The Effect of ENSO Events on the Tropical Pacific Mean Climate: Insights from an Analytical Model

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ABSTRACT

To better understand the causes of climate change in the tropical Pacific on the decadal and longer time scales, we delineate the rectification effect of ENSO events into the mean state by contrasting the time-mean state of a low-order model for the Pacific with its equilibrium state. The model encapsulates the essential physics of the ENSO system, but remains simple enough to allow us to obtain its equilibrium state, bypassing an inherent difficulty in using a GCM or observations of the real climate system to address this problem. The model has an oscillatory regime that resembles the observations. In this oscillatory regime, the time-mean SST in the eastern equatorial Pacific is found to be significantly different from the corresponding equilibrium SST, with the former being warmer than the latter. The difference is found to be proportional to the amplitude of ENSO. In addition, the zonal SST contrast of the time-mean state is found to be less sensitive to increases in external forcing than that of the equilibrium state, due to warming effect of ENSO events on the eastern Pacific. The study elucidates the role of ENSO events in shaping the tropical mean climate state. In particular, the results suggest that decadal warming in the recent decades in the eastern tropical Pacific may be more a consequence than a cause of the elevated ENSO activity during the same period. The results also provide a simple explanation for why it is difficult to detect an anthropogenically forced trend in the zonal SST contrast in the observations.

1. Introduction

The importance of the tropical Pacific sea surface temperature (SST) in predicting climate variability over North American and the world at larger has been vividly demonstrated in our rich experience with ENSO (Philander 1990). The apparent regime-like shift in the tropical Pacific SST from about 1976 has underscored another fact about tropical Pacific SST: it also varies on decadal time-scales (Wang and Ropelewski 1995; Zhang et al. 1997; Fedorov and Philander 2000). As the society increasingly needs a climate outlook beyond the time-scale of ENSO, understanding the mechanisms that give rise to the decadal variability in the background state of ENSO (or the time-mean state relative to the time-scale of ENSO) has become a forefront issue facing climate research community (Meehl et al. 2010).

This regime shift shown in Fig. 1a is accompanied with the change in the level of ENSO variability - the variance of the interannual variability of the tropical Pacific SST (Fig. 1). The level of ENSO activity during the epoch with a warmer time-mean SST in the eastern tropical Pacific is anomalously higher than the previous epoch with a colder time-mean SST in the eastern tropical Pacific. Is the change in the level of ENSO activity caused by the change in the time-mean state, or the change in the time-mean state is a consequence of the change in the level of ENSO activity? A numbers of studies have examined the impact of a warming in the mean state of the tropical Pacific on the level of ENSO activity (Fedorov and Philander 2000, 2001; An and Jin 2001; and Wang and An 2001 among others). These studies employ the traditional linear instability analysis of the mean state and deduce the impact of changes in the mean state on the growth rate of the ENSO modes. These studies have nicely illuminated a consistency between the changes in the level of ENSO activity and the corresponding changes in the time-mean state, within the mathematical framework of linear instability analysis. However, these studies do not address the cause of the warming in the time-mean state, in particular the question whether an increase in the level of ENSO activity can induce a warming in the time-mean state. We here employ a different methodology and explore the possibility that the decadal warming over the eastern Pacific is due to the rectification effect of elevated ENSO events into the mean state (i.e. the time-mean effect of ENSO events).

The possibility that ENSO may have an important time-mean effect on the tropical Pacific climatology has been highlighted by preliminary studies of the role of ENSO in the heat balance of the tropical Pacific. In a numerical experiment with a coupled model, Sun and Zhang (2006) found that the response in the upper ocean temperature to an increase in the tropical heating is very different between the case with ENSO and the case without ENSO. The presence of ENSO can increase considerably the response in the subsurface temperature, and shift the maximum surface level response from the western Pacific warm-pool to a broad region in the central and eastern Pacific. Sun and Zhang (2006) further noted that this time-mean effect of ENSO is linked to an asymmetric response to an increase in the tropical heating between the two phases of ENSO.

The surface manifestation of the asymmetry between El Niño and La Niña events - the strongest El Niño event, measured by the Niño3 SST anomaly, being stronger than the strongest La Niña event - has long been noted (Zebiak and Cane 1987; Burgers and Stephenson 1999). It has also been suggested by recent studies of decadal variability that the asymmetry between El Niño and La Niña events may result from a "residual" effect of ENSO on the background state (Rodger et al. 2004; Sun and Yu 2009). Rodgers et al. (2004) found in a long simulation by a coupled GCM that changes in the mean state between decades with high ENSO activity and decades with low ENSO activity resemble the residual of the two phases of ENSO in the model. They thereby suggest that the asymmetry could be a mechanism for decadal changes in the tropical Pacific SST. Noting a 15 year cycle in the level of ENSO activity in an extended SST data set consisting of historical and paleo-climate data, and a change in the asymmetry of ENSO with this decadal cycle, Sun and Yu (2009) has argued that the residual effect from the ENSO asymmetry may provide an explanation for the decadal cycle they have noted in the level of ENSO activity.

Specific mechanisms have also been proposed to explain the asymmetry between the two phases of ENSO. Jin et al. (2003) and An and Jin (2004) suggest that the asymmetry is due to the nonlinear term in the heat budget equation for the surface ocean. Schopf and Burgman (2006) shows that the skewness of the SST distribution could be due to a kinematic effect of oscillating a nonlinear temperature profile. While the relative contributions to the asymmetry between the two phases of ENSO from these two mechanisms need to be further studied, these studies suggest that the basin-scale dynamics of ENSO is inherently nonlinear, and a climate regime that has a higher level of ENSO activity may result in a different time-mean climate because the effects of stronger El Niño events may not be balanced by a corresponding change in the strength of the La Niña events.

Although the aforementioned studies are suggestive about a significant time-mean effect of ENSO on the climatology, this effect remains to be delineated clearly. We may divide the observations and model simulations of ENSO into epochs with different levels of ENSO activity and then try to discern the time-mean effect of ENSO by contrasting the mean states of these epochs as done in Rodgers et al. (2004), but this approach only confirms a correspondence between a change in the level of ENSO activity and a change in the mean state. The asymmetry between the two phases of ENSO only suggests a non-zero residual effect of ENSO, to the extent that a finite threshold value is used to define El Niño and La Niña events. But the asymmetry alone is not a sufficient condition for a significant time-mean (or rectification) effect of ENSO because such a residual effect will depend quantitatively on how you define El Niño and La Niña events.

Ideally, we want to contrast the equilibrium state of the coupled tropical ocean-atmosphere in which ENSO as an instability has not manifested with the actual realized climatology in which ENSO has manifested. The difficulty for doing so is that if the equilibrium state of the coupled tropical ocean-atmosphere is unstable, it is by definition not observed. The same difficulty exists for complex GCMs whose state evolutions have to be obtained by numerical integration of a set of equations which also misses the unstable equilibrium state. In this paper, we present a low-order analytical system for the coupled tropical ocean-atmosphere to explore the effects of ENSO on the time-mean state. The model encapsulates the essential physics of ENSO and has been shown to capture the major characteristics of ENSO (Sun 1997; Timmerman and Jin 2002). The realized time-dependent state in the model can be calculated numerically; the equilibrium state can be obtained analytically. Thereby, we can delineate the role of ENSO events in the climatology (i.e., the time-mean state) by comparing the two states. With this methodology, we will also be able to address another question, which is whether ENSO plays a role in determining the sensitivity of the climatology of the tropical Pacific to a change in external forcing. This methodology we employ is analogous to that used by Manabe and his collaborators in their attempt to establish the effect of moist convection on the mean climate – they calculated the radiative equilibrium of their model atmosphere and compared with the radiative convective equilibrium of their model atmosphere (Manabe and Moller 1961;

Manabe and Strickler 1964; Manabe and Wetherald 1967).

This paper is organized as follows. We first briefly describe the model in section 2. We then present the main results concerning the differences between the time-mean state and the equilibrium state in section 3. Summary and discussion are provided in section 4.

2. The Model

We use the model of Sun (1997, 2000). It is an extension of the model of Sun and Liu (1996) by adding the thermocline dynamics in the manner given by Jin (1996). The heat budget of the ocean surface layer can be written as

$$\frac{dT_1}{dt} = c(T_e - T_1) + sq(T_2 - T_1) \tag{1}$$

$$\frac{dT_2}{dt} = c(T_e - T_2) + q(T_{sub} - T_2) \tag{2}$$

$$s = \frac{U}{L_x} / \frac{W}{H_1} \tag{3}$$

where T_1 and T_2 represent the western and eastern equatorial Pacific surface temperature, respectively; T_e is the radiative–convective equilibrium temperature; $1/c$ is a typical thermal damping time scale; T_{sub} is the subsurface ocean temperature; q=W/H_1, where W is the upwelling velocity in the equatorial eastern Pacific and H_1 is the depth of the mixed layer; zonal mass flux is assumed to be a fraction of the total upwelling and this fraction can be measured by s. L_x in (3) represents the half zonal width of the basin, and U represents the zonal velocity. The value of q is given by

$$q = \frac{\alpha}{a}(T_1 - T_2) \tag{4}$$

where α measures the sensitivity of wind-stress to changes in the SST gradients; a defines the adjustment time scale of the ocean currents to surface winds. The subsurface temperature T_{sub} depends strongly on the eastern Pacific thermocline depth and can be parameterized as

$$T_{sub} = \Phi(-H_1 + h_2^{'}) \tag{5}$$

$$\Phi(z) = T_e - \frac{T_e - T_b}{2}(1 - \tanh(\frac{z + z_0}{H^*})) \tag{6}$$

$h_1^{'}$ and $h_2^{'}$ are the western and eastern equatorial thermocline anomalies; z_0 is the depth at which W takes its characteristic value. H^* measures the sharpness of the thermocline. T_b may be regarded as the temperature of the deep ocean. Following Jin (1996), $h_1^{'}$ and $h_2^{'}$ are governed by the following two equations:

$$h_2^{'} - h_1^{'} = -\frac{H_1}{H_2} H \frac{\alpha}{b^2}(T_1 - T_2) \tag{7}$$

$$\frac{1}{r}\frac{dh_1^{'}}{dt} = -h_1^{'} + \frac{H_1}{2H_2} H \frac{\alpha}{b^2}(T_1 - T_2) \tag{8}$$

A balance between zonal pressure gradients and zonal wind stress is shown in (7). H_2=H-H_1 with H being the zonal mean depth of the upper ocean at rest. b=c_k/Lx where c_k is the speed of the first baroclinic Kevin wave. A slow adjustment process of the thermocline depth to its equilibrium value determined by the surface wind-stress and mass conservation is adopted in (8). Parameter r in (8) measures the time-scale for this slow adjustment process. As shown by Sun (1997) and Timmerman and Jin (2002), the model simulates the major characteristics of observed ENSO. Readers are referred to these two studies for temporal characteristics of the oscillation (i.e., time series of T_1, T_2, h_1' and $h_2^{'}$) simulated by the model. The focus of the present presentation is on the differences between the time-mean state and the equilibrium state of the model.

3. The Differences between the Time-Mean State and the Equilibrium State

The time-mean state and the equilibrium state of the western equatorial Pacific SST (T_1) and the eastern equatorial Pacific SST (T_2) as a function of T_e are shown in Fig. 2a. The equilibrium state of the system has already been shown in Fig. 2 in Sun (1997); here we add the plot of time-mean state to contrast its difference from the equilibrium state. The parameters used here are the same as in Sun (1997). A standard Runge–Kutta method of fourth order is used to integrate the model equations and thereby obtain the time-mean state. The equilibrium state is obtained by setting the time derivatives on the left side of (1), (2), (7) and (8) to zero, and then reducing (1)-(8) to a single nonlinear algebraic equation.

As described by Sun (1997), Figure 2a shows that when the radiative forcing T_e achieves 25.5°C, a pitch-fork bifurcation (Strogatz 2001) of the system takes place and the coupled system starts to have SST gradients, winds, and currents. Further increasing T_e to 29.2°C, the system experiences a Hopf bifurcation (Strogatz 2001) and begins to enter an oscillatory state. The amplitude of the oscillation increases with further increase in T_e (Fig. 2b). The time-mean value and the equilibrium value of either T_1 or T_2 are the same before the occurrence of Hopf bifurcation, validating the accuracy of the numerical methods used to obtain the time-mean state. After the system enters the oscillatory regime, the two states are significantly different. The time-mean value of T_2 (or T_1) in the presence of ENSO are observed to be larger than the corresponding equilibrium value under a given radiative forcing, and this discrepancy between the two values becomes even larger as we further increase the value of T_e to increase the amplitude of ENSO.

The difference in T_2 between the two states is much more profound than the difference in T_1. The two T_2 actually go to opposite directions as T_e increases in the presence of ENSO oscillation. The equilibrium T_2 decreases as T_e increases, a result that is reminiscent of that from Clement et al. (1996) [see also Cane et al. (1997)]. However, the time-mean value of T_2 increases with the increase of T_e. Note that in the present model, the background subsurface temperature is allowed to change in response to changes in T_e according to (5) and (6) while that in the Zebiak-Cane model (Zebiak and Cane 1987) - the model used by Clement et al. (1996) - is fixed. As discussed by Sun (2003) which employs an ocean model [the model of Gent and Cane (1989)] that has a heat budget for the subsurface ocean, the present approach implicitly takes into account the rectification effect of ENSO events into the reference subsurface temperature profile in a way that is consistent with the results from the more complicated ocean model used in Sun (2003).

For a given T_e, the time mean value of T_2 is much warmer than its equilibrium value. Correspondingly, the zonal SST contrast in the time-mean state is much reduced from that in the equilibrium state. Given the stability of the system is determined by the zonal SST contrast (Jin 1997; Sun 1997), the time-mean state is more stable than the equilibrium state. So the reason behind the warming effect of ENSO events on the eastern Pacific is that ENSO events tend to neutralize the equilibrium state. [Just in case it helps to bring this explanation to a general framework for what instability generally does to its mean state, we recall that tropical deep convection collectively warms the upper troposphere and maintain a moist adiabatic lapse rate (Xu and Emanuel 1989). In other words, what ENSO events in the coupled ocean-atmosphere system do to the time-mean zonal SST contrast is analogous to what convective events in the tropical atmosphere do to the time-mean lapse rate].

Because the time-mean value of T_2 increases as T_e increases while the equilibrium

T_2 actually decreases, the time-mean zonal SST contrast in the presence of ENSO increase at a much smaller rate than the equilibrium zonal SST contrast. The former is about 0.25^{o}C per 1^{o}C increase in T_e while the latter is 0.58^{o}C per 1^{o}C increase in T_e. This reduced sensitivity may explain the difficulty in detecting the anthropogenically forced increase in the zonal SST contrast in the observations (Vecchi et al. 2008): the data we have are yet good enough to detect this small change. We will return to this point in the summary section.

Differences between the time-mean subsurface ocean temperature T_{sub} and the equilibrium T_{sub} in the presence of ENSO oscillation are similar to those between the time-mean and the equilibrium T_2, but are more pronounced, consistent with the observations (Fig. 3a). The time-mean value of T_{sub} increases as T_e increases in the presence of ENSO, in contrast with its equilibrium solution which decreases. The relationship between T_{sub} and T_e shows even stronger nonlinearity than that between T_2 and T_e, indicating the importance of subsurface dynamics. As expected, the time-mean upwelling is less strong than that in the equilibrium state [recall Eq. (3)] (Fig. 3b). In the presence of ENSO, the depth of the thermocline in the east is deeper in the time-mean state than in the equilibrium state (Fig. 3c). The reverse is true for the thermocline in the west (Fig. 3d). As the amplitude of ENSO increases, the depth of the thermocline in the time-mean state in the east Pacific becomes increasingly deeper than that in the equilibrium state, underscoring the impact of ENSO on the depth of the thermocline.

Using the same model, Timmermann and Jin (2002) showed that the temporal characteristics of the oscillation can be sensitive to the choice of s. For example, they found that a periodic solution described by Sun (1997) can become chaotic when the strength of zonal advection relative to the strength of the upwelling (the parameter s)

is reduced while keeping the value of T_e fixed. We investigate whether the findings concerning the effect of ENSO on the tropical Pacific mean state depends on the details of ENSO characteristics by varying the value of s.

The case shown in Fig. 2 has the value of s set to 1/3. Figure 4 shows two more cases with s set respectively to 0 (a, b) and 0.096 (c, d). The two panels (a and b, or c and d) correspond to the two panels in Fig. 2. When we reduce the strength of zonal advection to be neglected (s=0), the two states of eastern equatorial Pacific SST T_2 again diverges after the Hopf bifurcation takes place and brings in the existence of ENSO. Note that Hopf bifurcation occurs at a much smaller value of T_e (T_e=26.8°C), indicating a stabilizing role from the existence of zonal advection. Unlike the case with s=1/3, the difference in T_2 between the two states in the case with s=0 doesn't increase monotonically as T_e increase. It comes to its maximum value at T_e=28°C, when the amplitude of ENSO reaches its maximum, and then decreases rapidly as the amplitude of ENSO decreases (Fig. 4b). The two states merges into a single one again at T_e=28.3°C when the oscillation disappears completely. This confirms that the differences between the two states are proportional to the amplitude of ENSO. Figure 4a shows clearly again that in the presence of ENSO, the time-mean T_2 is warmer than the equilibrium T_2. (i.e., the time mean state of the equatorial eastern Pacific in the presence of ENSO is warmer than the equilibrium state in which ENSO is mathematically prevented from occurring). Figure 4c and 4d show the case with s=0.096, a value close to the one used by Timmermann and Jin (2002). Again, the results confirm the effect of ENSO on the mean state of the tropical Pacific: In the presence of ENSO, the two states are different with the time-mean T_2 warmer than the equilibrium T_2. Also, note that the regime of oscillation becomes wider as the value of s increases, presumably because zonal advection plays a stabilizing role as zonal advection is a cooling mechanism for the western Pacific. It has been shown by earlier studies that zonal advection is significant in observations and may play an important role in ENSO dynamics (Picaut et al. 1997; Fedorov and Philander 2001).

4. Summary and Discussion

Motivated for a more complete understanding about the observed co-occurrences of an elevated (reduced) level of ENSO activity and a background warming (cooling) in the eastern tropical Pacific, we have employed a novel methodology to delineate the effect of ENSO events on the time-mean equatorial upper ocean. This new methodology is to contrast the time-mean state of a low-order nonlinear model with its equilibrium state. The realized time-dependent state in this model is calculated numerically, and the corresponding equilibrium state is obtained analytically, allowing us to compare the two states of coupled equatorial Pacific hand by hand, and thereby delineate the role of ENSO in shaping the tropical Pacific climatology.

The results from such an exercise show unambiguously that in the presence of ENSO, the differences between the equilibrium state and the realized time-mean state is significant. In particular, it is found that the time-mean equatorial eastern Pacific SST is significantly higher than that in the equilibrium state and that the time-mean zonal SST contrast is significantly weaker than that in the equilibrium state. The differences between the two states are further shown numerically to be proportional to the magnitude of ENSO oscillation.

The present results advance our understanding of the effect of ENSO events on the time-mean equatorial ocean beyond that from the empirical studies (Rodger et al. 2004; Sun and Yu 2009). This result, together with that from Sun and Zhang (2006) and Schopf and Burgman (2006) add weight to the argument that the recent decadal warming in the eastern tropical Pacific may be a consequence of the elevation of ENSO events during this period.

Although the present results strengthens the argument that the recent decadal warming in the eastern tropical Pacific may be a consequence of the elevation of ENSO events during this period, such a causality can not be firmly established unless the causes of the elevation of ENSO activity are shown independent of the decadal background warming in the tropical Pacific. As earlier studies have shown that a decadal warming in the background state can cause an elevation of ENSO activity (Fedorov and Philander 2000, 2001; An and Jin 2001; and Wang and An 2001), the possibility is raised that a nonlinear interaction between ENSO events and the time-mean state may act as a viable mechanism for decadal variability in the tropical Pacific region. We note, however, the study by Wittenberg (2009) which shows that the level of ENSO activity in a GFDL model can change substantially from one decadal epoch to another without any notable change in the time mean state over the epoch. We agree that there may be other causes for decadal variability in the level of ENSO activity, such as random forcing from weather events. The apparent lack of rectification into the mean state in the GFDL model, however, does not necessarily contradict our conclusion here because the ENSO events in the model may be too linear (Sun et al. 2011).

The analytical model also shows that at least in certain regimes, the amplitude of ENSO events increase with enhanced radiative heating. Thus an interesting emerging scenario is that ENSO events become stronger in response to an enhanced radiative heating, which cause a warming in the tropical Pacific. Such a scenario is not supported by coupled GCM simulations, however. A survey of coupled GCM simulations has not revealed any systematic change in the level of ENSO activity in response to global warming (Collins et al. 2010). This apparent contradiction may be again due to that the nonlinearity of ENSO is either nonexistent or severely underestimated by coupled GCMs (An et al. 2005; Sun 2010; Sun et al. 2011). It is also questionable whether the tropical Pacific region in the coupled GCMs is in the same dynamic regime as in the real world (Sun et al. 2006; Guilyardi et al. 2009; Guilyardi et al. 2011). Of course, it is also possible that the present model is too simple. A key issue ahead is to bridge the gap between simple models and GCMs in their predictions of the response of ENSO to global warming. Addressing this issue may necessarily entail a more critical assessment of the nonlinearity of ENSO events in the models including a quantification of the rectification effect of ENSO into the mean state in the various GCMs.

The results from the present analysis also suggest that the sensitivity of the tropical Pacific mean climate, the zonal SST contrast in particular, to an increase in the greenhouse effect, may be a function of the time-mean effect of ENSO events. The reduced rate of increase in the time-mean zonal SST contrast ($T_1 - T_2$) in the present model in response to an increase in the radiative-convective equilibrium SST (T_e), compared to that in the equilibrium state, suggests that the zonal SST contrast may be regulated by ENSO events. Whether this provides a viable explanation for the difficulty to detect a significant trend in the zonal SST contrast in the observations discussed by Vecchi et al. (2008) is a question worth exploring. In the same vein, recognizing this nonlinear effect of ENSO and the apparent inability to fully capture this effect by all the models may prove useful for fully understanding the differences among model predictions of the response of the zonal SST contrast to global warming. The results thus underscore the importance for climate models to correctly simulate ENSO, its nonlinear dynamics in particular, to be able to capture correctly the response of ENSO and the climatological state to anthropogenic forcing.

We would like to note that the results reported in this article are from a highly truncated version of the real coupled tropical Pacific ocean-atmosphere system. A salient feature in the decadal warming of the east tropical Pacific (Fig. 1) is that the maximum warming is not right on the equator. But the model in its current form does not carry any information about the meridional structure of the rectification effect. The results will have to be compared with those obtained by more sophisticated models in order to fully ascertain the time mean effect of ENSO events. Regardless the accuracy of the present results, the framework they constitute is likely to be useful for diagnosing and understanding the results from more complicated climate models, such as GCMs.

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Figure Captions

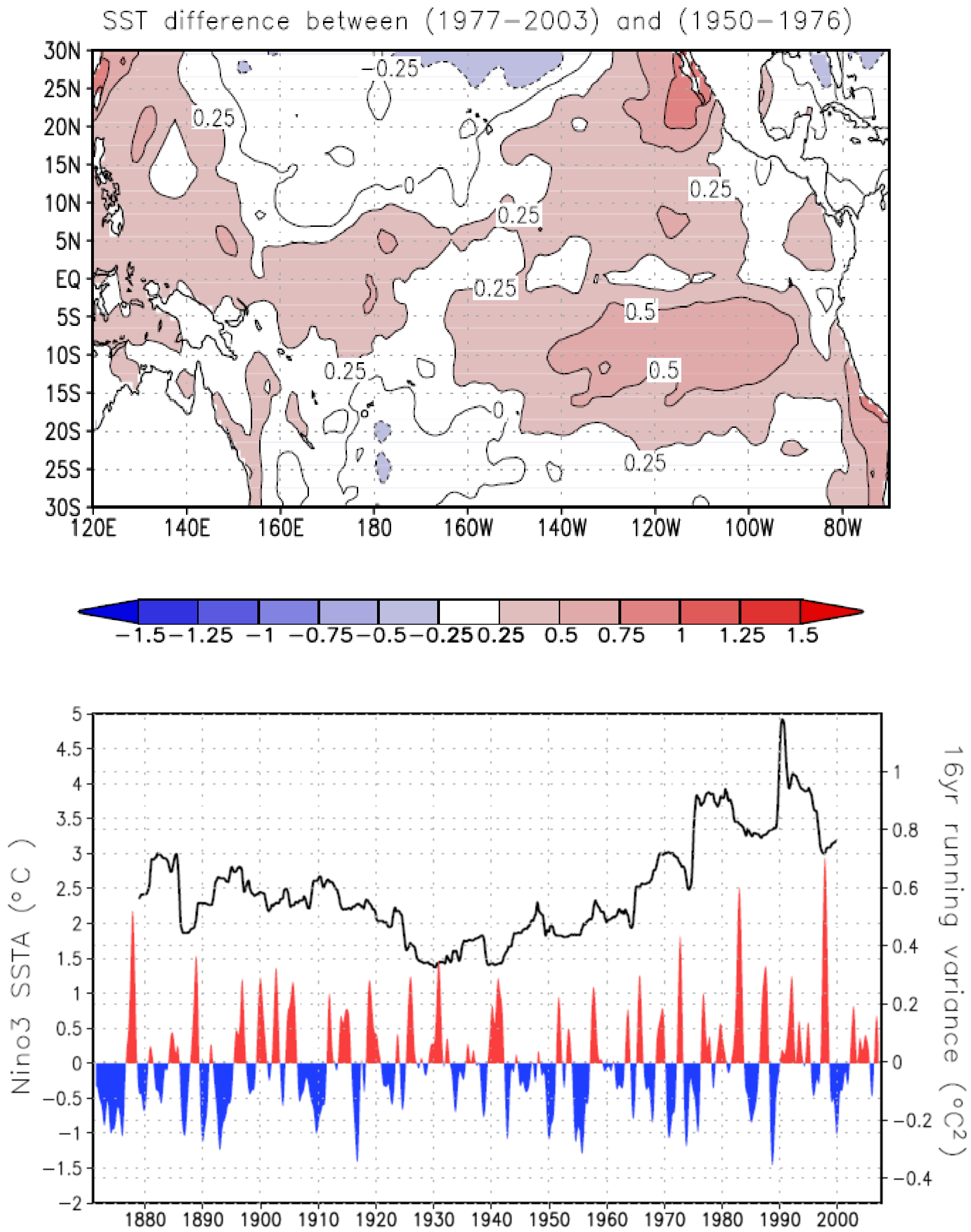
FIG. 1. (a) Sea Surface Temperature (SST) differences between two epochs: 1977-2003 and 1950-1976. (b) Niño3 SST time series. Niño3 SST (anomalies) (in color). The black solid line is the variance of Niño3 SST anomalies obtained by sliding a moving window of a width of 16 years. Note the epoch 1976-2001 has higher level of ENSO activity than the previous period 1950-1976. (SST data used are from the Hadley Center for Climate Prediction and Research) (Rayner et al. 1996).

FIG. 2. (a) Equatorial Pacific SST as a function of T_e. T_1 and T_2 are respectively for the western and eastern Pacific SST. Solid lines are for the time-mean state, and the dashed lines are for the equilibrium state. (b) Amplitude of oscillation for T_2 as a function of T_e. The amplitude is defined here as the half value of the difference between the maximum and minimum value of T_2. Also shown in Fig. 2b is the zonal SST contrast as measured by the difference between T_1 and T_2 for the equilibrium state (red) and the time-mean state (blue). Note that the rate of increase in the zonal contrast in the time-mean state with T_e is less than half of the corresponding rate of increase in the equilibrium state (0.25 versus 0.56). The parameter values used in this

figure are the same as in Sun (1997, 2000).

FIG. 3. Same as in Fig. 2a except for the subsurface temperature (a), the upwelling (b), the thermocline depth of the eastern equatorial Pacific (anomaly) (c), and the depth of the thermocline in the western equatorial Pacific (anomaly) (d). Note that a negative anomaly in h_2' means a reduction in the thermocline depth. The positive difference between the time-mean solution of h_2' and the equilibrium h_2' in the presence of ENSO implies a deepening of h_2' in the eastern Pacific due to the presence of ENSO.

FIG. 4. Same as in Fig. 2, except for s=0 (a, b) and s=0.096 (c, d)



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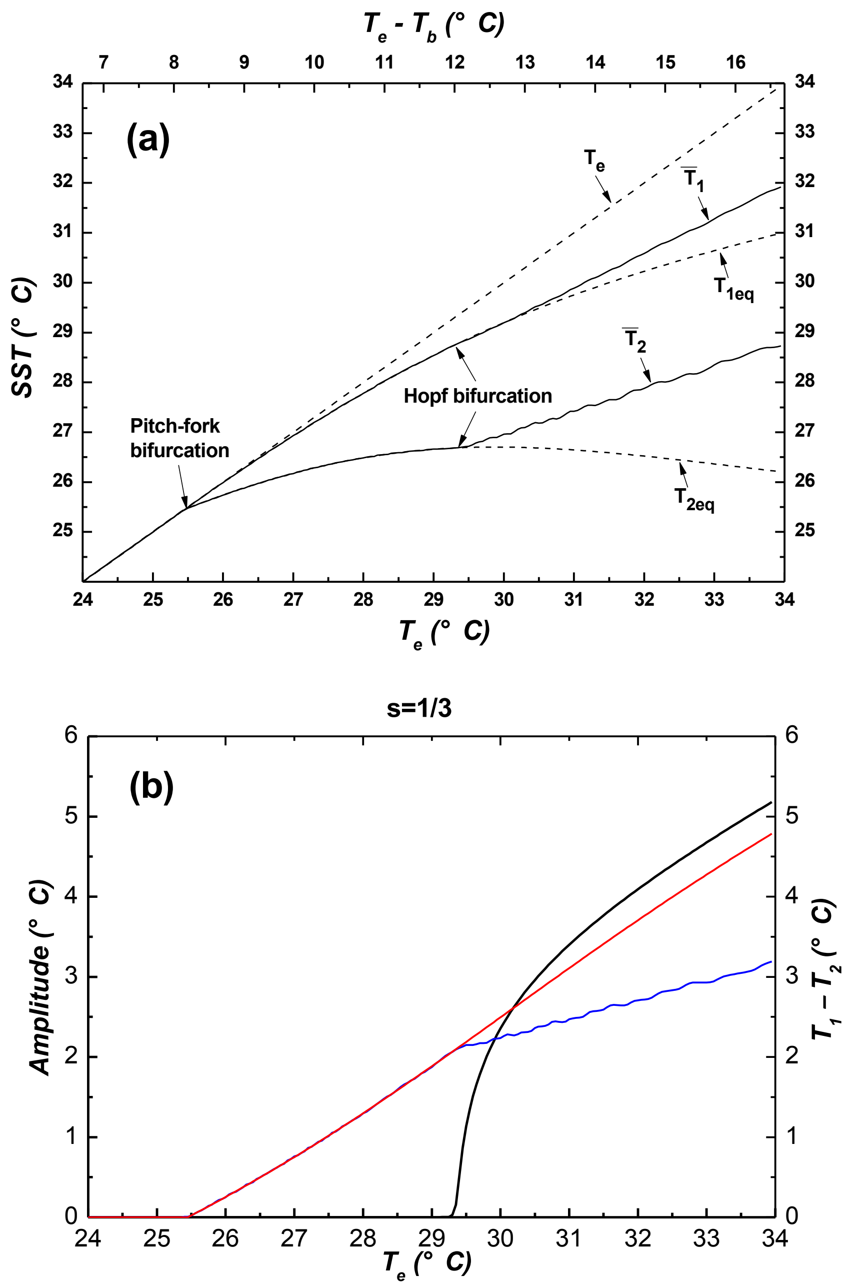

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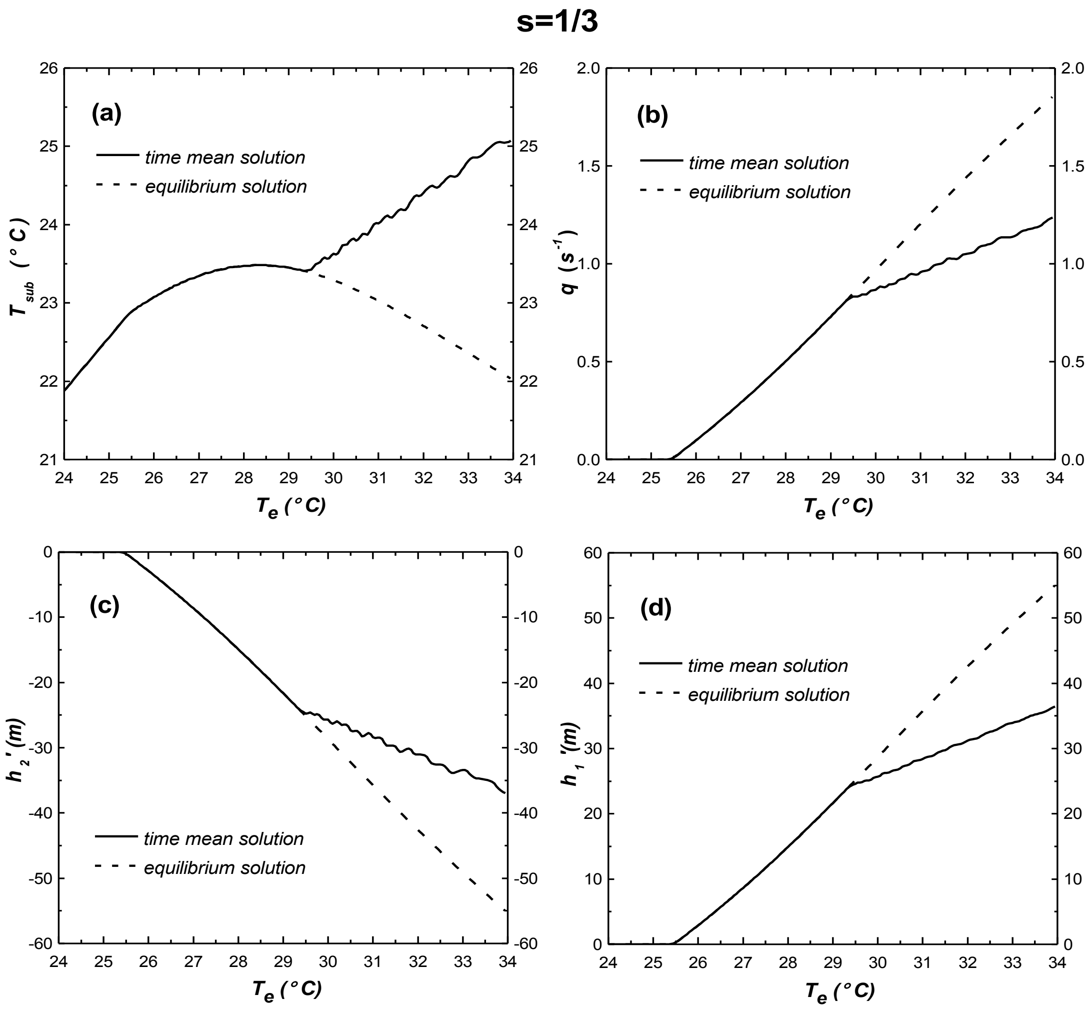

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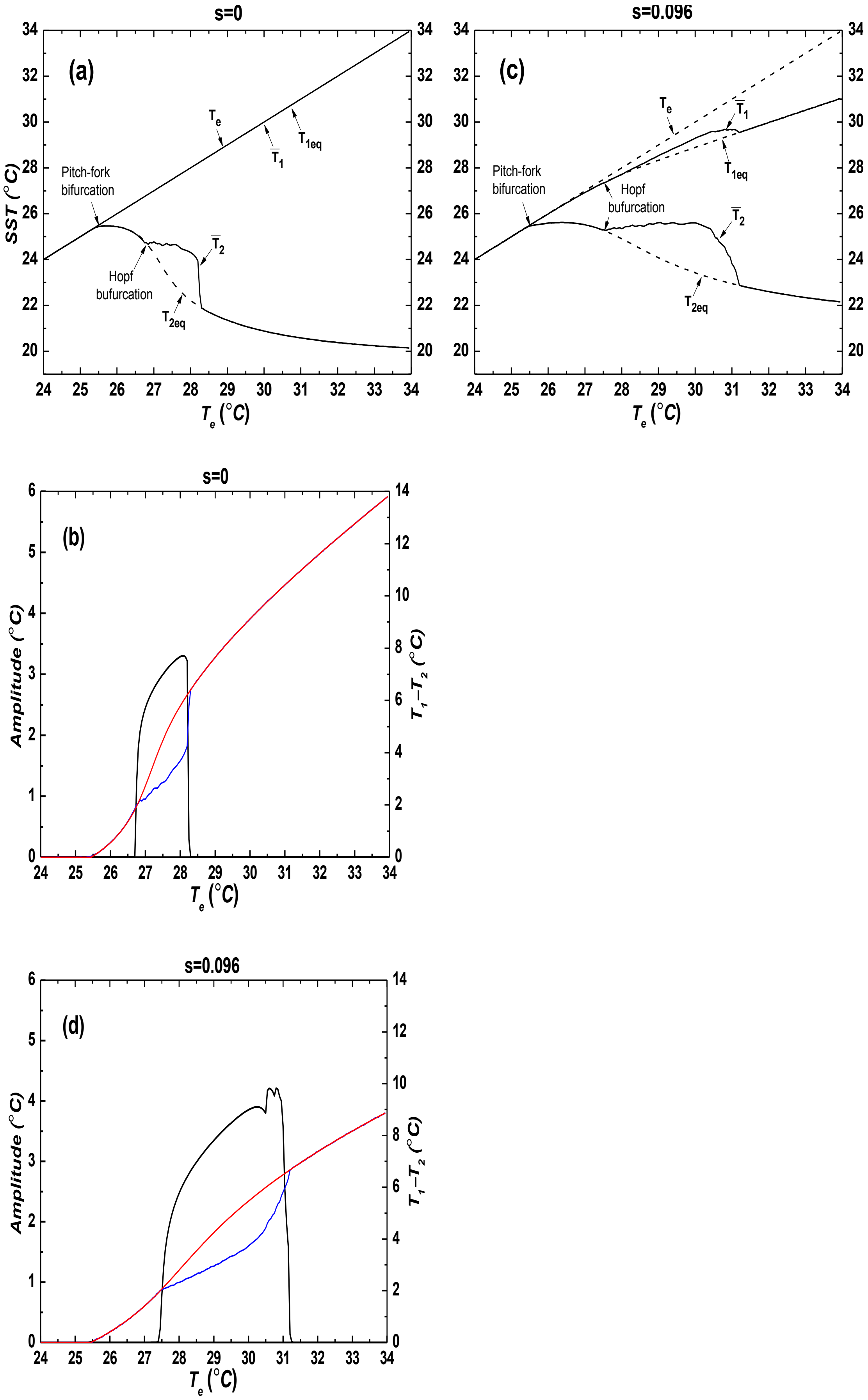

s=0
(a)
SST (°C)
Pitch-fork bifurcation
Hopf bufurcation
T_e
$\overline{T}_1$
T_{1eq}
$\overline{T}_2$
T_{2eq}
T_e (°C)
s=0.096
(c)
Pitch-fork bifurcation
Hopf bufurcation
T_e
$\overline{T}_1$
T_{1eq}
$\overline{T}_2$
T_{2eq}
T_e (°C)
s=0
(b)
Amplitude (°C)
T_1-T_2 (°C)
T_e (°C)
s=0.096
(d)
Amplitude (°C)
T_1-T_2 (°C)
T_e (°C)

FIG. 4. Same as in Fig. 2, except for s=0 (a, b) and s=0.096 (c, d).