The Inverse Effect of Annual-Mean State and Annual-Cycle Changes on ENSO

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ABSTRACT

The influence of the tropical Pacific annual-mean state on the annual-cycle amplitude and El Niño–Southern Oscillation (ENSO) variability is studied using the Max Planck Institute for Meteorology coupled general circulation model (CGCM) ECHAM5/Max Planck Institute Ocean Model (MPI-OM1). In a greenhouse warming experiment, an intensified annual cycle of sea surface temperature (SST) in the eastern tropical Pacific is associated with reduced ENSO variability, and vice versa.

Analysis showed that the annual-mean states, especially the surface warming in the western Pacific and the thermocline deepening in the central Pacific, which is concurrent with the strong annual cycle, act to suppress ENSO amplitude and to intensify the annual-cycle amplitude, and vice versa. The western Pacific warming acts to reduce air–sea coupling strength and to shorten the ocean adjustment time scale, and the deepening of central Pacific thermocline acts to diminish vertical advection of the anomalous ocean temperature by the annual-mean upwelling. Consequently, ENSO activity is suppressed by the annual-mean states during the strong annual-cycle decades, and the opposite case associated with the weak annual-cycle decades is also true. Furthermore, the time integration of an intermediate ENSO model forced with different background state configurations, and a stability analysis of its linearized version, show that annual-mean background states during the weak (strong) annual-cycle decades are characterized by an enhanced (reduced) linear growth rate of ENSO or similarly large (small) variability of ENSO. However, the annual-cycle component of the background state changes cannot significantly modify ENSO variability.

Using a hybrid coupled model, it is demonstrated that diagnosed annual-mean background states corresponding to a reduced (enhanced) annual cycle suppress (enhance) the development of the annual cycle of SST in the eastern equatorial Pacific, mainly through the weakening (intensifying) of zonal temperature advection of annual-mean SST by the annual-cycle zonal current. The above results support the idea that climate background state changes control both ENSO and the annual-cycle amplitude in opposing ways.

1. Introduction

A robust feature of the El Niño–Southern Oscillation (ENSO) is its seasonal variance modulation, with large anomalies peaking in boreal wintertime (Rasmusson and Carpenter 1982; An and Wang 2001; Galanti and Tziperman 2000). Two proposed mechanisms to explain this feature are the nonlinear frequency locking of ENSO to an annual period (Jin et al. 1994) and the seasonal change in the linear stability of ENSO (Tziperman et al. 1998). From a time series perspective, ENSO can be interpreted as an interannually modulated annual cycle (e.g., Wang 1994). However, in addition to ENSO being influenced by the annual cycle, it also modulates the strength of seasonal sea surface temperatures (SST) and wind variations (Xie 1995). For example, the amplitude of the annual cycle in the eastern equatorial Pacific tends to be weaker during El Niño periods and stronger during La Niña periods (Gu and Philander 1995; Xie 1995). Theoretical studies suggest that this two-way interaction between these almost equally energetic modes of natural climate variability might lead to the generation of deterministic chaos, hence explaining the irregularity of the ENSO phenomenon (Jin et al. 1994; Chang et al. 1994, 1996; Tziperman et al. 1994, 1995; Wang and Fang 1998).
2. Data and models

Twenty-four CGCMs were used as part of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) CMIP3 model evaluation. However, only 12 models were integrated for more than 150 years using the greenhouse gas emission scenario A1B. Table 1 provides general information for these 12 models. The long-term simulations were used to investigate the relationship between ENSO variability and the annual cycle in the eastern equatorial Pacific, beyond the time of CO2 stabilization. Note that the analyzed CGCMs use various ocean mixing and sunlight penetration parameterization schemes. No systematic effects of these schemes on the results were found.

Preindustrial ("control run") and CO2 doubling ("2CO2 run") experiments using these 12 models are analyzed. The control run simulates an unperturbed climate state with preindustrial CO2 levels at 280 ppmv. The CO2 doubling and quadrupling experiments simulate the transient climate response to a 1% yr\(^{-1}\) increase of CO2 concentrations. The CO2 concentration is initialized at 348 ppmv and increases within 70 years to 696 ppmv using a rate of 1% yr\(^{-1}\). Thereafter, the CO2 concentration is held constant in the 2CO2 run.

One long-term simulation of the ECHAM5/MPI-OM1 model will be used to address how decadal changes in the background climate state modulate both ENSO and annual-cycle amplitudes under greenhouse warming conditions. The atmospheric component of this model uses a horizontal T63 resolution (1.9° × 1.9°) and 31 layers in the vertical (Roeckner et al. 2003). It includes simplified bulk cloud microphysics (Lohmann and Roeckner 1996) and a mass flux scheme for convection (Tiedtke 1989). Its oceanic component uses a regular horizontal resolution of 1.0°, 40 vertical levels, a free surface, the Gent and McWilliams (1990) parameterization for eddy transport, and the Richardson number–dependent scheme of Pacanowski and Philander (1981) for the mixed layer. No flux adjustment is applied, and the frequency of air–sea coupling is daily.

For the dynamical understanding, we use three different kinds of numerical models. The main purpose of the exercise with these models is to check the sensitivities of climate variability (i.e., annual cycle or ENSO) to an externally given climate background state, which can be either an annual-mean climate state or an annually varying one. Thus, the stability of the coupled atmosphere–ocean system will be calculated with respect to these different climate background state configurations using eigenvalue analysis. Utilized models are the following:

1) A linear version of an intermediate ocean–atmosphere model for the eigenanalysis.

This model was developed based on the Cane–Zebiak model (CZ model) (Zebiak and Cane 1987) but differs from the original CZ model by using smoothed versions of the subsurface temperature parameterization, modifications to the vertical advection scheme, and the convergence feedback (see more details in An et al. 2004 and Bejarano 2006). Using
this model, eigenanalyses for given annual-mean states will be performed. The resulting eigensolutions, among which the leading mode is usually corresponding to ENSO, characterize the linear stability of normal modes with respect to a given climate state. These experiments will provide insight into the linear stability of ENSO (e.g., growth rate and frequency).

2) An intermediate ocean–atmosphere model for the time integration.

This is the original version of CZ model, in which the background states including annual-mean and annual cycle states are still externally given, and which simulates the main climate anomaly with respect to this background state. Thus, with this model configuration and by varying the annual-mean and annual-cycle components of the CZ model we can quantify the sensitivity of ENSO to changes in either the annual cycle or annual mean. Furthermore, much more realistic configurations, including effects such as nonlinearity and stochasticity due to atmospheric random process, are included in this experiment.

3) Hybrid coupled general circulation model.

This coupled model is based on the CZ reduced-gravity ocean model that covers the tropical Pacific domain (30°S–30°N) and a global atmospheric general circulation model, the simplified parameterizations primitive equation dynamics (SPEEDY) AGCM.

<table>
<thead>
<tr>
<th>Model</th>
<th>Resolution</th>
<th>Atmosphere</th>
<th>Ocean</th>
<th>Flux correction</th>
<th>Mixed layer treatment</th>
<th>Sunlight penetration</th>
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<tr>
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<td>T63, L32</td>
<td>192 × 96, L29</td>
<td>H, W</td>
<td>Richardson number–dependent scheme</td>
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<td></td>
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<tr>
<td>Goddard Institute for Space Studies Model E-H (GISS-EH)</td>
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<td>360 × 180, L33</td>
<td>None</td>
<td>Kraus–Turner scheme</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIROC3.2(medres)</td>
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<td>256 × 192, L33</td>
<td>None</td>
<td>Turbulence closure of Noh and Kim</td>
<td></td>
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<tr>
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<td>180 × 170, L33</td>
<td>None</td>
<td>1.5 turbulent closure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L’Institut Pierre-Simon Laplace Coupled Model, version 4 (IPSL CM4)</td>
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<td>None</td>
<td>Turbulent kinetic energy (TKE) scheme</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GFDL CM2.0</td>
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<td>360 × 200, L50</td>
<td>None</td>
<td>K-profile parameterization (KPP) scheme</td>
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<td>KPP scheme</td>
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<td>144 × 84, L33</td>
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<td>360 × 180, 40L</td>
<td>None</td>
<td>Richardson number–dependent scheme</td>
<td></td>
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<tr>
<td>Meteorological Research Institute Coupled General Circulation Model, version 2.3.2a (MRI CGCM2.3.2a)</td>
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<td>144 × 111, L23</td>
<td>H, W, M</td>
<td>Level 2 turbulent closure</td>
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<td>None</td>
<td>1.5 turbulent closure</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Heat, water, and momentum flux adjustment corrections are indicated by H, W, and M, respectively. |
The CZ coupled model cannot simulate annual-cycle variations and thus cannot be used to test the sensitivity of the annual cycle in the eastern equatorial Pacific to changes in the annual mean. The hybrid coupled model simulates both annual-cycle and interannual variations, of which the annual-mean states are controlled externally. The annual cycle simulated by this model is quite reasonable (see Figs. 10 and 11), but the ENSO variability is too weak (not shown here). Thus, the hybrid coupled model is valid for the annual-cycle sensitivity experiment to changes in the annual-mean state, and the intermediate CZ model will be used for ENSO sensitivity experiments with respect to changes in both annual mean and annual cycle. Details regarding the hybrid coupled model are found in the appendix.

3. Relationship between the annual cycle and ENSO

Both observed and simulated changes in ENSO amplitude have been negatively correlated with changes in the annual-cycle strength in the eastern equatorial Pacific (Gu and Philander 1995; Xie 1995; Fedorov and Philander 2001; Guilyardi 2006; Timmermann et al. 2007b). Inspired by a significant decadal change in ENSO variability (An and Wang 2000; An and Jin 2000; Timmermann and Jin 2002), this work focuses on the decadal-to-interdecadal relationship between ENSO and the annual cycle. Model outputs from 12 models participating in the IPCC AR4 CMIP3 intercomparison were used to assess the relationship, on decadal time scales, between the annual cycle strength and ENSO amplitude.

Correlations were computed between the 15-yr sliding variance of the scale-averaged wavelet power over a 2–7-yr band (i.e., interannual band or ENSO) for Niño-3.4 (5°N–5°S, 170°–120°W) SSTA and over a 0.5–1.5-yr band (i.e., annual-cycle band) for Niño-3.4 SSTA. The first column is for the control run and the second column is for the CO2 run (>70 yr). Statistically significant correlations with 95% confidence level are shown in bold. Correlation for the observation is calculated using the extended reconstructed SST version 3.0 (ERSST v3.0) for 1897–1991.

<table>
<thead>
<tr>
<th>Model</th>
<th>Control run</th>
<th>CO2 run</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCCma GCM3.1</td>
<td>0</td>
<td>−0.30</td>
</tr>
<tr>
<td>CNRM-CM3</td>
<td>0.15</td>
<td>0.20</td>
</tr>
<tr>
<td>GFDL CM2.0</td>
<td>0.54</td>
<td>0.40</td>
</tr>
<tr>
<td>GFDL CM2.1</td>
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<td>−0.58</td>
</tr>
<tr>
<td>INM-CM3.0</td>
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<td>0</td>
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<tr>
<td>IPSL CM4</td>
<td>0.01</td>
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<tr>
<td>MIROC3.2(medres)</td>
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<td>−0.55</td>
</tr>
<tr>
<td>MRI CGCM2.3.2a</td>
<td>−0.09</td>
<td>−0.24</td>
</tr>
<tr>
<td>GISS-EH</td>
<td>0.15</td>
<td>−0.39</td>
</tr>
<tr>
<td>INGV ECHAM4</td>
<td>0.43</td>
<td>0.38</td>
</tr>
<tr>
<td>MIUBECHOG</td>
<td>0.12</td>
<td>−0.68</td>
</tr>
<tr>
<td>ECHAM5/MPI-OM1</td>
<td>0.37</td>
<td>−0.74</td>
</tr>
<tr>
<td>Observation</td>
<td>−0.10</td>
<td></td>
</tr>
</tbody>
</table>

As seen in Table 2, the correlations in the control runs of these models are not statistically significant, except for the Geophysical Fluid Dynamics Laboratory Climate Model version 2.0 (GFDL CM2.0) model. In this model, the correlation on decadal/interdecadal time scales between ENSO variability and annual-cycle strength achieves values up to +0.54, which is statistically significant with a 95% confidence level. While negative correlations have been frequently reported in various experiments (e.g., Timmermann et al. 2007b; also this study), to our knowledge a positive correlation between annual-cycle strength and ENSO under preindustrial and present-day conditions (as seen in GFDL CM2.0) has not been reported before.

For the CO2 run, the correlations calculated from four models {GFDL CM2.1; Model for Interdisciplinary Research on Climate 3.2, medium-resolution version [MIROC3.2(medres)]; Meteorological Institute of the University of Bonn, ECHAM and the global Hamburg Ocean Primitive Equation [ECHO-G] Model [MIUBECHOG]; and ECHAM5/MPI-OM1} are negative and significant at the 95% confidence level. The correlations obtained from the control runs of these four models are weakly negative or positive. Thus, greenhouse warming seems to promote a significant out-of-phase relationship between ENSO activity and the annual-cycle intensity on decadal/interdecadal time scales. It is known that greenhouse warming may lead to changes in the dominant mode of ENSO variability (Guilyardi 2006; An et al. 2008). Such changes may cause a shift in the relationship between ENSO activity and annual-cycle amplitude (this point will be discussed later). The following sections examine the results of the ECHAM5/MPI-OM1 model, which can realistically simulate both ENSO and the annual cycle as well as simulate changes in their relationship during the greenhouse warming simulation.

Figure 1a shows the wavelet spectrum of the SST averaged over the Niño-3.4 region (5°S–5°N, 170°–120°W), obtained from the CO2 run of ECHAM5/MPI-OM1.
We observe decadal-to-multidecadal variations in the annual-cycle amplitude (amplitude changes around the 1-yr cycle) and in the interannual variability associated with ENSO. Extracted from the wavelet spectrum, Fig. 1b shows the 15-yr sliding variance of the scale-averaged wavelet power over the 2–7-yr band (i.e., interannual band or ENSO; dashed line, right axis) and that over the 0.5–1.5-yr band (i.e., annual-cycle band; solid line, left axis) for the Niño-3.4 SST. The Morlet wavelet spectrum is used (Torrence and Compo 1998).

To further study the differences between the strong and weak annual-cycle decades, we calculate composite maps for each of the above time periods using 2CO₂ run output. As a comparison, the same methods were applied to the control run output of the ECHAM5/MPI-OM1 model. The time–longitude sections of SST along the equatorial band are shown in Fig. 2 for the strong and weak annual-cycle periods and their differences. In both runs, the important characteristics of the annual cycle of the tropical eastern Pacific SST are well simulated, such as the warming during boreal spring, the cooling during boreal fall, and the characteristic westward propagation of the SST anomalies. The general features in the 2CO₂ run are similar to those in the control run. However, only in the 2CO₂ run (Figs. 2d–f) are both the warm and cold phases intensified—by about 0.5°C relative to the weak annual-cycle situation in the region between 150° and 110°W. On the other hand, the difference in the control run (Figs. 2a–d) is too weak, which possibly results in insignificant correlation between annual-cycle and ENSO amplitudes. The weak multi-decadal variability of the annual cycle is presumably
related to that of the annual mean (An et al. 2008). This point will be addressed in section 5. The following discussion addresses the question of whether this intensification of the annual cycle causes a suppression of ENSO amplitude, as conjectured in many previous studies (e.g., Timmermann et al. 2007b and its references).

Figure 3 illustrates that the amplitude difference between the weak and strong annual-cycle case (−0.25°C) is most strongly pronounced during the boreal spring and fall seasons. Conversely, the differences in ENSO variability (−25%) are almost evenly spread throughout the year. Thus, there is uncertainty regarding the existence of a simple linear relationship between the amplitudes of these modes. It points to the possible significance of multidecadal changes of the annual-mean background state in modulating both ENSO and the annual cycle. The next section explores the relationship between the annual-mean climate state and ENSO amplitude and addresses a possible physical mechanism.

4. Multidecadal variations of the annual-mean climate state and its effect on modulations of ENSO

In the first part of this section, we analyze the CGCM output to investigate the dynamical relationship between the simulated annual-mean climate state and ENSO. In the second part, we perform the stability analysis of ENSO on the modified annual-mean state and a time integration of the nonlinear intermediate ocean–atmosphere
model in which either annual-mean or annual-cycle background states are modified.

a. Change in air–sea coupling strength and dominant pattern associated with ENSO

To explore the impact of either annual-mean or annual-cycle background state changes on ENSO variability, we measure the air–sea coupling strength that is a key component of ENSO stability. The air–sea coupling strength is calculated in the following two-step procedure. First, a maximum covariance analysis (MCA) method (a.k.a. singular value decomposition analysis) (Bretherton et al. 1992; Wallace et al. 1992) is applied to the monthly-mean surface zonal wind and SST anomalies over the tropical Pacific. Second, a seasonally stratified regression is computed between the principal components (PC) of the leading MCA mode. For example, to obtain the regression coefficient for January, PC values for each-year Januaries associated with the first MCA modes of both surface zonal wind (PC1_wind) and SST (PC1_SST) are collected, and then the regression coefficient, which is defined as the covariance between PC1_wind and PC1_SST divided by the variance of PC1_SST, is calculated. In this calculation, the PC time series corresponding to the strong and weak annual-cycle periods have been used separately. A higher regression coefficient indicates stronger air–sea coupling strength in the equatorial Pacific and obviously results in a larger amplitude of ENSO.

As seen in Fig. 4, the coupling strength for the weak annual-cycle period is larger than that for the strong annual-cycle period, except for March and December. This implies that the modification of the coupling strength by the annual-mean background state is more effective than the annual-cycle background state. In particular, during the prominent growing season of ENSO, that is, from spring to late fall, the coupling strength for the weak annual-cycle periods is greater than that for the strong annual-cycle periods. Therefore, the opposite relationship between annual-cycle strength and ENSO amplitude is possibly due to multidecadal variations of the annual-mean air–sea coupling strength. The physical mechanism behind this relationship is explored in the following.

Figure 5 shows the difference maps of annual-mean physical quantities, which will be incorporated into the intermediate ENSO model. The difference in the thermocline depth (i.e., approximated from the 20°C isotherm depth) is about 5 m in the equatorial central Pacific and less than 5 m in the equatorial eastern Pacific. The highest difference in the SST, 1.1°C, is observed over the tropical western Pacific; the surface zonal and meridional winds converge slightly into the eastern part of the warm SST center in the tropical equatorial western Pacific. The difference maps of oceanic and atmospheric variables are dynamically consistent. For example, the convergence center of the surface winds is located to the east of the warm SST center; this is consistent with the steady response of the tropical atmospheric circulation to a given atmospheric forcing, as proposed by Gill (1980). The deepening of the thermocline in the equatorial central Pacific is associated with the mass convergence driven by the surface wind stress.

The difference in the annual-mean background states provides a clue on how the annual-mean background state for the strong (weak) annual-cycle period reduces (enhances) the amplitude of ENSO. It is related to the relative position of the surface zonal wind anomaly with respect to SST anomaly. That is, the active center of ENSO identified by the first MCA mode is located in the central-easter Pacific around 150°–160°W (Fig. 4), while the surface maximum warming in the annual-mean background state for the strong annual-cycle period is located in the western Pacific around 160°E–180°. The atmospheric convective heating that is a major driving forcing of the atmospheric circulation in the tropics is sensitive to the total SST rather than SST anomaly itself;
thus the further warming in the western Pacific by the annual mean allocates the maximum surface wind anomaly farther west from the maximum SST anomaly. By so doing, the local air–sea coupling strength becomes weaker.

To confirm the aforementioned argument, here we calculate the regression coefficient of the equatorial-band-averaged precipitation and zonal wind stress anomalies with respect to the Niño-3.4 index. As seen in Fig. 6, the maximum loading of precipitation is commonly observed west of the date line. However, west of the date line, the magnitude for the strong annual-cycle period is greater than that for the weak annual-cycle period; east of the date line the situation is reversed. The surface zonal wind stress shows an almost identical feature to the precipitation because of their tight dynamical relationship. Therefore, Fig. 6 supports the above argument. Furthermore, the westward migration of the center of the maximum surface zonal wind stress anomaly actually diminishes the ocean adjustment time scale, which shortens the growing period of ENSO (An and Wang 2000). This is because a time lag between the Bjerknes positive feedback (Bjerknes 1966, 1969) and the negative feedback of ENSO that is due to the reflected Kelvin waves originated from the equatorially trapped Rossby waves (i.e., “delayed oscillator theory”) (Battisti and Hirst 1989) becomes shorter as the wind patch moves to the west. That is, the westward shift of the wind patch shortens the Rossby wave’s path toward the western boundary and thus leads to a quicker reversal of SST anomalies associated with ENSO (Wang and An 2001, 2002). The longer the time lag for the delayed negative feedback, the larger the ENSO amplitude, because ENSO has more time to grow before the negative feedback operates to damp ENSO.
and zonal wind stress (N m^{-2}(interannual) quantities; where the overbar (prime) indicate the annual-mean equatorial band (5\textdegree S-5\textdegree N) indicated by the solid (dashed) lines. regressions for the strong (weak) annual-cycle periods are indicated by the solid (dashed) lines.

b. Heat budget analysis in the ocean mixed layer

To further elucidate which factors in the annual-mean background state influence the model ENSO, we perform the heat budget analysis in the ocean mixed layer. The tendency equation of the anomalous temperature in the mixed layer (referring to sea surface temperature anomaly) can be represented as

\[ \frac{\partial T'}{\partial t} = F_N - \frac{u'}{\partial x} - \frac{v'}{\partial y} - \frac{w'}{\partial z} + R, \]  

where the overbar (prime) indicate the annual-mean (interannual) quantities; \( F_N \) refers to the net surface heat flux including net shortwave radiation, net longwave radiation, latent heat flux, and sensible heat flux; and \( R \) represents all other processes such as nonlinear thermal advectons, thermal advection by the annual cycle, turbulence mixing, etc. Since our focus is on the thermal advection by the annual-mean state, the advection term consists of the advection of the annual-mean temperature gradient by the interannual currents and the advection of the interannual temperature gradient by the annual-mean currents. To identify the effect of each annual-mean climate state on the ENSO, the heat budget terms based on the annual-mean state for the strong annual-cycle period and those for the weak annual-cycle period are separately calculated. To quantify the thermal advection associated with the evolution of ENSO, we further calculate the regression map of each heat budget term with respect to Ni\~no-3.4. As seen in Fig. 7, the largest difference in the ENSO amplitude is attributed to the vertical advection of anomalous temperature gradient by the annual-mean upwelling (-\( \pi \partial T'/\partial z \)), which is small for the strong annual-cycle period and large for the weak annual-cycle period. Thus, ENSO amplitude reduces (increases) during the strong (weak) annual-cycle period. In further calculations, we have confirmed that this different behavior is due to differences in the vertical temperature gradient rather than those in the mean upwelling (not shown here). This implies that deepening of the annual-mean thermocline depth for the strong annual-cycle period (as shown in Fig. 5) presumably reduces the sensitivity of subsurface temperature to changes in the thermocline, hence resulting in a weaker vertical temperature gradient.

c. Linear stability analysis

An eigenanalysis of an intermediate ENSO model was performed to estimate the direct effects of annual-mean climate state changes on ENSO stability (see section 2 for details). As in a previous study performed with the same model (An et al. 2004), the annual-mean background states of the model, but not the annual-cycle components, are prescribed. Two annual-mean background states corresponding to the strong and weak annual-cycle periods are constructed from the composite analysis (see Fig. 5). To calculate the stability of the linear dynamic operator of the intermediate ENSO model for background conditions (including ocean currents in the surface layer, SST, thermocline depth, surface winds, and atmospheric surface divergence), the Jacobian matrix was computed using a perturbation method, separately for each background state, in which the matrix elements are computed from small variable perturbations and their simulated corresponding time derivatives. Then the eigenmodes are computed using standard numerical eigenanalysis techniques.

Here the model background climate states are perturbed such that the annual-mean anomalies obtained from ECHAM5/MPI-OM1 [i.e., the difference, \( \Delta_{am} = (\text{annual-mean states for the strong annual-cycle periods}) - (\text{annual-mean states for the weak annual-cycle periods}) \)] are added to the model annual-mean fields (\( \Lambda_{am} \)). Thus, the modified background states of the model become \( \Lambda_{am} = \Lambda_{am} + \alpha \Delta_{am} \), where we set \( \alpha \) having -0.8, -0.5, 0.5, 0, and 0.8 for the purpose of tracking the eigensolution behavior. Positive (negative) \( \alpha \) indicates an annual-mean background state modification toward the strong (weak) annual-cycle periods. Figure 8 shows the growth rate and frequency of the resulting “ENSO eigenmodes,” which are associated with five cases of the different annual-mean background states. ENSO is seen as the leading eigenmode of the linearized equations of
the intermediate ENSO model with an interannual period. When annual-mean background state changes are assumed for all relevant variables (see above), the growth rate and frequency of the ENSO mode associated with the weak annual-cycle period (i.e., $a = -0.8$) are 0.044 and 0.273 yr$^{-1}$, respectively, and those associated with the strong annual-cycle period (i.e., $a = 0.8$) are 0.037 and 0.304 yr$^{-1}$, respectively. Hence, the eigen-analysis results are qualitatively consistent with the ECHAM5/MPI-OM1 results. This suggests that annual-mean state changes corresponding to different strengths of the annual cycle in the eastern equatorial Pacific alone may cause the changes of ENSO variability in ECHAM5/MPI-OM1 on multidecadal time scales.

**d. Nonlinear model experiment**

Our eigenanalysis of the linearized ENSO model does not allow us to quantify the direct effects of annual-cycle changes on ENSO; further experiments are necessary to test the ENSO sensitivity to the diagnosed multidecadal changes of the annual cycle in the eastern equatorial Pacific. Here, we use a nonlinear intermediate ENSO model that is basically the same as the CZ model (Zebiak and Cane 1987). In contrast to the model used for the eigen-analysis, the equations have not been linearized, and the ENSO sensitivity is tested by integrating the dynamical equations forward in time for different annual-cycle amplitudes and background state changes. To compare the

![Figure 7](image1.png)

**FIG. 7.** (a) Regression map of each dynamical advection terms averaged over the Niño-3.4 region with respect to Niño-3.4 SST anomaly index. Results for the strong (weak) annual-cycle periods are indicated by solid (dashed) line. (b) Difference map between two periods. Units are °C month$^{-1}$. Details are in text.

![Figure 8](image2.png)

**FIG. 8.** Scatterplot of the growth rate vs frequency obtained from the eigenanalysis of the linearized intermediate ENSO model. The model response to a composite of annual-mean conditions for the strong annual-cycle periods is indicated by the “ST” sign, and that for the weak annual-cycle periods is located at the end of curve.
results with CGCM output, a random noise is added into the CZ model at every time step of 10 days. The random noise is provided as a surface zonal wind stress with a bell-shape pattern in latitude, and it focuses on the equatorial western Pacific, thereby mimicking the short-term atmospheric variability of the equatorial Pacific.

Again, the experimental strategy of this model resembles that of Jin et al. (1994), Wang and An (2001), and the previous eigenanalysis. This is because the prescribed background climate states of the model are controlled (SST, surface winds, divergence, and thermocline depth), and the model response is based on these changes, particularly on the variability of ENSO (in this study, the background states of the strong and weak annual-cycle periods are again obtained from ECHAM5/MPI-OM1).

As in the previous studies (Wang and An 2001), an abrupt shift in the ENSO regime from the original CZ model was avoided by adding the differences between the climate states for the strong annual-cycle periods and those for the weak annual-cycle periods [i.e., the difference is $\Delta = (\text{climate states for the strong annual cycle periods}) - (\text{climate states for the weak annual cycle periods})$] to the original background states of the model (symbolically, $\Lambda$). For each experiment, a portion of the difference was added to the original background states, between $-30\%$ and $30\%$ of the difference [i.e., the tuning percentage of the modified background states of each experiment is referred to on the x axis. Positive (negative) percentages on x axis indicate the weighting rate of the background conditions of the strong (weak) annual-cycle periods. The open rectangle, cross, and closed dot indicate the $1\%$ higher, standard, and $1\%$ lower value of a coupling parameter, respectively. Details are in the text].

Figure 9 shows the standard deviations of Niño-3 indices obtained from the nonlinear intermediate ENSO model integrations. Each symbol corresponds to a result for a different coupling parameter and relative contribution rate from the modified background states. The maximum amplitude of random noise used in these experiments is $0.035 \text{ dyn cm}^{-2}$, which is known to be the amplitude of the surface zonal wind stress associated with the Madden–Julian oscillation in the tropical Pacific (Kessler and Kleeman 2000).

First, we perform an experiment for the annual-mean part modification (i.e., $\Lambda^* = \Lambda + \alpha \Delta_{\text{am}}$). As seen in Fig. 9a, the annual-mean states for the weak annual-cycle periods intensify ENSO, while those for the strong annual-cycle periods weaken ENSO. The decreasing ratios between the two end points in the diagram ($-30\%$ versus $30\%$) are $0.2 \sim 0.07$, depending on the coupling coefficient, with the higher values occurring in the weak coupling case. Thus, as the annual-mean background states change from those for the weak annual-cycle periods to those for the strong annual-cycle periods, the weakening of ENSO variability is clearly observed in Fig. 9a.

Conversely, Fig. 9b shows that, when the annual-cycle parts are modified (i.e., $\Lambda^* = \Lambda + \alpha \Delta_{\text{ac}}$), the ENSO variability is not systematically changed. There is a slight decreasing tendency of ENSO variability as the annual-cycle strength increases, but this trend is not significant. To associate the model sensitivity with the noise level, the same experiments as above were repeated, except for changes in the weak and moderate noise levels ($0.001$ and $0.01 \text{ dyn cm}^{-2}$). As the noise levels decrease, the
decrease in ENSO variability becomes clearer in the annual-mean modification case. In the annual-cycle modification case, the ENSO variability becomes less sensitive to changes in the annual-cycle strength (not shown here). Thus, the intensification or suppression of the annual cycle does not significantly influence ENSO intensity, at least in this simplified modeling framework.

5. The effect of annual-mean climate state changes on the annual cycle in the eastern equatorial Pacific

In this section, the mechanism for how the annual-mean state modifies the annual cycle is explored using a hybrid coupled model. This model combines the tropical Pacific Ocean model from the CZ model with the SPEEDY atmosphere general circulation model ("CZ–SPEEDY" model) [see the appendix and Ham et al. (2009)]. The hybrid coupled model simulates the annual cycle with respect to a prescribed annual-mean state. Also, it is a reasonable tool for examining the effect of annual-mean state changes on the annual-cycle strength.

In the CZ–SPEEDY coupled model experiments, two different annual-mean conditions associated with the strong and weak annual-cycle periods are prescribed, and the deviations from the annual mean (i.e., annual cycle) are simulated. Similar to the previous intermediate ENSO model experiment, the differences between the climate states for the strong and weak annual-cycle periods under CO₂ doubling conditions are added to the original background states. Figure 10 shows the annual-cycle evolution of equatorial SST anomalies in the time-longitude section, obtained from the experiments, showing impacts of two annual-mean conditions for strong and weak annual-cycle periods. The general evolutions of the SST seasonal cycle in the two experiments are quite similar. However, as shown in the difference map, especially over the central to eastern Pacific, the annual cycle simulated in the experiment with the annual-mean background state corresponding to a strong annual cycle is larger by about 0.6°C over the central Pacific (150°–120°W) compared to the experiment that uses an annual-mean state corresponding to weak annual-cycle phases in the MPI-OM1 greenhouse warming simulation. Thus, the change in the annual-cycle amplitude is possibly driven by changes in the annual-mean patterns.

The annual cycle in the equatorial eastern/central Pacific is attributed to the local air–sea interaction rather
than the direct radiative heating so that the intensification of the northwestward trade over the equator during boreal summer and its weakening during boreal winter causes the annual variation of surface evaporative cooling and, hence, of SST (Xie 1994). On the other hand, it induces annually varying meridional advection of ocean temperature associated with the asymmetric coastal upwelling and, hence, asymmetric SST with respect to the equator (Li and Philander 1996). The annual-cycle SST initiated near the eastern coastal region will propagate to the west by virtue of the zonal advection of the mean temperature gradient by anomalous zonal currents in the mixed layer (i.e., $-u'\partial T/\partial x$) (Xie 1994). To investigate how the annual-mean states affect the annual cycle, here we perform a heat budget analysis on Niño-4.3 SST obtained from the hybrid coupled model. The results show that the zonal advection of mean temperature gradient by anomalous zonal current ($-u'\partial T/\partial x$, where prime and overbar actually indicate annual-cycle and annual-mean quantities, respectively) mainly contributes the intensification of the annual cycle over the central Pacific (Fig. 11), which is directly linked to the intensified zonal thermal contrast between the warm pool and cold tongue in the annual-mean state, that is, simply the surface warming in the western Pacific (see Fig. 5). In other words, rather than intensification of annual cycle due to thermodynamical heating at the ocean surface, the far-reaching/intensified westward propagation of SST due to the zonal temperature advection is a major component of the intensified annual cycle shown in Fig. 11c.

6. Conclusions and discussion

An inverse relationship between the annual-cycle amplitude and ENSO amplitude in the tropical eastern Pacific SST is both observed (Wang 1994) and simulated with CGCMs (Guilyardi 2006; Timmermann et al. 2007b). This inverse relationship, especially on decadal-to-interdecadal time scales, becomes more pronounced in the CGCM simulations under greenhouse warming conditions. The results from the ECHAM5/MPI-OM1 model show a significant negative correlation ($-0.74$) in the greenhouse warming scenario experiment and a positive correlation (0.37, not statistically significant) in the control experiment. These results are analyzed to reveal the cause of the negative correlation. The eigenanalysis
and time integration of an intermediate ENSO model constrained by the prescribed annual-mean/annual-cycle background states and an experiment with the CZ–SPEEDY coupled model all clearly show that changes in the annual-mean states could lead to changes in both the annual-cycle amplitude and the ENSO amplitude; these amplitude changes are negatively correlated.

The changes in annual-mean states, especially the surface warming in the western Pacific and the thermocline deepening in the central Pacific, have acted to suppress the ENSO amplitude and to intensify the annual-cycle amplitude, and vice versa (see the schematic diagram of Fig. 12). On one hand, the surface warming in the western Pacific causes a weakening of air–sea coupling strength through promoting the convective center to migrate to the west, and the westward shift of the convective center further suppresses the ENSO amplitude by shortening the oceanic adjustment time. On the other hand, the deep annual-mean thermocline makes the subsurface temperature less sensitive to the change in thermocline depth, which results in the reduction of the vertical advection of anomalous temperature by mean upwelling and consequently suppressing the ENSO amplitude. The surface warming in the western Pacific intensifies the annual-cycle amplitude through increasing the zonal advection of annual-mean temperature by the annual-cycle zonal current.

An intermediate ENSO model and the CZ–SPEEDY model were used to investigate the one-way interaction, namely from the annual-mean state to the ENSO/annual-cycle response. The potential role of two-way interactions among the annual mean, the annual cycle, and ENSO were not investigated in this study. In particular, the results do not provide any insight into the nonlinear frequency–entrainment mechanism between ENSO and the annual cycle (Chang et al. 1994; Xie 1995; Timmermann et al. 2007a,b; Choi et al. 2009). However, it was found that simple annual-mean background state forcing can account for much of the out-of-phase relationship between ENSO and the annual cycle in the ECHAM5/MPI-OM1 CO2 doubling simulation.

In general, it has to be noted that the amplitude of ENSO can be changed by mechanisms other than those discussed here. For example, regardless of any changes in either the annual cycle or annual mean, the ENSO amplitude can experience a decadal bursting via a purely nonlinear mechanism (Timmermann and Jin 2002; Timmermann et al. 2003). Timmermann et al. (2003) showed that the decadal occurrences of the strong El Niño event could be driven by nonlinearities in the tropical heat budget. It has also been argued that stochastic excitation can explain a fraction of decadal climate variability observed in the tropics, even under a linearly stable regime with only prescribed stochastic forcing (Chang et al. 1996; Eckert and Latif 1997; Blanke et al. 1997; Moore and Kleeman 1999; Wang et al. 1999). Thus, future research should address how these effects modify the relationships between the annual mean, the annual cycle, and ENSO.

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APPENDIX

A Hybrid Coupled Model

The oceanic component of the hybrid coupled model is the Cane–Zebiak model (Zebiak and Cane 1987). The horizontal resolution is 5.625° (2°) in the longitudinal
(latitudinal) direction. Note that the model domain covers the Pacific regions only. The atmospheric component of the hybrid model is SPEEDY AGCM (Molteni 2003), and the resolution of the model is T42L10. SPEEDY is simplified for computational efficiency; however, it still includes most of the basic components for physical parameterizations, including convection, large-scale condensation, clouds, shortwave radiation, longwave radiation, surface fluxes of momentum and energy, and vertical diffusion. The air–sea coupling interval is 10 days. The oceanic (atmospheric) model provides the anomalous SST (anomalous wind stress) and receives the anomalous zonal and meridional wind stresses (anomalous SST), with values that are 10-day averaged. Details on the hybrid model are provided in Ham et al. (2009). This hybrid coupled model has been used for ENSO prediction and predictability studies (Ham et al. 2009).

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