An Embedding Method for Improving Interannual Variability Simulations in a Hybrid Coupled Model of the Tropical Pacific Ocean–Atmosphere System

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ABSTRACT

An embedding approach is developed and tested to improve El Niño–Southern Oscillation (ENSO) simulations in a hybrid coupled model (HCM), focusing on the ocean thermocline effects on sea surface temperature (SST) in the eastern equatorial Pacific. The NOAA/GFDL Modular Ocean Model (MOM 3) is coupled to a statistical atmospheric model that estimates wind stress anomalies based on a singular value decomposition (SVD) of the covariance between observed wind stress and SST anomalies. Analogous to the Cane–Zebiak (CZ) coupled model, a separate SST anomaly model is explicitly embedded into the z-coordinate ocean general circulation model (OGCM). The three components exchange predicted anomalies within the coupled system: The OGCM provides anomalies of ocean currents in the surface mixed layer and the thermocline depth, which are used to calculate SST anomalies from the embedded SST model; wind anomalies are then determined according to the statistical atmospheric model, which in turn force the OGCM. Results from uncoupled and coupled runs with and without the embedding are compared. With the standard coupling, the system exhibits similar behavior to previous HCMs, including interannual variability with a dominant quasi-biennial oscillation and a westward propagation of SST anomalies on the equator. These characteristics suggest that the horizontal advection is playing a more important role than the vertical advection in determining SST changes over the eastern equatorial Pacific. Incorporating the embedded SST anomaly model, with which the thermocline effects on SST can be enhanced in the eastern equatorial Pacific, has a significant impact on performance of the HCM. The embedded HCM exhibits more realistic SST variability and coupled behavior, characterized by 3–4-yr oscillations and a more standing SST pattern along the equator.

The results support the hypothesis that current physical parameterizations in the OGCM provide insufficient thermal linkage between the thermocline and the sea surface in the eastern equatorial Pacific. It is demonstrated that the long-known deficiency of some OGCMs in their depiction of the thermocline and its interactions with SST may contribute to unrealistic coupled variability in HCMs of ENSO. The embedding approach not only provides a diagnosis for parameterization deficiencies in current OGCMs but, pending progress on this difficult problem, provides a straightforward means to bypass it and improve coupled model performance.

1. Introduction

It has for some time been well recognized that a principal natural mode of coupled climate variability exists in the ocean–atmosphere system over the tropical Pacific, with a preference for a 3–4-yr period (i.e., the ENSO; Rasmusson and Carpenter 1982). A critical element of this phenomenon is the subsurface dynamics (e.g., Cane and Zebiak 1985; Suarez and Schopf 1988; Philander 1990; Neelin and Jin 1993). Subsurface variability affects sea surface temperature (SST) in the eastern equatorial Pacific where the thermocline is shallow and upwelling is strong. The resultant SST anomalies force an atmospheric response to the west, which feeds back to the ocean, supporting a continual oscillation over the basin. As shown by Kleeman (1993) and Jin and An (1999), the vertical advection of anomalous subsurface temperature by the mean upwelling, often referred to as the thermocline feedback, is a predominant term in the eastern equatorial Pacific, playing an essential role in the growth and phase transition of El Niño in the coupled system. Since its maximum amplitude is located east of 120°W (see Jin and An 1999), the far eastern equatorial Pacific is a key region for SST anomaly development and amplification fundamental to El Niño. Through the positive thermocline feedback, SST anomalies are able to develop and persist for long enough (more than one year) over the far eastern equatorial Pacific to sustain an interannual oscillation with a 3–4-yr period. Kleeman (1993) has further demon-
strated that the most realistic coupled variability and better prediction skill of SST can be obtained by appropriately taking into account the thermocline effect in the eastern equatorial Pacific.

Various coupled models have been developed to simulate the ENSO phenomenon, but significant intermodel differences exist (e.g., McCreary and Anderson 1991; Neelin et al. 1992; Stockdale et al. 1998; Latif et al. 2001). Intermediate coupled models have been quite successful in depicting this natural mode (e.g., Zebiak and Cane 1987, hereafter ZC87; Kleeman 1993). It appears that the success in these models can be attributed to the specific treatment of the entrainment process that affects SST in the eastern equatorial Pacific. In the Cane–Zebiak (CZ) model, thermocline depth anomalies are used explicitly in estimating the entrainment temperature \( T_e \), which is then used to calculate SST anomalies in the surface mixed layer (ZC87). Consequently the thermocline changes effectively influence SST in the eastern equatorial Pacific where the mean position of the thermocline is close to the surface. The model produces a 3–4-yr oscillation, with coherent space–time evolution and phase relationships among anomalous SST, wind, and thermocline depth throughout an El Niño cycle, analogous to what is observed in nature. Sensitivity analyses indicate that, if the thermocline effect on SST in the far eastern equatorial region is reduced somehow, oscillations weaken and increase in frequency.

The development and application of OGCM-based coupled models, hybrid coupled models (HCMs), and coupled general circulation models (CGCMs) have made great progress recently (e.g., Lau et al. 1992; Philander et al. 1992; Barnett et al. 1993; Syu et al. 1995; Anderson et al. 1998; Ji et al. 1998). However, some problems remain to be addressed (e.g., Latif et al. 2001). Systematic biases are still a major challenge in most models; the simulated interannual variability associated with ENSO is still not realistic in comparison with corresponding observations, such as the strength and structure of SST anomalies on the equator and the preferred oscillating periods (e.g., Latif et al. 2001). OGCM-based coupled models commonly have weak interannual variability and especially underestimate SST variability in the eastern equatorial Pacific (e.g., Meehl et al. 2001). Although the real system is characterized by interannual oscillations with a main period of 3–4 yr, some coupled models tend to produce shorter El Niño periods, favoring a quasi-biennial (QB) oscillation in particular (e.g., Barnett et al. 1993; Syu et al. 1995). Another feature common to some coupled models is the predominance of westward propagation of SST anomalies over the eastern and central equatorial Pacific (e.g., Syu et al. 1995; Lau et al. 1992; Harrison et al. 2002), indicating that the horizontal advection is playing a more important role than vertical advection in these models.

Some of the problems in OGCM-based coupled models can be likely related to deficiencies in the OGCM since the changes in model physics (e.g., the vertical mixing) can significantly improve simulations of SST variability in the equatorial Pacific (e.g., Syu et al. 1995; Ji et al. 1998; Syu and Neelin 2000; Meehl et al. 2001). Generally, the OGCM thermocline is too diffuse, that is, the vertical gradient of temperature is much weaker than observed (e.g., Rosati and Miyakoda 1988; Stockdale et al. 1998). While observed interannual changes in SST are largest over the eastern basin, those simulated from the OGCM are commonly centered in the central equatorial Pacific. Physically, it has been further identified that among the processes less well represented in current OGCMs are vertical links between thermal variability at depth and at the sea surface in the eastern equatorial Pacific (e.g., Zhang and Zebiak 2002). In coupled experiments with this kind of OGCM, the thermocline effect on SST can be reduced significantly, resulting in weak and short-lived SST anomalies over the eastern equatorial Pacific. It is likely that errors in representing the thermocline effects on SST in OGCMs, compounded by ocean–atmosphere interaction and feedback, lead to some systematic biases often seen in many coupled models.

Since systematic errors in SST are often largest in the eastern equatorial Pacific, this is still a major problem area for model simulation and prediction. The obvious biases in OGCM-based coupled models, that is, weak SST anomalies in the eastern equatorial Pacific, the dominant QB oscillating period and westward propagation of SST anomalies on the equator, suggest that something needs to be fixed. Based on some modeling studies (e.g., Ji et al. 1998; Syu and Neelin 2000; Meehl et al. 2001) and particularly on comparisons between the CZ coupled model and an OGCM-based HCM (Zhang and Zebiak 2003), we hypothesize that weakened OGCM thermocline effects on SST in the eastern equatorial Pacific may contribute to the systematic biases seen in some coupled models. Apparently, improvement is needed in some OGCMs for enhancing the interactions between the thermocline and SST. The preferred solution would be to improve model physics in a comprehensive and consistent manner, but this has proven to be very difficult (e.g., Large and Gent 1999; Zhang and Zebiak 2002). The alternative presented here, while dissatisfying, provides a simple means for testing our hypothesis and for improving model performance. In addition, the importance of the thermocline effects on interannual oscillations has been recognized in many observational and simplified modeling studies, but this has not been emphasized in the OGCM context.

Here, we propose a novel embedding strategy for improving behavior and performance of OGCM-based coupled simulations (Zhang and Zebiak 2003). The approach shares some aspects of intermediate coupled models (e.g., ZC87): A separate SST anomaly model is explicitly added into a HCM consisting of an OGCM and a statistical atmospheric model. The governing equation of the embedded SST anomaly model describes the evolution of temperature anomalies in the surface
mixed layer, driven by ocean horizontal and vertical advections associated with both mean and anomalous currents, which are provided by the OGCM. The main purpose of such embedding is to more realistically link thermocline strength and SST anomalies in the eastern equatorial Pacific (ZC87). The paper is organized as follows. Section 2 describes briefly the model components and some observational data used in this work. Section 3 provides a brief description of the performance of uncoupled simulations forced by corresponding observed forcing fields. Simulated results from the standard and embedded coupled runs are detailed in sections 4 and 5, respectively. Section 6 deals with some further supporting experiments. The paper is concluded in section 7.

2. Model descriptions and observational data

To test our hypothesis (i.e., the role of OGCM thermocline effects on SST in determining the interannual variability in coupled models), we have developed a HCM consisting of an OGCM and a statistical atmospheric model. Furthermore, a SST anomaly model is explicitly embedded into the HCM. These model components are briefly described in this section, as well as observation datasets that are used in this paper.

a. The OGCM

The ocean component is a version of the National Oceanic and Atmospheric Administration/Geophysical Fluid Dynamics Laboratory (NOAA/GFDL) Modular Ocean Model (MOM3; Pacanowski and Griffies 1998). The ocean model domain covers the tropical Pacific basin from 30°S to 30°N, 124°E to 80°W with horizontal resolution 1° latitude by 1° longitude (but 0.33° latitude between 10°S–10°N). It has 40 vertical levels with a constant 10-m resolution in the upper 210 m; the model incorporates realistic continents and bottom topography. Near the model’s southern and northern boundaries [poleward of 20°S(N)], sponge layers are introduced; that is, a Newtonian damping term is added to temperature and salinity equations, which damps the model solution back to observational data. Some newer features in the model include the implementation of a non-local K-profile parameterization (KPP) scheme for vertical mixing (Large and Gent 1999) and an explicit free surface.

b. The CZ ocean model

The CZ model is an intermediate coupled model that calculates the departures of specific fields relative to their prescribed mean seasonal climatology (ZC87): The large-scale ocean dynamics are represented by a linear shallow-water model. A SST anomaly model is embedded into the ocean model, which determines changes in currents and upper-ocean layer depth. The SST anomaly equation can be written as (see ZC87 for details)

\[
\frac{dT_e}{dt} = -u \cdot \nabla(T_e + T) - \nabla \cdot \mathbf{u} T_e - \left[ M\left(\overline{w}_e + w_e\right) - M\left(\overline{w}_c + w_c\right) \right] T_e - \frac{T_e - T_s}{H_1} - \alpha T_e,
\]

where \( T_e \) is the subsurface temperature entrained into the mixed layer. As expressed, the local rate of SST change (tendency) is controlled by horizontal advection (term 1), entrainment (term 2), and thermal damping (term 3), respectively. The thermocline effects on SST are associated with the \( T_e \) anomaly, which is parameterized in terms of the upper-ocean layer depth (\( h \)) from the ocean dynamics:

\[
T_e = \gamma T_{sub} + (1 - \gamma) T_s
\]

\[
T_{sub} = \begin{cases} T_{d1} \left( \tanh[b_1(h + h)] - \tanh[b_1(h)] \right) & , \quad h > 0 \\ T_{d2} \left( \tanh[b_2(h - h)] - \tanh[b_2(h)] \right) & , \quad h < 0. \end{cases}
\]

The surface heat flux anomaly is (negatively) proportional to the local SST anomalies. For the definition of variables, functions, and parameters, the reader is referred to ZC87 for more details.

c. The embedded ocean model

We have developed an embedded ocean model in which the CZ SST anomaly model is explicitly added into the OGCM. The anomaly SST equation is the same as in ZC87 (given above) but the \( T_e \) anomaly is now parameterized in terms of thermocline depth anomalies (defined as the 20°C isotherm depth) from the OGCM. Since the amplitude of the thermocline depth anomalies derived from the OGCM is much larger than that of the upper-ocean layer depth from the original CZ ocean model, we have reduced the parameter relating the thermocline depth anomalies to the \( T_e \) anomaly from a value of \( \gamma = 0.75 \) in the original CZ model (ZC87) to \( \gamma = 0.40 \) in the embedded simulations (sections 5 and 6). In addition, the mean currents in the embedded SST anomaly model are taken from a climatological run of the OGCM forced by observed atmospheric forcing fields, while mean SST fields and vertical gradients of temperature are from the corresponding observations.
d. Hybrid coupled models

1) THE SVD-BASED STATISTICAL ATMOSPHERIC MODEL

The statistical atmospheric model adopted in this work is the same as that described by Chang et al. (2001). The empirical feedback response of wind stress to an SST anomaly is estimated using singular value decomposition (SVD) of the covariance matrix calculated from observed time series of monthly mean SST and wind stress fields (e.g., Syu et al. 1995). With the SVD technique, a SST anomaly pattern from simulations can be projected onto the SST component of the wind stress–SST modes constructed from observations. The corresponding wind stress anomalies are then estimated. Two versions of such SVD calculations have been tested: One version is seasonally invariant (i.e., the SVD analysis is performed on all time series data regardless of seasonal variations) and another is seasonally varying (i.e., the SVD analysis is performed separately for each calendar month to construct seasonally dependent models). Since seasonality can have an important effect on the onset and evolution of El Niño, as demonstrated by Barnett et al. (1993) and Syu et al. (1995), we use the monthly SVD model for calculating wind anomalies in the coupled experiments shown below.

The performance of such statistical atmospheric models depends not only on the inclusion of seasonality, but also on factors such as the truncation number for the SVD modes (e.g., Barnett et al. 1993; Syu et al. 1995). From the consideration of the sequence of the SVD singular values (not shown) and some reconstruction tests from observed SST anomalies to retrieve wind stress anomalies with a reasonable level of amplitude comparable to the original wind stress fields used for the SVD analysis, we chose to include the first five SVD modes in estimating wind stress fields from SST anomalies. In addition, a combined SVD analysis of the covariance among anomalies of SST and zonal and meridional wind stress components is performed.

2) STANDARD HCM

With standard coupling procedures (e.g., Barnett et al. 1993; Syu et al. 1995), the OGCM is coupled to the SVD-based statistical atmospheric model: The OGCM provides SST anomalies that are used to calculate wind anomalies, which in turn are added to the observed mean seasonal climatology of wind stress to drive the OGCM. The SST anomalies are obtained by subtracting the OGCM-produced SST fields from a reference state, which is predetermined from an uncoupled run forced by observed climatological wind stress.

3) HCM WITH EMBEDDED SST ANOMALY MODEL

A methodology is developed to embed a SST anomaly model between the OGCM and the statistical atmospheric model in the HCM. Note that, in the embedded system, two SST anomaly fields can be available, one directly from its anomaly model and the other from the OGCM itself. Different from the standard HCM in which SST anomalies from the OGCM are used to couple to the atmospheric model, those from the embedded SST model are used to determine wind anomalies in the embedded coupling.

Figure 1 illustrates the hybrid embedded system consisting of the OGCM, the SST anomaly model, and the statistical atmospheric model. The three components exchange anomaly information every day, with the calculated SST anomalies directly from the embedded model serving as the interface from the ocean to the atmosphere. At each time step, the OGCM calculates three-dimensional currents, which are averaged over the surface mixed layer. These fields are then averaged each day and the corresponding anomalies are obtained by subtracting from them prescribed climatological fields.
that are predetermined from the OGCM-only run forced by observed atmospheric fields. The anomalous 20°C isotherm depth is estimated in the same way. These interannual anomalies, together with mean climatological fields, are passed to the separate embedded SST anomaly model to calculate its own evolution, which is used in determining wind anomalies via the atmospheric model. The wind anomalies are then used to force the OGCM.

e. Observational data

Various observational data are needed for constructing the statistical atmospheric models as well as for verifying model simulations. The Florida State University (FSU) wind data (Goldenberg and O’Brien 1981) are used to construct the SVD-based statistical atmospheric models for the HCM. In addition, the National Centers for Environmental Prediction—National Center for Atmospheric Research (NCEP–NCAR) reanalysis data (Kalnay et al. 1996) are also used to force ocean models in some uncoupled experiments (section 3).

Observed SST data are from Reynolds and Smith (1994). Figures 2a and 3a illustrate the observed total SST field and its anomalies along the equator. Associated with El Niño and La Niña events, the eastward migration of the western warm pool and the westward spread of the cold tongue on the equator are clearly evident. Large SST anomalies can be seen in the eastern equatorial Pacific, with a dominant standing pattern on the equator. The corresponding monthly time series for the Niño-1+2 region (0°–10°S, 90°–80°W) and the Niño-3 region (5°N–5°S, 150°–90°W) are shown in Fig. 4. Interannual variations are characterized by 3–4-yr oscillations, with nearly in-phase variations of SST at these two sites. To quantify the dominant time scales of variability, spectra are estimated from the Niño-3 SST anomalies and are shown in Fig. 5a. There are three peaks with enhanced power: the first at 3.6 yr, the second at 5.6 yr, and the third at 2.2 yr, respectively. The first two correspond to the typical El Niño periods of about 3–7 yr while the third is at the biennial oscillation period of near 2 yr. Rasmusson and Carpenter (1982), analyzing SST data for the 1953–74 period, also demonstrated spectrum maxima at the 3–4-yr time scales (their Fig. 6). Note, however, that our analysis is based on only 20 years of data and the fact that for the period from 1980 through 1999, there are no two El Niño warm events were separated by more than 5 years. So, the 5.6-yr peak may be purely a statistical artifact.

3. Uncoupled simulations

To examine the performance of each component model, in this section we briefly review some results from uncoupled simulations of the tropical oceanic models forced by observed atmospheric wind stress.

a. The OGCM (MOM 3) simulations

The mean climatological forcing fields for the OGCM are the same as in Zhang and Zebiak (2002). Monthly climatological wind stress is from the NASA/DAO Special Sensor Microwave Imager (SSM/I) analysis from 1987 to 1996 (Atlas et al. 1996). The OGCM is coupled to an advective atmospheric boundary model (Seager et al. 1995) for calculation of the sea surface heat flux. Due to a systematic bias in the total heat flux calculated, another damping term is included in the SST equation of the OGCM for restoring the model SST toward the corresponding climatological observations with a relaxation time of 30 days. The freshwater flux in the model includes two terms: one is concerned with the differences in evaporation and precipitation estimated from the NCEP–NCAR reanalyses (Kalnay et al. 1996), and the second is concerned with a restoring boundary condition on sea surface salinity by which the model top-level salinity is restored to the Levitus (1982) seasonally varying climatology with a relaxation time of 10 days. All other atmospheric forcing fields necessary for the OGCM are from the NCEP–NCAR reanalysis products, including surface winds, wind speed, cloud, and so on. The OGCM, initiated from the Levitus (1982) temperature and salinity fields, is integrated for 10 years with the climatological forcing fields, by which time it has achieved a near-equilibrium seasonal cycle. All uncoupled interannual runs and coupled runs are initiated from this climatological run.

For ocean-only interannual simulations, we use wind stress anomalies from the NCEP–NCAR reanalysis data that are relative to their corresponding long-term mean seasonal climatology. These interannual anomalies are added on the NASA/DAO SSM/I mean climatology (Atlas et al. 1996) to force the OGCM for interannual experiments from January 1948 to April 2000. Simulated monthly anomalies are obtained relative to corresponding model climatology that is derived from January 1948 to December 1999.

Figure 3b shows longitude–time sections of simulated SST anomalies along the equator from the OGCM. The model reproduces quite well the observed interannual variability, including major El Niño and La Niña events. Compared to corresponding observations (Fig. 3a), however, some problems are evident. There is a cold bias in the simulated SST field in the eastern equatorial Pacific, accompanied by overly strong westward flow in the central and eastern equatorial Pacific [not shown, but see Zhang and Zebiak (2002)]. Seasonal and interannual variabilities from the forced run are generally weak over the eastern tropical Pacific. In particular, the simulated SST variability is very weak in the far eastern Pacific and along the coast of South America. While observed interannual changes in SST are largest in the eastern basin (Fig. 3a), those simulated from the OGCM are centered in the central equatorial Pacific (Fig. 3b).
The simulated thermocline depth anomalies along the equator (manifested as the 20°C isotherm in the OGCM) indicate that the largest thermocline variability is located in the far eastern equatorial Pacific and the eastern coastal regions, but temperature anomalies are weak at the sea surface. This is suggestive of a potential problem in the physical parameterization of the OGCM, where the thermocline effects on SST appears to be underestimated in the far eastern equatorial Pacific.

b. The CZ ocean model simulations

We have performed an experiment with the ocean component of the CZ coupled model, driven by wind anomalies from the NCEP–NCAR reanalysis, as in the OGCM run. Due to an obvious linear trend in the original wind anomaly data, we detrended them first before using them for the forced run with the CZ model. Figure 3c shows the simulated SST anomalies along the equator. As is well known (e.g., ZC87; Chen et al. 1995, 2000), the standard CZ model can well simulate warm SST anomalies in the eastern equatorial Pacific, while there are problems in simulating cold SST anomalies and the SST anomaly amplitude over the central equatorial basin.

There are noticeable differences in simulated SST anomaly fields between the OGCM (Fig. 3b) and the CZ ocean model (Fig. 3c). As has been previously noticed (e.g., Barnett et al. 1993), the spatial structure of SST variability is very different from the two models. The OGCM tends to have the largest SST variability over the central basin, while it has weak anomalies in the eastern basin; the CZ model is the other way around: the maximum anomalies tend to be located in the eastern equatorial Pacific, while those in the central basin are weak. Further experiments indicate that the enhanced SST variability in the eastern equatorial Pacific from the CZ ocean model can be mainly ascribed to the stronger influence of $T_e$ (i.e., thermocline variability) on the SST in this region (Fig. 3c). The obvious problem in simulating cold anomalies in the CZ model is also related with the parameterization of $T_e$ (in this case the coupling to the thermocline is more strongly nonlinear and evidently too weak for the case of large anomalies). The differences of the two ocean models in their depiction of the thermocline and its interactions with SST are responsible for the large differences in their SST simulations. This simple intercomparison suggests that the thermocline effects on SST appear to be underestimated in the OGCM, which leads to weak SST variability over the far eastern equatorial Pacific.
c. The embedded simulations

Next, we performed experiments with the CZ SST anomaly model embedded into the OGCM, with atmospheric forcing from the same NCEP–NCAR reanalysis products as above. Figure 3d presents the longitude–time sections of simulated SST anomalies along the equator directly from the embedded anomaly model. Compared to the observations (Fig. 3a), the embedded simulation (Fig. 3d) tends to overestimate the SST variability between 80°W–90°W on the equator. Compared to the corresponding fields from the OGCM (Fig. 3b) and from the original CZ ocean model (Fig. 3c), there are clear improvements in terms of the amplitude and spatial structure of SST variability over the equatorial basin. The embedded simulations optimally capture some good aspects of both ocean model simulations: Large SST variability is depicted very well in both the central and eastern equatorial Pacific. The latter feature can be apparently attributed to the $T_c$ parameterization in terms of thermocline depth anomalies, which tends to enhance the subsurface effect on SST in the eastern equatorial Pacific. As observed (Fig. 3a), large SST anomalies cover the whole eastern basin (~2°C) during the mature phase of El Niño and La Niña events. In the central
equatorial basin, on the other hand, SST variability is significantly enhanced as well in the embedded model, which can be related to stronger zonal surface currents in the OGCM during El Niño/La Niña developments. These are expected because the full nonlinear OGCM can produce three-dimensional current structure better than the linear shallow-water ocean model (ZC87). The embedded SST model also has a much better depiction of cold SST anomalies as compared to those in the original CZ ocean model (Fig. 3c). Clearly, it is evident that SST anomaly simulations in the embedded experiments can be improved in both the eastern and central equatorial Pacific. The quantitative comparisons for the three simulations are illustrated in Fig. 6, showing the correlation between simulated and observed SST anomalies. The OGCM has much better simulation skill in the central basin while the CZ ocean model does better in the far eastern basin and along the coast of Central and South America (e.g., Barnett et al. 1993).

The embedded SST model appears to have higher skill than the CZ model in the central basin and the OGCM in the far eastern basin, respectively.

4. The standard coupling experiments

We performed numerical experiments using the standard HCM: Coupling begins from the end of the climatological run (see section 3a) through addition of an external zonal wind stress anomaly for 4 months, exactly as in ZC87. As examined previously by numerous studies (e.g., Syu et al. 1995), coupled behavior depends on the so-called relative coupling coefficient ($\alpha$), that is, the wind stress anomalies from the atmospheric model can be further multiplied by a scalar parameter before being added to the climatological wind stress fields to drive the OGCM. Several tuning experiments were performed with different values of $\alpha$ to examine the cou-
Figure 6. Correlations between observed and simulated SST anomalies calculated during the period 1980–98 for (a) the OGCM, (b) the original Cane–Zebiak ocean model, and (c) the embedded SST anomaly model with the OGCM, respectively. The contour interval is 0.1°C.

amped variability: \(\alpha = 1.0\) does not produce a sustained interannual variability in the HCM; rather, a damping oscillation emerges. Doubling the coupling strength can produce a weak oscillation with a period of about two years; \(\alpha = 2.5\) produces a pronounced interannual variability. Further increase in the coupling coefficient does not change the oscillation period significantly. In all cases, similar to previous HCMs (e.g., Barnett et al. 1993; Syu et al. 1995), the hybrid coupled model is dominated by a quasi-biennial oscillation. In the following, as an example, results are shown for a 14-yr coupled run with \(\alpha = 2.5\).

### a. Annual mean state and its seasonal variations

Figure 7a illustrates the simulated long-term annual mean SST fields in the standard coupling run. The model produces a generally realistic mean SST structure over the tropical Pacific Ocean, including the warm pool in the western equatorial basin and the cold tongue in the east. Figure 8b shows the corresponding mean seasonal cycle along the equator in terms of the deviation from its annual mean. As compared to the corresponding observations (Fig. 8a), the model realistically captures the phase and amplitude of the seasonal cycle, as well as the westward propagation of the seasonal maxima and transition in the eastern basin. However, the simulated structure of the seasonal variations shows two variability centers, the major one around 100°W and another one around 140°W. The model tends to overestimate seasonal variability at 140°–160°W but underestimates that in the eastern equatorial basin significantly.

### b. Interannual variations

Figure 2b shows the simulated total SST fields along the equator from the standard coupling run. The model simulates quite well the basic structure of SST fields. As compared to the observations (Fig. 2a), however, the westward propagating signal is overestimated in the
Fig. 7. Simulated long-term annual mean SST fields from the HCMs for the (a) standard and (b) embedded coupling runs, respectively. The contour interval is 1°C.

Fig. 8. Longitude-time sections of mean seasonal variations in SST along the equator for (a) observations and for models from the (b) standard and (c) embedded coupling runs, respectively. The contour interval is 0.5°C.
model. In association with La Niña events, the westward spread of the cold tongue, which can be seen to penetrate far westward into the western Pacific, is obviously too strong along the equator. On the other hand, the eastward migration of the western warm pool is weak during the El Niño events.

Figure 4b presents time series of simulated SST anomalies for the Niño-1+2 region and the Niño-3 region, respectively. A clear phase lag between SST variations can be seen at the Niño-1+2 region and at the Niño-3 region, with the former leading the latter, indicating a westward propagation of SST anomalies along the equator from the eastern basin to the central region. Spectrum estimates from the model Niño-3 SST anomalies are shown in Fig. 5b. In the standard coupling run, the first enhanced power peak is at the biennial oscillation period (2.2 yr), followed by the second peak at 3.6 yr and the third peak at 2.7 yr, respectively. Similar to previous HCMs, interannual variability in this coupled model is characterized by a quasi-biennial oscillation.

Anomalies of SST, zonal wind stress, and sea level (SL) along the equator are shown in Fig. 9. These atmospheric and oceanic anomaly fields show a coherent interannual oscillation of about 2-yr period. In terms of spatial structure, largest wind stress variability regions are focused on the central basin (Fig. 9b), while maximum SST anomalies are centered in the eastern equatorial Pacific (Fig. 9a). Sea level (or closely related thermoline) anomalies are largest in the west (e.g., Fig. 9c). These different anomaly fields have different propagation characteristics. The SST anomalies exhibit a significant westward propagation on the equator, first appearing in the eastern equatorial Pacific around 110°W, then propagation westward as they amplify (Fig. 9a). Sea level shows a clear eastward phase propagation on the equator in the western half of the basin, whereas throughout the central and eastern Pacific the changes are practically coincident (Fig. 9c).

Clear phase relationships are evident among anomalies of SST, surface zonal wind stress, and SL (Fig. 9). SST and surface wind variations are nearly in phase temporally, while thermoline depth variations (sea level) in the west have a phase lead relative to SST anomalies in the east, representing the influence of earlier winds to which the ocean is still adjusting. Space–time evolution of ocean anomaly fields can be more clearly seen in Fig. 10 at different periods during a model El Niño/La Niña oscillation. These maps, at six monthly intervals, start with La Niña conditions of model year.
3, proceed to El Niño condition of year 4, and continue
to La Niña condition in year 5. In the ocean, largest
temperature anomalies are located subsurface at the
20°C isotherm depth. Representing changes in the verti-
cally integrated thermal structure, SL changes show
clear phase propagation around the basin (Figs. 10f–j)
and coherent phase relations with SST. For example,
during the development and mature phase of La Niña,
SST anomalies are negative in the east (Figs. 10a–b),
and positive SL anomalies are located in the western
Pacific (Fig. 10g). These positive SL anomalies prop-
gate eastward on the equator: once they have penetrated
far enough to the east in the eastern equatorial Pacific
where the thermocline is shallow, warm SST anomalies

Fig. 10. Horizontal distributions of (left) SST and (right) sea level anomalies at different periods during the model El Niño/La Niña–like
oscillation from the standard coupling run. The contour interval is 0.5°C in the left panels and 4 cm in the right panels, respectively.
emerge in the east (Fig. 10c). Due to the dominant role of the horizontal advection in determining SST evolution in the OGCM, they migrate westward on the equator (Figs. 10c and 10d). Once the warm SST anomalies are present over the central basin (Fig. 10d), the atmospheric feedback and local coupled instability play a role in the future evolution, producing wind anomalies in the central basin and in turn feeding back to the ocean by elevating the thermocline in the west (Fig. 10i). Note that the large SL anomalies in the western basin are not merely the result of wave propagation, but to a large extent are locally forced by the atmosphere. The produced negative SL anomaly signal propagates eastward along the equator and in due course affects SST in the east. The evolution into the La Niña operates in a similar way but with opposite polarity, keeping an interannual cycle of 2 yr going on in the standard coupled model. The coupled variability in this case appears to be dominated by the SST mode as discussed by Neelin and Jin (1993).

5. The embedded coupling experiments

We ran the embedded version of the HCM for 14 years: The embedded coupling run is initiated with an imposed westerly wind anomaly for four months, similar to the standard coupling run above. Evolution of anomalous conditions thereafter is determined solely by coupled interaction in the system. With this three-component embedded system, we find that a relatively large coupling coefficient (\( \alpha \)) is not necessary for producing realistic interannual variability, and thus we have used the actual value of \( \alpha = 1.0 \) for the numerical experiments below.

a. Annual mean state and its seasonal variations

The embedded system has reasonable simulations of both annual mean state and its seasonal variations, as shown in Figs. 7b and 8c. Similar to observations, SST variations have an annual cycle that is strongest in the eastern part of the basin around 120°W with warm anomalies (+2°C) in spring and cold anomalies (−1.5°C) in fall, respectively. A pronounced westward propagation can be seen in the eastern and central equatorial Pacific. Compared to that from the standard coupling run (Figs. 7a and 8b), the simulated mean SST from the embedded run is a little warmer in the western equatorial Pacific but colder in the cold tongue region and thus features a stronger SST gradient along the equator. However, the simulated amplitude of the annual cycle is relatively weak west of 100°W in the embedded run, as compared to observation and the standard coupling run.

b. Interannual variations

Figure 2c exhibits the simulated total SST fields from the OGCM in the embedded run. Compared to Fig. 2a (observations) and Fig. 2b (the standard run), more realistic SST fields are evident in the embedded run, including the eastward migration of the western Pacific warm pool during El Niño events and the westward spread of the cold tongue during La Niña events.

The time series of simulated SST anomalies are shown in Fig. 4c for the Niño-1+2 region and the Niño-3 region, respectively. Here the SST anomalies are outputs directly from the embedded anomaly model without performing any kind of correction. The most striking feature is that the system now has pronounced interannual oscillations with a 3–4 yr period. The estimated spectra (Fig. 5c) from the Niño-3 SST anomalies in the embedded run show similar enhanced power spectra to the observations (Fig. 5a): the first at 3.6 yr, the second at 5.6 yr, and the third at 2.2 yr, respectively. Furthermore, as in observations (Fig. 4a), warm and cold SST anomalies can persist more than 1 year over the eastern equatorial Pacific. In contrast to the standard run (Fig. 4b), no clear phase lag can be seen in the SST variations at these two sites, indicating a predominant standing pattern.

Figure 11 illustrates the interannual variability of SST, zonal wind stress, and sea-level along the equator from the embedded run. The overall time scale, the variability structure, and coherent phase relationships among these anomalies in the HCM are consistent with corresponding observations (e.g., Zhang and Levitus 1997). As compared with results from the standard coupling case (Fig. 9), significant differences exist in the time scale and the way El Niño/La Niña events evolve. The SST anomalies, produced directly from the embedded model, have more reasonable amplitude and structure in the eastern equatorial Pacific and are clearly free from some systematic biases seen in the standard coupling run (e.g., weak anomalies in the eastern basin and dominant westward propagation on the equator). As a result, at the height of El Niño large warm SST anomalies (−2°C) cover the whole eastern basin. This is apparently due to the enhanced thermocline effects on SST in the eastern equatorial Pacific through the \( T_e \) parameterization in terms of the thermocline depth anomalies.

Figure 12 further illustrates the detailed structure of SST and SL anomalies at 6-month intervals throughout a simulated ENSO cycle from the embedded run. The space–time evolution and phase relationships among these anomalies differ from those in the standard run (Fig. 10). Notably, due to the enhanced role of the thermocline variations in controlling SST variability in the embedded model, large SST anomalies are sustainable in the far eastern equatorial Pacific. For example, during the mature phase of La Niña, while SST anomalies are still negative in the east (Figs. 12a–b), positive SL anomalies are located in the western Pacific, which propagate slowly eastward along the equator. As they have penetrated far enough to the east, SST anomalies become positive (Fig. 12c). In the embedded SST anomaly model, the enhanced subsurface effect allows the
thermocline feedback to operate more strongly: Once positive SST anomalies are initiated in the far eastern equatorial Pacific, they can grow locally due to the dominant thermocline effect; at the same time they are advected by surface currents westward along the equator towards the central basin (Figs. 12c–e). A combination of horizontal advection and vertical advection supports the growth of SST anomalies farther west to the central basin where wind anomalies are generated. These westerly wind anomalies depress the thermocline in the east and reinforce the warm SST anomalies there, setting up the positive feedback among the wind, thermocline, and SST within the coupled system. Here, the positive thermocline feedback, associated with the vertical advection of anomalous $T_e$ by the mean upwelling, plays an important role in rapid growth of SST and wind anomalies. As a result, large warm SST anomalies can be seen to exist over the central and eastern basin for more than one year (Figs. 12c–e).

6. Thermocline effect and coupled behaviors: Some supporting analyses

We have performed the standard and embedded coupling experiments with the identical high-resolution OGCM that is coupled to the same SVD-based atmospheric model. As can be clearly seen in Figs. 10 and 12, there are large differences in the simulated oscillation period, structure, and variability characteristics from these two. The manner in which the El Niño–like states evolve and the phase relationships among different atmosphere–ocean anomalies are strikingly different. Why are the coupled behaviors different in the two cases? What determines the period of interannual oscillations in the coupled system? To further understand the impact of the embedding approach, numerous additional analyses were performed; some results are briefly reviewed in this section.

a. The model biases in the standard coupling experiments

As shown in Figs. 3–5, observations show the main oscillation periods of about 3–4 yr, whereas the coupled variability in the HCM with the standard coupling is dominated by quasi-biennial oscillations, similar to previous HCMs. The predominance of the westward propagation in SST variations on the equator from the standard coupling run indicates that the horizontal advection is playing a more important role in determining SST

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**Fig. 11.** Longitude–time sections of simulated anomalies along the equator for (a) SST, (b) zonal wind stress, and (c) sea level from the embedded coupling run. The SST anomalies are directly from its embedded model. The contour interval is 0.5°C in (a), 0.1 dyn cm$^{-2}$ in (b), and 2 cm in (c), respectively.
evolution than the vertical advection process (e.g., Neelin and Jin 1993). Detailed examination further indicates that the OGCM has a notable problem in the eastern equatorial Pacific: it exhibits a weak link between thermal variability in the thermocline and at the sea surface. A significant warm bias exists at depth in the OGCM, accompanied by a diffuse thermocline and a weak vertical gradient of temperature. As a result, the thermocline effect on SST can be weak in the upwelling regions, with the surface processes predominating over the subsurface processes in SST evolution (e.g., Neelin and Jin 1993). This is consistent with the fact that the

FIG. 12. Horizontal distributions of (left) SST and (right) sea level anomalies at different periods during the model El Niño/La Niña–like oscillation from the embedded coupling run. The SST anomalies are directly from its embedded model. The contour interval is 0.5°C in the left panels and 2 cm in the right panels, respectively.
simulated SST variability, even in the forced run, is quite weak in the far eastern equatorial Pacific and along the coast of South America (Fig. 3b).

An example of this behavior can be further seen in the phase relationships between temperature variations at the sea surface and at depth during the model El Niño evolution in the standard coupling run. Following the westerly wind anomaly over the western-central equatorial Pacific in September of model year 4, large positive subsurface temperature anomaly signal can be seen to propagate eastward along the equator. When it progresses to the far eastern basin, warm SST anomalies are generated locally. Due to the horizontal advection, the warm SST anomalies spread westward along the equator thereafter. Figure 13 shows one snapshot of surface and subsurface temperature anomalies in March year 5. At this time, while temperature anomalies at subsurface are still positive over the central and eastern basin (Fig. 13b), those at the sea surface have become negative first in the far eastern equatorial Pacific (east of 120°W). It is indicative that the positive subsurface contribution to SST tendency is not strong enough to compete with the negative contribution associated with the horizontal advection in the surface layer. So, the warm SST anomalies could not persist locally but are short lived in the east (less than 6 months). As a result, SST variations in that region show a lead relative to those subsurface. This appears to be different from observations in which SST changes in the far eastern equatorial Pacific follow thermal changes in the subsurface: During an El Niño, large warm SST anomalies can persist for more than one year due to a dominant positive contribution from the subsurface (e.g., Kessler and McPhaden 1995).

As demonstrated with the CZ model (Jin and An 1999), the eastern equatorial basin is the key region for anomaly growth necessary for El Niño development. The local problem seen in the OGCM can thus have significant consequence on coupled behavior when it is coupled to an atmospheric model. The weakened thermocline effect on SST in the OGCM results in SST anomalies that are weak and short lived over the eastern equatorial Pacific. As a result, the thermocline feedback could not operate effectively in such a coupled model.

b. The phase relationships at the sea surface and at depth

Figure 14 shows the time series of anomalous SST and SL in the Niño-1+2 region from the standard and embedded coupling runs. The phase relationships between temperature changes at the sea surface and at depth (manifested as sea level) can reflect the relative importance of subsurface temperature perturbations versus surface current perturbations in affecting SST in the east. In the standard coupling run (Fig. 14a), accompanied with the development of an El Niño, positive subsurface anomaly signals can be seen to propagate along the equator into the eastern Pacific where warm SST anomalies are generated (Figs. 10b–c). Since the
thermocline effect on SST is underestimated in the OGCM, no local amplification of the warm SST anomalies can be clearly seen in the far eastern basin (also see Figs. 10c–d). Instead, the warm SST anomalies migrate westward along the equator due to the horizontal advection. Following the El Niño event, cold anomalies appear first at the sea surface in the far eastern basin (also see Fig. 13). As such, variations in SST lead those at subsurface depth over the eastern equatorial Pacific.

The situation is quite different in the embedded system (Fig. 14b) in which the thermocline effects on SST have been enhanced in the embedded SST model. After an initial warming of SST in the east (e.g., Fig. 12c), we can clearly see an amplifying SST anomaly pattern over the eastern equatorial Pacific: SST anomalies grow locally due to positive contributions to the SST tendency from the thermocline due to the thermocline feedback. At the height of El Niño, therefore, large warm SST anomalies can be seen to cover the whole equatorial basin (Fig. 12e). Following the El Niño events, changes in SST tend to lag those at subsurface depth over the eastern equatorial Pacific (Fig. 14b).

c. The sensitivity to $T_e$ parameterization

Another experiment has been designed to show the sensitivity of model oscillation period to the strength of the thermocline feedback in the embedded runs. As mentioned above, if the thermocline effect on SST is reduced in its embedded model, the resultant SST anomalies can be weaker in the eastern equatorial Pacific and correspondingly the oscillation period will be shorter in the HCM. One particularly interesting example is the sensitivity of the model oscillation period to how $T_e$ is parameterized in the embedded SST model. Since the OGCM itself has three-dimensional temperature fields, $T_e$ can be estimated at some subsurface depth (e.g., at the base of the surface mixed layer) and then directly used in the embedded SST model. We have simply evaluated $T_e$ anomalies from the OGCM temperature anomaly fields. It is found that $T_e$ has a value of about $\sim 4^\circ$C for the peak amplitude during El Niño in the eastern equatorial Pacific, while $T_e$, when parameterized in terms of the thermocline depth anomaly, attains values of about $6^\circ$C. Thus, using the subsurface temperature field directly for $T_e$ in the embedded SST anomaly model can be expected to significantly reduce the relative importance of subsurface temperature perturbations versus mixed layer current perturbations in affecting SST. We ran experiments using this formulation of $T_e$, and they indeed show that the coupled system has weaker SST anomalies in the eastern basin and a shorter oscillation period of about 2 yr, as seen in the standard coupled experiment. Simple parameter changes could not rectify this bias, suggesting that this parameterization for $T_e$ is not effective in sustaining 3–4 yr oscillations in the coupled system. On the other hand, the $T_e$ parameterization in terms of the thermocline depth anomalies is desirable to enhance the thermocline effects on SST in the eastern equatorial Pacific. These experiments suggest a critical importance of the appropriate depiction of the entrainment processes in ocean models for sustaining SST anomalies in the far eastern equatorial Pacific and realistic coupled variability.

7. Conclusions

In this study, we have investigated the sensitivity of uncoupled and coupled simulations of interannual variability to the thermocline effects on SST in the eastern equatorial Pacific using an HCM incorporating an OGCM. We identified some potential problems associated with the simulation of SST anomalies and proposed a simple method to improve simulations of SST and coupled variability in the HCM.

With the current physical parameterizations, the thermocline-to-surface temperature connection appears to be weak in this OGCM, particularly in the eastern equa-
torial Pacific. As a result, the subsurface effect on SST is underestimated significantly in the region. We have argued that this contributes to the unrealistic characteristics of 2-yr oscillations and the dominant westward propagation of SST anomalies on the equator, as seen in the standard coupling run. In this case, the ocean thermocline variability indeed appears to provide a phase transition mechanism for initiating SST anomalies in the eastern equatorial Pacific. However, as SST anomalies are generated there, they then drift away westward along the equator due to the dominance of horizontal advection over vertical advection/entrainment. So, the generated SST anomalies in the far eastern equatorial Pacific do not persist locally sufficiently long (less than 6 months). Without sufficient support from the subsurface ocean, the positive feedback among the thermocline, SST, and surface winds is weak in the system, and correspondingly, there is a lack of local amplification of SST anomalies in the far eastern equatorial Pacific. Thus, the standard HCM has weak SST anomalies in the eastern basin, a shorter oscillation period, and a dominant westward propagation characteristic on the equator.

Numerical experiments have been performed in an attempt to correct this systematic bias, but it turns out to be quite difficult within the context of the standard HCM. We have then proposed a simple embedding approach to enhance the thermocline effect on SST in the eastern equatorial Pacific. This approach borrows some aspects of intermediate coupled models: a separate SST anomaly model is explicitly embedded into a more general dynamic framework.

An advantage of the embedded SST anomaly model in the HCM is that only SST perturbations are calculated explicitly, and the seasonal climatology is prescribed directly from observations (such as SST and vertical gradient of temperature). Though a compromise in terms of consistency, this allows a realistic representation of anomalous SST tendencies associated with mean thermal structure. Another advantage of the simplified embedded SST anomaly model is that, with fewer explicit processes and parameters, SST anomaly simulations can be more easily controlled (tuned) to a regime that mimics nature. For example, the amplitude and structure of SST variability in the eastern equatorial Pacific can be much better controlled in the embedded SST anomaly model than in an OGCM, through adjustment of explicit parameters controlling efficiency of entrainment and the mean thermocline structure. As such, the embedded SST anomaly equation affords a different, seemingly better balance among different processes important to interannual SST variability. In particular, the thermocline feedback can be explicitly enhanced in the HCM so that SST variability in the eastern equatorial Pacific is influenced more strongly by the thermocline depth anomalies.

Extensive experiments demonstrate that the embedding approach has significant impacts on the behavior of the coupled system. By strengthening the linkage from the thermocline to the sea surface over the eastern equatorial Pacific, the vertical advection associated with mean upwelling against the anomalous temperature gradient can be enhanced so that it plays a more important role in determining SST variability of that region, as compared to the OGCM calculation. Thus the thermocline variability that is forced by wind anomalies in the west can effectively affect SST anomalies in the east. Coupled interactions among the thermocline, SST, and surface winds operate more strongly over the basin, allowing interannual oscillations with more realistic time scales and spatial structure. It is not necessary to have an artificially large relative coupling coefficient for sustaining interannual oscillations. It appears that the embedding impacts on the coupled variability are much greater than those caused by other tuning efforts (e.g., vertical mixing schemes) and even larger than those caused by using different atmospheric models (e.g., statistical or simplified dynamical models; Harrison et al. 2002). Note, however, that the parameters of the embedded SST anomaly model may still overstate the coupling between the atmosphere and ocean. Whether or not the coupled system displays a self-sustained oscillation may not be especially important, as the presence of stochastic atmospheric forcing can easily sustain a system that is weakly damped. What is more important are intrinsic time scales and spatial patterns of the deterministic coupled system, which appears to depend sensitively on the balance of processes controlling SST.

The embedding approach is not an ultimate solution to long-standing problems common to most coupled models, but the results presented suggest the importance of improving thermal links from subsurface to surface in some OGCMs for better El Niño simulations in the tropical Pacific. Further improvements of the embedded system are clearly necessary, especially in a better parameterization of the temperature of entrained water beneath the mixed layer and a better heat flux formulation for the embedded SST anomaly model. The demonstrated improvements of the embedded system in the coupled anomaly simulation in the eastern equatorial Pacific and coupled variability of the HCM are promising for improved El Niño predictions since this is a key region for seasonal-to-interannual climate forecasting. The proposed embedding method will be evaluated in terms of forecast ability. Experiments to explore this issue are being undertaken and will be addressed elsewhere.

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