Rectification of El Niño–Southern Oscillation into Climate Anomalies of Decadal and Longer Time Scales: Results from Forced Ocean GCM Experiments

DE-ZHENG SUN AND TAO ZHANG
Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, and NOAA/Earth System Research Laboratory/Physical Science Division, Boulder, Colorado

YAN SUN
Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, and NOAA/Earth System Research Laboratory/Physical Science Division, Boulder, Colorado, and Key Laboratory of Ocean Circulation and Waves, Institute of Oceanology, Chinese Academy of Sciences, Qingdao, China

YONGQIANG YU
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

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ABSTRACT
To better understand the causes of climate change in the tropical Pacific on the decadal and longer time scales, the rectification effect of ENSO events is delineated by contrasting the time-mean state of two forced ocean GCM experiments. In one of them, the long-term mean surface wind stress of 1950–2011 is applied, while in the other, the surface wind stress used is the long-term mean surface wind stress of 1950–2011 plus the interannual monthly anomalies over the period. Thus, the long-term means of the surface wind stress in the two runs are identical. The two experiments also use the same relaxation boundary conditions, that is, the SST is restored to the same prescribed values. The two runs, however, are found to yield significantly different mean climate for the tropical Pacific. The mean state of the run with interannual fluctuations in the surface winds is found to have a cooler warm pool, warmer thermocline water, and warmer eastern surface Pacific than the run without interannual fluctuations in the surface winds. The warming of the eastern Pacific has a pattern that resembles the observed decadal warming. In particular, the pattern features an off-equator maximum as the observed decadal warming. The spatial pattern of the time-mean upper-ocean temperature differences between the two experiments is shown to resemble that of the differences in the nonlinear dynamic heating, underscoring the role of the nonlinear ocean dynamics in the rectification. The study strengthens the suggestion that rectification of ENSO can be a viable mechanism for climate change of decadal and longer time scales.

1. Introduction
Among the many milestones marking the conceptual advances in our understanding of the origin of natural climate variability, we find that the study by Kessler and Kleeman (2000) stands out as distinctly as that by Hasselmann (1976) in their originality of pointing out that climate variability of one time scale can be an important cause or significant contributor for climate variability of a different time scale. Specifically, the study by Kessler and Kleeman (2000) points out that the Madden–Julian oscillation (MJO)—an intraseasonal climate signal in the surface winds—can be converted to a sea surface temperature (SST) anomaly in the tropical Pacific that resembles what is normally associated with the El Niño–Southern Oscillation (ENSO), an interannual climate signal. The underlying mechanism for this conversion is provided by nonlinear ocean dynamics and is termed “rectification” by Kessler and Kleeman (2000). A question that naturally follows up on the study of Kessler and Kleeman (2000) is whether this upscale conversion stops with MJO and ENSO. Can an ENSO signal in the surface winds be converted to SST anomalies resembling the observed decadal signal, that is, the tropical
Pacific decadal variability (Zhang et al. 1997)? This paper deals with this question in a manner that is analogous to that of Kessler and Kleeman (2000). This study is also meant to complement earlier studies that use a hybrid coupled model (Sun and Zhang 2006; Sun 2007) as well as an analytical model (Liang et al. 2012) in delineating the time-mean effect of ENSO events.

The observational motivation for this study is provided by Fig. 1. The regime-like shift in the tropical SST since 1976 (Wang and Ropelewski 1995; Zhang et al. 1997) is accompanied with a change in the level of ENSO variability—the variance of the interannual variability of the tropical Pacific SST (Fig. 1, bottom). 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 is the change in the time-mean state a consequence of the change in the level of ENSO activity?

A number of studies have examined the impact of a warming in the mean state of the tropical Pacific on the level of ENSO activity (e.g., Fedorov and Philander 2000, 2001; An and Jin 2001; Wang and An 2001). These

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**Fig. 1.** (top) SST differences between two epochs: 1977–2003 and 1950–76. (bottom) Time series of Niño-3 SST anomalies (in color) and the variance of the Niño-3 SST anomalies (solid black line). The moving variance of Niño-3 SST anomalies is obtained by sliding a moving window of a width of 16 yr. Note the epoch 1977–2003 has higher level of ENSO activity than the previous period 1950–76. (SST data used are from the Hadley Center for Climate Prediction and Research; Rayner et al. 1996.)
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 of whether an increase in the level of ENSO activity can induce a warming in the time-mean state resembling the observed decadal warming (Fig. 1, top).

The possibility that ENSO may have an important time-mean effect on the tropical Pacific climate has been highlighted by studies of the role of ENSO events in the long-term heat balance of the tropical Pacific. Using a hybrid coupled model in which the ocean component is an upper-ocean GCM—the National Center for Atmospheric Research (NCAR) Pacific basin model (Gent and Cane 1989), a model that has an explicit heat budget for the subsurface ocean—Sun (2003) not only finds a positive impact of an increase in the tropical maximum SST on the amplitude of ENSO, but he also finds that in the presence of ENSO, the time-mean zonal SST contrast is less sensitive to an increase in the tropical maximum SST than in the absence of ENSO because the resulting stronger ENSO variations tend to cool the western Pacific and warm the eastern Pacific. The time-mean effect of ENSO events was further studied in Sun and Zhang (2006). In the experiments conducted in that study, they perturbed the long-term heat balance of the model in more ways, subjecting the model to an enhanced cooling in the subtropics as well as to an increase in the tropical heating. Again, they find 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 results suggest that the time-mean effect of ENSO events is to cool the western Pacific warm pool and warm the subsurface thermocline water and the broad region of the surface tropical eastern Pacific (see Fig. 4 in Sun and Zhang 2006). Sun (2007) discussed the implications of the time-mean effect of ENSO events for understanding the response of the tropical Pacific climate to the rise of $\text{CO}_2$ in the atmosphere.

There are also more empirically based studies of the time-mean effect of ENSO events (Rodgers et al. 2004; Yeh and Kirtman 2004; Sun and Yu 2009; Yu and Kim 2011; Choi et al. 2011). These studies note the surface manifestation of the asymmetry between El Niño and La Niña events: the strongest El Niño event, measured by the Niño-3 SST anomaly, is stronger than the strongest La Niña event (Zebiak and Cane 1987; Burgers and Stephenson 1999). Rodgers et al. (2004) and Yeh and Kirtman (2004) are probably among the first to suggest that decadal variability in the tropical Pacific may result from a “residual” effect of ENSO on the background state due to the asymmetry between El Niño and La Niña events. They find in a long simulation by two different coupled GCMs 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 therefore suggest that the asymmetry could be a mechanism for decadal changes in the tropical Pacific SST. Noting a 15-yr cycle in the level of ENSO activity in an extended SST dataset consisting of historical and paleoclimate data and a change in the asymmetry of ENSO with this decadal cycle, Sun and Yu (2009) have 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. A similar conclusion has been reached by examining a long-term simulation of Geophysical Fluid Dynamics Laboratory (GFDL) coupled Climate Model version 2.1 (CM2.1; Choi et al. 2011). Yu and Kim (2011) have further investigated the decadal variability in the Coupled Model Intercomparison Project Phase 3 (CMIP3) models from the angle of ENSO asymmetry. 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) have showed that the skewness of the SST distribution could be due to a kinematic effect of oscillating a nonlinear temperature profile.

A basic assumption is implicit in these empirical studies: asymmetry results in a time-mean effect of ENSO events. However, ENSO asymmetry by itself does not guarantee a significant time-mean effect of ENSO events. The asymmetry between the two phases of ENSO only suggests a nonzero residual effect of ENSO, to the extent that a finite threshold value is used to define El Niño and La Niña events. But because such a residual effect will depend quantitatively on how you define El Niño and La Niña events, the asymmetry alone does not necessarily imply a significant time-mean (or rectification) effect of ENSO. For the same reason, while 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), we can only confirm through this approach a correspondence between a change in the level of ENSO activity and a change in the mean state. A correspondence between the degree of asymmetry of
ENSO and its time-mean effect is found in a nonlinear box model for the tropical Pacific (Liang et al. 2012), but they show that this correspondence occurs not because the former causes the latter, but because they are both caused by the nonlinear term in the heat budget equation.

The approach employed by Liang et al. (2012) is novel in that they quantify the time-mean effect of ENSO by contrasting the equilibrium state of the coupled tropical ocean–atmosphere with the actual realized climatology. At the equilibrium, ENSO as an instability has not manifested, while in the actual realized climatology, ENSO has manifested. Thus, the difference between the two is a good measure of the ENSO effect in the climatology. Indeed, they have succeeded in doing such analysis with the use of an analytical model—the model of Sun (1997). The model is a highly simplified representation of the coupled tropical ocean–atmosphere system, but it encapsulates the major physics of the ENSO system (Sun 1997, 2000; Timmermann and Jin 2002; Sun 2010). In the context of this model, they show unambiguously that the time-mean effect of ENSO is a warming to the eastern tropical Pacific. The simplicity of the model, however, does not give the corresponding meridional structure of the warming, limiting the application of the mechanism revealed in that model to the observed decadal warming. A key feature of the observed warming in the eastern tropical Pacific is the off-equatorial maximum in contrast to the El Niño warming or the residual SST signal between the two phases of ENSO. Nonetheless, the results of Liang et al. (2012) demonstrate the origin of the rectification as the nonlinear advection of heat by ocean currents, suggesting rectification effect may show up even in forced ocean GCM experiments.

In this paper, we explore the time-mean effect of ENSO events by conducting forced ocean GCM experiments. The methodology is analogous to that used by Kessler and Kleeman (2000) in their study of the rectification effect of MJO on ENSO. In the present study, the fluctuations in the surface wind stress are interannual fluctuations and the “rectified” effect of these fluctuations are climate anomalies on the decadal and longer time scales. Complementing the study by Liang et al. (2012), the present methodology will allow us to see the meridional structure of the rectified warming to the eastern Pacific. A distinguished feature in the meridional structure of the observed tropical decadal warming in the eastern tropical Pacific is that the maximum warming is located off equator because of an apparent minimum warming right on the equator (Fig. 1, top). This feature is in contrast to the residual between El Niño and La Niña, which has its maximum right on the equator.

This paper is organized as follows. The methodology and the model used for the experiments are described in section 2. Key results from this study are reported in section 3, and some key implications from the results are provided in section 4.

2. Methodology

As already mentioned, the methodology is similar to that of Kessler and Kleeman (2000), except that it is applied to delineate the rectification effect of ENSO time-scale fluctuations onto the climate variability on decadal and longer time scales. Two experiments are conducted with a tropical upper-ocean GCM. In one of them, the long-term mean surface wind stress of 1950–2011—the surface wind stress averaged over the entire period—is applied [Eq. (1a)], while in the other, the surface wind stress used is the long-term mean of 1950–2011 plus the interannual monthly anomalies over the period [Eq. (1b)]:

\[ \tau_A = \langle \tau_o \rangle, \]  \hspace{1cm} (1a)

\[ \tau_B = \langle \tau_o \rangle + \tau_o', \]  \hspace{1cm} (1b)

where \( \langle \rangle \) represents the long-term mean and \( \tau_o' \) is the interannual anomaly relative to the long-term mean:

\[ \tau_o' = \tau_o - \langle \tau_o \rangle. \]  \hspace{1cm} (2)

Thus, the long-term means of the surface wind stress in the two runs are identical as the anomalies have (by their definition) zero long-term mean:

\[ \langle \tau_A \rangle = \langle \tau_B \rangle. \]  \hspace{1cm} (3)

The two experiments also use the same linear relaxation boundary condition—the SST is linearly restored to the same prescribed values:

\[ F_S = cC_p \rho H_m (SST_p - SST), \]  \hspace{1cm} (4)

where \( F_S \) is the net surface heat flux into the ocean; \( C_p \) is the specific heat; \( \rho \) is the density of water; \( c \) is the restoring coefficient; \( H_m \) is the depth of the mixed layer, which has a fixed value in the ocean model (50 m); \( SST_p \) is the prescribed equilibrium SST; and SST is the actual model-predicted SST. Equation (4) is the same as Eq. (2) in Sun (2003). The form of \( SST_p \) used here is also the same as in Sun (2003)—it is constant with time and is zonally symmetric [see Eq. (5) in Sun (2003)]. To focus on the effect of interannual variability, seasonal cycle is excluded from both the long-term means of the surface wind stress and \( SST_p \). If the ocean dynamics are linear, then the time-mean state of the two experiments should be identical.
The tropical upper-ocean GCM used here is the NCAR Pacific basin model (Gent and Cane 1989; Gent 1991). The model has fine horizontal resolution for the equatorial ocean (1° × 0.25°). In the vertical, it uses sigma coordinates and has seven layers for the upper ocean. It is the same tropical upper-ocean model used by Kessler and Kleeman (2000), except it has a restoring thermal boundary condition [Eq. (4)] rather than using the original formulation by Seager et al. (1988). This allows us to focus on delineating the nonlinearity in the upper-ocean dynamics. As we will see, the restoring boundary condition provides a realistic simulation of ENSO when forced with the observed wind stress. The surface wind stress used for the pair of experiments is from the National Centers for Environmental Prediction (NCEP; Kalnay et al. 1996).

3. Results

a. ENSO in the forced ocean experiments

With ENSO fluctuations included in the surface wind forcing, the model simulates the ENSO events as manifested in the SST field as well as in the upper-ocean temperatures. Figure 2 compares the time series of the Niño-3 SST from observations and the forced ocean GCM experiment. The simulation captures all the observed El Niño events. The two strongest events in the instrumental record—the 1982/83 El Niño and the 1997/98 El Niño event are well simulated in both timing and magnitude.

The overall correlation between the simulated monthly Niño-3 anomalies and those in the observations are about 0.75. The composite of the warm-phase and cold-phase SST anomalies are shown in Fig. 3 together with their residuals (warm phase plus cold phase) as a measure of the ENSO asymmetry in the surface field. A 0.5°C threshold value for the monthly SST anomaly was used for obtaining the warm-phase and cold-phase composites, and the same criterion was used for both the model data and observations. The major features of the spatial pattern of the SST anomalies in both of the two phases are well captured. The only noticeable discrepancy with the observations is found in the immediate region of the coast, particularly in the cold phase. The SST anomaly for the cold phase in the observations has its maximum clearly detached from the coast, but this feature is less distinct in the model simulations. The consequence on the asymmetry pattern is that ENSO in the models is slightly less asymmetric in the models than in the observations in the immediate region of the coast. But the overall pattern of the asymmetry is captured by the model, implying the nonlinear aspects of the dynamics are adequately represented in the model used.

The corresponding subsurface signatures from the observations and the model are further presented in Fig. 4. The subsurface temperature data are from the simple ocean data assimilation system (SODA) for the period 1950–2007 (Carton et al. 2000). Again, the major features of the subsurface temperature anomalies for the two phases of ENSO are well captured by the models.
The differences are mostly quantitative. The most noticeable differences are an underestimate of the cooling to the western Pacific subsurface in the warm phase of ENSO, which in turn causes an underestimate of the cooling in the residual anomaly between the two phases. The warming in the eastern Pacific near the surface is less pronounced than in the observations during the warm phase of ENSO. The somewhat weaker El Niño events as shown in the composite could be mostly due to the known biases in the NCEP wind stress used (Auad et al. 2001; Wittenberg 2004). The observed relationship between the subsurface temperature anomaly in the western Pacific and the Niño-3 SST over an ENSO cycle, as first quantified by Meinen and McPhaden (2000) and used to support the recharge–discharge oscillator theory for ENSO (Jin 1996), is well captured by the model, as is evident in Fig. 5, which shows the equatorial upper-ocean temperature anomalies at four representative stages of the 1997/98 El Niño. Overall and as far as the major features are concerned, ENSO events in the simulation are realistic, and this gives confidence on the fidelity of the upper-ocean dynamics as represented in the NCAR Pacific basin model.

**b. Differences in the mean state between the two experiments**

Despite the identical long-term surface wind stress and the identical restoring SST and restoring coefficient,
the long-term mean climate is significantly different between the two forcing experiments. Figures 6a and 6b present the differences in the time-mean state of these two experiments measured respectively by the equatorial upper-ocean temperature (Fig. 6a) and the SST (Fig. 6b). The difference is characterized by a cooling of the western Pacific warm pool, a warming of the equatorial thermocline water, a warming of the central equatorial Pacific, and a warming of the broad region of the surface eastern tropical Pacific. Note that right on the equator in the far eastern Pacific, the climate with ENSO actually is somewhat cooler than in the one without ENSO, but the surrounding off-equatorial region is considerably warmer. By comparing Fig. 6a with Fig. 4a and Fig. 6b with Fig. 3a, we note that the warming in the eastern Pacific is as big as the temperature changes across an ENSO cycle, particularly for the subsurface region, thus indicating the significance of the time-mean effect of ENSO events. In fact, the cooling in the surface western Pacific is much bigger than that observed temperatures change during an ENSO cycle.

To gain a more quantitative understanding of the time-mean effect of ENSO events as a function of the variance of the interannual fluctuations, we have done...
an additional forced ocean GCM experiment in which the magnitude of wind stress anomalies is amplified by 50%, that is, the time series of the wind stress anomalies is multiplied by 1.5. The magnitude of ENSO, as measured by the standard variation in the Niño-3 SST, is found to be increased about the same amount (i.e., 50%). The resulting differences in the time-mean upper-ocean temperature and SST between the enhanced ENSO run and

![Fig. 5. Evolution of the subsurface temperature anomalies in the equatorial upper ocean (5°S–5°N) over the life cycle of 1997/98 El Niño. The snapshots presented are monthly anomalies for (from top to bottom) December 1996, March 1997, December 1997, and June 1996 for (left) the model and (right) the observations (Carton et al. 2000). They are chosen to represent the initiation, development, maturing, and decaying stage of this El Niño. The definition of these stages is the same as in Sun (2003). The base period used for calculating the anomalies is 1985–2007.](image-url)
the control run without ENSO are presented in Figs. 7a and 7b. Comparing Figs. 7a and 7b with their counterparts in Fig. 6, we see that the time-mean effect of ENSO is further enhanced as the variance of ENSO in the surface winds is further increased. This sensitivity experiment also confirms the robustness of the spatial pattern of the time-mean effect of ENSO events.

The time-mean effect of ENSO events as outlined by these differences between the two forced experiments are qualitatively consistent with what is found in Sun and Zhang (2006, their Fig. 4). The time-mean effect of ENSO as indicated by the present experiments are also consistent with those between the time-mean state and the equilibrium state found by Liang et al. (2012). Recall that they have found that 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. The reverse is true for the thermocline in the west. As the amplitude of ENSO increases, the depth of the thermocline in the time-mean state in the east Pacific becomes

![Figure 6](image-url)
increasingly deeper than that in the equilibrium state, underscoring the impact of ENSO on the depth of the thermocline. Owing to a much more realistic ocean model, the present study reveals new features, in particular, the meridional structure of the warming in the tropical eastern Pacific as well as the pronounced cooling in the western Pacific.

c. Mechanisms responsible for the rectification

One key insight from the study of Liang et al. (2012) is that it is the nonlinear advection of heat in the upper ocean that is responsible for the rectification. In an earlier study by Liang et al. (2012) focusing on the surface heat budget, they have also argued for the importance of the nonlinear dynamical heating (NDH) in the ENSO asymmetry and, by implication (to the extent the asymmetry of ENSO is linked to the time-mean effect of ENSO), the importance of this quantity for the corresponding rectified effect of ENSO into the mean state. Accordingly, we have calculated the NDH—the convergence of $\nabla \cdot \mathbf{T}$ (where $\mathbf{V}$ and $\mathbf{T}$ are the fluctuating part of the velocity and temperature, respectively, relative to the long-term mean and the overbar denotes the time average over 1950–2011, which covers many cycles of ENSO).

The distribution of NDH in the equatorial upper ocean ($5^\circ$S–$5^\circ$N) in the run with ENSO is presented in Fig. 8a. The pattern has a clear correspondence with that in the temperature differences between the run with ENSO and the run without ENSO in the surface forcing.

![Diagram](image_url)
regions with a positive temperature difference in Fig. 6a have heating in Fig. 8a, while regions with a negative temperature difference in Fig. 6a have a cooling in Fig. 8a. The distribution of NDH in the surface layer of the tropical Pacific is shown in Fig. 8b. The pattern notably differs from that in Fig. 6b. In the heating pattern, it is warming right on the equator in the eastern Pacific, while in the temperature difference pattern, it is negative and therefore implies cooling. It turns out that this difference is due to the presence of NDH in the run without ENSO due to tropical instability waves (Legeckis 1977; Weisberg and Weingartner 1988; Qiao and Weisberg 1988).

Fig. 8. Distribution of NDH in the run with ENSO (a) for the equatorial upper ocean (5°S–5°N) as a function of longitude and depth and (b) for the surface layer of the tropical Pacific as a function of latitude and longitude. The contours are the corresponding time-mean upper-ocean (a) temperature and (b) SST. The units for the heating rate are in degrees Celsius per month.
Recall that the ocean has fine spatial resolution for the equatorial region (1° × 0.25°) and is able to resolve tropical instability waves (Gent and Cane 1989; Gent 1991). When the NDH presented in the run with climatological winds is deducted from the NDH in the run with ENSO forcing (Fig. 9b), the region right on the equator again has negative heating in that region, consistent with the sign of the time-mean temperature difference in that region. To show the significance of the changes in the NDH from the run without ENSO to the run with ENSO, the corresponding changes in the heating rate for the surface mixed layer due to the surface heat flux are presented in Fig. 10b together with the heating to the surface mixed layer from the surface heat flux in the run with ENSO (Fig. 10a). Note that NDH for the surface mixed layer has the same magnitude as in the heating from the surface heat flux and that the changes in NDH are considerably greater than changes in the heating rate from the surface heat flux. It has been shown before that instability waves contribute significantly to the heating of the equatorial cold tongue (Jochum and Murtugudde 2004; Menkes et al. 2006; Seo et al. 2006; An 2008). In particular, An (2008) has shown that the heating to the equatorial cold tongue from the instability waves has a nonlinear relationship with the intensity of the cold tongue, resulting in a residual effect when ENSO is presented. The present results (Figs. 8b, 9b) are consistent with the finding of An (2008). Thus, the equatorial minimum of the time-mean effect of ENSO in the eastern tropical Pacific appears to have a lineage with the asymmetric dynamics of the instability waves, underscoring the depth of dependence of climate anomalies of a longer time scale on climate processes of shorter time scales.

The overall pattern of NDH in the depth–longitudinal plane shown in Figs. 8a and 9a is mainly determined from its zonal component—the advection of the anomalous temperature by the anomalous zonal current. Figure 11 presents the three components of the total NDH shown in Figs. 8a and 9a. Note that the close resemblance between the zonal component of the NDH and the total NDH. In terms of magnitude, the meridional component and the vertical component of NDH are as significant as the zonal component, but their broad spatial pattern is different from that of the total NDH. In fact, the meridional component and the vertical component largely cancel each other out in the equatorial upper ocean, except in the surface layer. Focusing on the warming pattern in the longitude–latitude plan in the surface eastern Pacific, however, the meridional component of the NDH is also a significant contributor (Fig. 12).
Fig. 11. The (a) zonal, (b) meridional, and (c) vertical components of the NDH in the equatorial upper ocean (5°S–5°N) as a function of longitude and depth in the run with ENSO [contours in (a)–(c) are the corresponding time-mean upper-ocean temperature]. (d)–(f) As in (a)–(c), but with the corresponding term in the run without ENSO removed [contours in (d)–(f) are the differences in the time-mean upper-ocean temperature between the run with ENSO and the run without ENSO]. The units for the heating rate are in degrees Celsius per month.
FIG. 12. The (a) zonal, (b) meridional, and (c) vertical components of the NDH as a function of longitude and latitude for the surface layer in the run with ENSO [contours in (a)–(c) are the corresponding time-mean SST]. (d)–(f) As in (a)–(c), but with the corresponding term in the run without ENSO removed [contours in (d)–(f) are the differences in the time-mean SST between the run with ENSO and the run without ENSO]. The units for the heating rate are in degrees Celsius per month.
4. Implications

The study advances our understanding of the time-mean effect of ENSO events on the thermal structure of the equatorial upper Pacific ocean beyond that from the empirical studies (Rodgers et al. 2004; Yeh and Kirtman 2004; Schopf and Burgman 2006; Sun and Yu 2009; Yu and Kim 2011). In particular, it shows that using the residuals between the two phases of ENSO to represent the time-mean effect of ENSO is only good for the broad pattern of the effect, but is inaccurate in details. The differences are particularly noteworthy in the equatorial eastern Pacific: the residual SST anomaly between the two phases of ENSO in the eastern Pacific has its maximum right on the equator, but the rectified effect of ENSO events obtained by the present method has an off-equator maximum.

The newly identified feature in the spatial pattern of the rectified effect of ENSO events in the eastern Pacific—the off-equator maximum—is in the observed decadal warming in the eastern Pacific (Fig. 1a). Thus, the present results actually 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 and, more generally, to the suggestion 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. Specifically, the present results combined with the studies by Fedorov and Philander (2000, 2001) and Liang et al. (2012) allow us to envision the following scenario as a possible explanation for decadal variability in the tropical Pacific: an initial increase in the level of ENSO activity results in a warming in the eastern Pacific, which in turn enhances the increase in the level of ENSO activity. [Recall that a decadal warming in the background state can cause an elevation of ENSO activity (Fedorov and Philander 2000, 2001; An and Jin 2001; Wang and An 2001).] As the associated deepening of the thermocline in the eastern Pacific exceeds a critical value, the reduced thermocline feedback is no longer able to sustain the level of ENSO activity already achieved, and the level of the ENSO activity then starts to decline (Fedorov and Philander 2000, 2001). The decline in the level of ENSO activity allows the radiative forcing that has been working in the background to re-take preeminence to bring the system closer to its equilibrium—an unstable situation that is characterized by a larger thermal contrast between the warm-pool water and the thermocline water (Liang et al. 2012). This unstable situation reopens the stage for another strong epoch of ENSO activity. The relevance of this picture to the decadal variability in the real world and in the models will be explored in detail in a subsequent paper. Tree-ring records analyzed by Li et al. (2011) indicate that interdecadal modulation of ENSO amplitude and its close coupling with interdecadal tropical Pacific mean climate change had been a norm in the past millennium. An analysis of the tropical Pacific decadal variability in a 2000-yr integration with the GFDL Climate Model 2.1 (Delworth et al. 2006; Wittenberg 2009) from the rectification prospective suggests that the rectification effect of ENSO time-scale variability is involved in the tropical Pacific decadal variability generated by the model (Ogata et al. 2013). An analysis of the variability on centennial time scales in the same model also reveals a spatial pattern of the variability resembling the time-mean effect of ENSO, as revealed here (Karnauskas et al. 2012), raising the potential that the importance of the rectification effect of ENSO may not be limited to variability on decadal time scales. Indeed, proxy data for the tropics indicate that the Medieval Climate Anomaly and the Little Ice Age were accompanied significant changes in the level of ENSO activity (Rein et al. 2004; Cobb et al. 2003; Graham et al. 2007).

The present results also show more clearly that the rectified effect of ENSO has a complex spatial structure in the equatorial upper ocean (Figs. 6, 7): an overall reduction in the thermal contrast between the surface warm pool and the subsurface thermocline water is accompanied by a strengthening of the vertical stratification in the central equatorial Pacific. Thus, the present study may also potentially provide a path to understand the dynamics behind the suggestion from empirical studies that the transition (or change) from a weak ENSO regime to a strong ENSO regime (or vice versa) on decadal and longer time scales may be accompanied by a change in the dominance by the two types of El Niño events—the central Pacific El Niño (warm-pool El Niño or Modoki) and the eastern Pacific El Niño (Sun and Yu 2009; Yeh et al. 2009; Lee and McPhaden 2010; McPhaden et al. 2011). Will the initial stabilization to the far eastern Pacific from an increase in the variance of ENSO be necessarily accompanied by a destabilization of the central Pacific? Will the eventual turn-around of the decadal warming follow right after the stabilization of the central Pacific region is completed? Those issues are clearly interesting and will be addressed in a subsequent study.

The current finding also highlights that the time-mean effect of ENSO includes a substantial cooling to the warm pool. The cooling is much more profound, particularly at the surface level, than the traditional ENSO residual map had suggested. The present finding of a profound cooling to the western Pacific by the collective effect of El Niño events highlights a role for other factors in causing the observed warming in the western Pacific over the last
few decades. Recall that in the two experiments conducted in the present study, the thermal boundary conditions are kept identical in order to isolate the role of upper-ocean dynamics in rectifying ENSO. To fully investigate the causes of the change in the tropical Pacific SST, one has to consider the increase in the tropical maximum SST due to enhanced radiative heating or other possible factors other than the nonlinear effect from ENSO dynamics. Based on a coupled model, Sun (2003) has suggested that the elevated ENSO activity during recent decades may be a consequence of the increasing tropical maximum SST. Combining the results of Sun (2003) and the present results, the following scenario surfaces as an enticing explanation for what has been going on over the last few decades in the tropical Pacific: owing to a deterministic external heating (such as the rise of CO$_2$) or accumulated effect from weather events, the SST in the center of the warm pool (the tropical maximum SST) has been experiencing a rise. In response, ENSO activity increases (Sun 2003), which results in a broad decadal warming signal in the central and eastern Pacific, but the corresponding cooling to the western Pacific is not strong enough to offset the decadal rise in the SST over that region forced by the external forcing or by the accumulated effect from the random weather events. This also means that without the time-mean effect of ENSO events, we would have seen a more pronounced warming in the warmest part of the world’s open oceans. Whether this scenario can be an adequate explanation for what has been happening over the last few decades in the tropical Pacific will be investigated in a subsequent study that will take into account the increases in the radiative heating due to the rise of CO$_2$ as well as the Hasselmann effect on the warm-pool SST from the weather events.

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REFERENCES


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