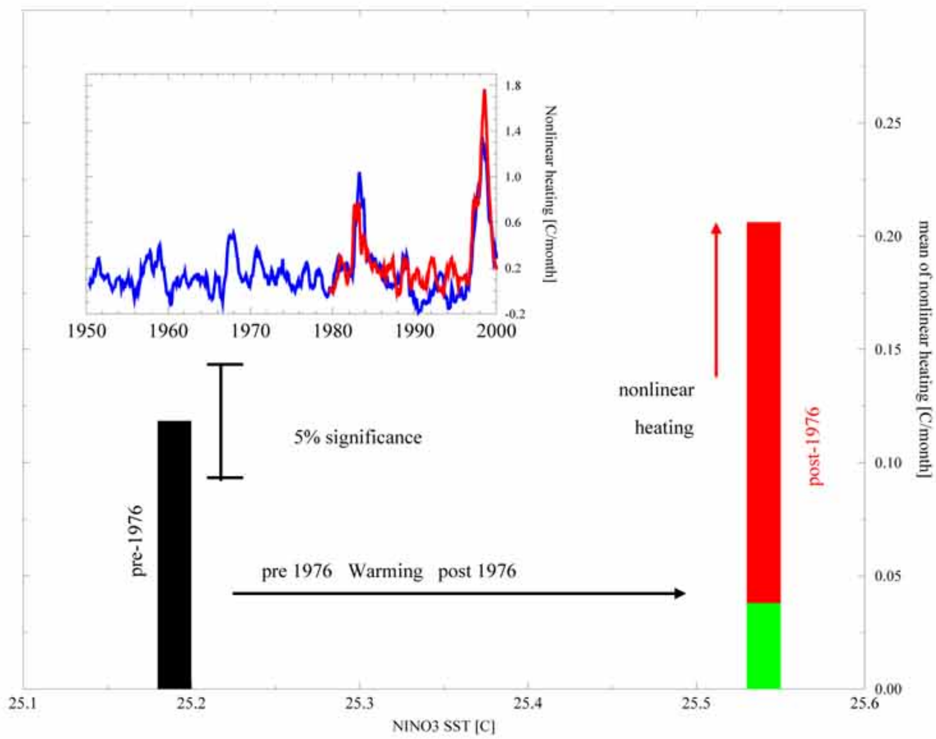

Fig. 4. The inserted plot shows the time series of the nonlinear dynamic heating rates (oC month-1) in the central-eastern equatorial Pacific (averaged over the area 2.5oS to 2.5oN, 150o to 100oW) based on NCEP (red) and SODA (black) data sets. The bar plot shows the mean nonlinear dynamic heating rates (oC 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.