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A new intermediate coupled model for El Niño simulation and prediction

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[1] A new intermediate coupled model (ICM) is developed and used to simulate and predict sea surface temperature (SST) variability in the tropical Pacific. The ocean component is based on an intermediate complexity model developed by *Keenlyside and Kleeman* [2002] that is an extension of the *McCreary* [1981] baroclinic modal model to include varying stratification and partial nonlinearity effects, allowing realistic simulation of the mean equatorial circulation and its variability. An empirical procedure is developed to parameterize subsurface entrainment temperature (Te) in terms of sea surface pressure (SSP) anomalies. The ocean model is then coupled to a statistical atmospheric model. The coupled system realistically produces interannual variability associated with El Niño. Hindcasts are made during the period 1980–1997 for lead times out to 12 months. Observed SST anomalies are the only field to be incorporated into the coupled system to initialize predictions. Predicted SST anomalies from this model do not show obvious systematic biases. Another striking feature is that the model skill beats persistence at all lead times over the central equatorial Pacific. *INDEX TERMS:* 4522 Oceanography: Physical: El Nino; 4215 Oceanography: General: Climate and interannual variability (3309); 4504 Oceanography: Physical: Air/sea interactions (0312); 9355 Information Related to Geographic Region: Pacific Ocean; 4263 Oceanography: General: Ocean prediction. **Citation:** Zhang, R.-H., S. E. Zebiak, R. Kleeman, and N. Keenlyside, A new intermediate coupled model for El Niño simulation and prediction, *Geophys. Res. Lett.*, *30*(19), 2012, doi:10.1029/2003GL018010, 2003.

1. Introduction

[2] Physical understanding and coupled modeling of El Niño have reached the stage where reasonable predictions of SST anomalies in the tropical Pacific can be made 6 to 12 months in advance (see a review by *Latif et al.* [1998]). Several forecast systems have been used routinely in real time to do so [e.g.,*Cane et al.*, 1986; *Barnston et al.*, 1994; *Barnett et al.*, 1993; *Ji et al.*, 1996]. Among these models, the Cane and Zebiak model [*Cane et al.*, 1986; *Zebiak and Cane*, 1987, ZC87 thereafter] was the first dynamical coupled model used to forecast El Niño. As recently demonstrated by *Chen et al.* [2000] who significantly improved the prediction skill of ZC87, the intermediate coupled model (ICM) approach provides an effective way to advance seasonal-to-interannual climate prediction associated with El Niño.

[3] In this work, we present a new ICM designed for improved El Niño simulation and prediction in the tropical Pacific Ocean. This model is based on an intermediate dynamical ocean model developed by *Keenlyside and Kleeman* [2002]. As with ZC87, a SST anomaly model is embedded within the dynamical ocean model. One crucial component with this kind of ICM is the parameterization of subsurface entrainment temperature (Te) into the surface mixed layer, within which the SST is computed. Several schemes have been tested, including the one used in ZC87 and a local statistical fitting scheme to estimate Te anomalies in terms of sea surface pressure (SSP) anomalies designed by *Keenlyside* [2001]. But these schemes are problematic in the central basin where simulated SST anomalies are significantly too weak (as was evident in ZC87). We have developed a non-local empirical parameterization scheme for Te in terms of SSP anomalies (which are directly available from the explicit dynamics). The improved ocean model has been coupled to an empirical atmospheric model. The coupled system exhibits quite realistic interannual variability associated with El Niño. We have utilized this model to predict SST anomalies over the tropical Pacific, the results of which are presented in this paper.

2. Description of Model Components and Various Data Sets

[4] A new intermediate ocean model has recently been developed by *Keenlyside and Kleeman* [2002]. Its dynamics consist of linear and non-linear components. The former is basically a *McCreary* [1981] type modal model but extended to have a horizontally varying background stratification; ten baroclinic modes plus a parameterization of local Ekman driven upwelling are included. The latter, described by residual non-linear momentum equations, is concerned with corrections to the solution where the linear assumption breaks

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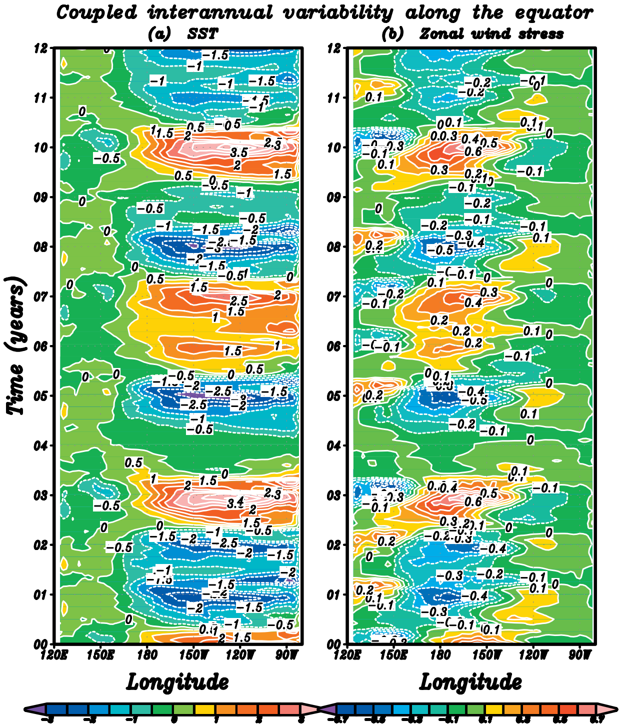


Figure 1. Interannual variability of simulated SST (a) and zonal wind stress (b) anomalies along the equator from an extended integration of the coupled model. The contour interval is 0.5°C in (a) and 0.1 dyn cm^{-2} in (b), respectively.

down. As a direct result of these extensions the model is able to realistically simulate the mean upper-ocean equatorial circulation and its variability. A SST anomaly model is embedded within this dynamic construct. The governing equation describes the evolution of surface mixed layer temperature anomalies, driven by ocean horizontal advection and entrainment associated with both specified mean and simulated anomalous currents. The surface heat flux is parameterized as being negatively proportional to local SST anomalies.

[5] In this paper, we adopt an EOF-based statistical method to calculate Te anomalies from SSP anomalies. The procedure is the same as used by *Barnett et al.* [1993] to estimate wind stress anomalies from SST anomalies. More specifically, the Te model is constructed from the regression of Te and SSP anomalies in a reduced space of empirical orthogonal functions (EOFs). Historical SSP anomalies during the period 1962–1999 are obtained from a dynamical ocean only integration, forced by interannual wind stress anomalies from the NCEP reanalysis. Historical Te anomalies are estimated from an inverse procedure as follows. First, mean current fields are obtained from a dynamical ocean only run forced by climatological NCEP winds. Then, current anomalies are produced from an interannual run, forced by the NCEP wind anomalies during the period 1962–1999. Finally, Te anomalies are estimated from the inverted SST anomaly equation for the period 1962–1999 using observed monthly SST fields from *Reynolds and Smith* [1994], and the simulated mean and anomaly currents.

[6] The atmospheric model is constructed from a singular value decomposition (SVD) of the covariance matrix calculated from observed time series of monthly mean SST and wind stress (Tau) fields [e.g., *Syu and Neelin*, 2000]. Observed SST data are from *Reynolds and Smith* [1994]. Wind stress data are the ensemble mean of 24-member ECHAM4.5 simulations, forced by observed SST anomalies during the period 1950–1999. Using the ensemble mean data allows a better estimate of atmospheric response to external SST anomalies by smoothing out unrelated atmospheric noise.

[7] The EOF analysis for the Te model and the SVD analysis for the Tau model are both performed for the period 1963–1996. Seasonally varying models are constructed [*Barnett et al.*, 1993]. As such, the EOF and SVD analyses are performed separately for each month (a total of 34 years or sample points in time) to construct seasonally dependent models. The first five EOF modes and SVD modes are retained in estimating Te fields from SSP anomalies and Tau fields from SST anomalies, respectively.

[8] All model components within the coupled system exchange simulated anomaly fields. At each time step, the dynamical ocean component produces anomalous ocean pressure, mixed-layer averaged currents, and vertical velocity at the based of the mixed layer (entrainment). The SSP anomaly field is projected onto the regression relations between the EOF-based modes of SSP and Te to estimate Te anomalies. SST anomalies are then calculated with the simulated and prescribed oceanic fields (mean and anomaly currents), the parameterized Te anomalies, and observed climatologies of mean SST and vertical gradient of temperature. The resultant SST anomaly field is projected onto the SST component of the SVD-based modes of SST and Tau to determine wind anomalies, which are used to force the dynamical ocean model.

3. Coupled Interannual Variability

[9] A simulation of the coupled system is initiated with an imposed westerly wind anomaly for four months, as in ZC87. The simulated interannual variability is shown in Figure 1. Overall, the time scale of the variability, its structure and the coherent phase relationships among these anomalies are consistent with observations [e.g., *Zhang and Levitus*, 1997]. The most striking feature is that the system has a pronounced interannual oscillation with a major 3-year period and a dominant standing pattern of SST anomalies on the equator. During the development of El Niño and La Niña events, zonal wind stress anomalies show an eastward migration along the equator from the western Pacific into the central basin, a feature that has been observed in nature.

4. Model Prediction Skill

[10] Twelve month hindcasts have been performed for the period 1980–1997, starting each month. Observed SST anomalies are incorporated into the coupled system to initialize hindcasts. First, the observed SST anomaly fields from *Reynolds and Smith* [1994] are used to calculate wind stress anomalies via the SVD-based Tau model that has been constructed from the ECHAM ensemble runs. The resultant wind stress anomalies are then used to integrate the ocean model up to the beginning of the predictions (1st of each month) to provide the initial states for the dynamical ocean model. In addition, the simulated SST anomalies in the SST model are simply replaced by the observed SST anomalies at

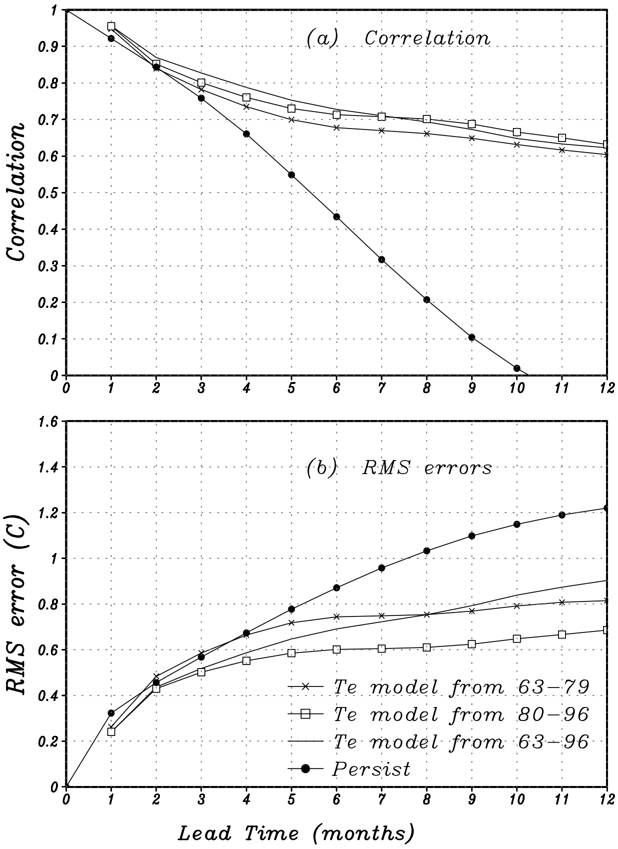


Figure 2. Anomaly correlation (a) and room mean square (RMS) error (b) for Niño 3.4 SST anomalies as a function of lead time for three Te models (trained on the indicated periods) and persistence for the period 1980–97.

the starting time. Compared to other documented coupled models, systematic errors of predicted SST anomalies in our system are significantly smaller—apparently due to the improved empirical Te parameterization. Without any additional corrections, the results shown below are directly from the model output.

[11] As with any statistical method, the performance of the EOF-based Te model for simulating and predicting SST variability depends on several factors, including the data period selected for constructing the SSP-Te regression relationship (the training period), which is then used to predict SST anomalies (the prediction period). If a prediction period overlaps with the training period, the skill for SST prediction (e.g., as measured by the correlation) can be artificially high, since some observational information of Te and SST variability has already been taken into account both in the inverse modeling of Te and the building of the SSP-Te relationship. To check if the prediction skill is strongly sensitive to the training period, three Te models are constructed separately during three different periods (the training period) from 1963 to 1979, from 1980 to 1996, and from 1963 to 1996, respectively. The Te model constructed from each period is then used to parameterize Te anomalies for producing SST anomalies in coupled prediction during the period 1980–97 (the prediction period). These experiments are termed dependent or independent cases, depending on whether or not the application period overlaps the model's training period.

[12] Considering the Niño 3.4 index, the correlation for the independent case does not drop significantly compared to the dependent cases (Figure 2a). In the central Pacific, the independent case shows slightly lower correlation at short lead times, and approximately the same skill correlation at longer lead times (beyond 9 months), with the maximum correlation (RMS error) differences being less than 0.1 (0.1°C). It is evident that using a Te model constructed from an independent period does not significantly degrade the prediction skill. This suggests that the performance of the coupled system is not very sensitive to the data period selected for training the Te model and that the artificial skill introduced may not be significant. It is interesting to note that the correlation skill for the Niño3.4 obtained from the independent case is higher than that in several other prediction systems [e.g., *Latif et al.*, 1998].

[13] In the following, only prediction results from the Te model that is constructed from the period 1963–96 are shown; the longer time sampling provides more stable statistics for constructing the seasonally varying Te and Tau models. The overall prediction skill, calculated from 216 member ensembles for the period 1980–1997, is shown in Figure 2. The striking feature is that the model skill is very high at short lead times; i.e., the correlation starts from 0.97 and remains above 0.8 up to a lead time of 4 months. As a result, the skill from this coupled system beats the persistence at all lead times in the central equatorial Pacific. This may be a beneficial result of the initialization procedure, in which SST anomalies observed in previous month are injected into the model at each start time (1st of each month). The better performance over persistence indicates that the model is able to assimilate observed SST information very well. Beyond 4 month lead time, there is a steady decrease in skill but the correlation remains greater than 0.6 up to a lead time of 12 months, with the RMS errors remaining lower than 0.8°C over the 12-month prediction period.

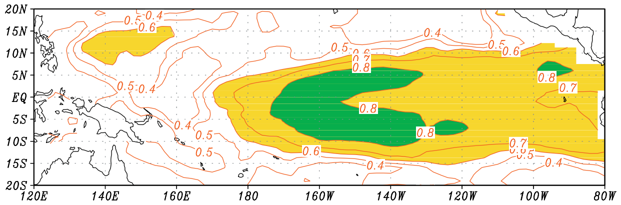
[14] The horizontal distributions of the SST prediction skill at lead times of 3, 6, and 9 months are presented in Figure 3. High correlation regions are located in the central and eastern equatorial Pacific. Compared to the persistence, the model has better skill at all lead times in most geographic locations. Regionally, this model performs considerably better in the central equatorial Pacific than in the eastern basin. At lead time 3 months, the correlation remains greater than 0.8 in the central basin (Figure 3a). With the increase in lead times, correlation drops first and faster in the eastern basin. At lead time 6 months, correlation skill is larger than 0.6 over a sizable region of the central Pacific, but drops down below 0.6 in the east. At 9-month lead time, the correlation has only a modest decrease in the central equatorial Pacific (about 0.1) but a large drop in the eastern basin. It is impressive that the skill correlation is still greater than 0.6 over the central equatorial Pacific near the date line (Figure 3c). The overall skill from this coupled model is evidently no worse than most advanced coupled systems which incorporate ocean data assimilation [e.g., *Ji et al.*, 1996; *Chen et al.*, 2000].

5. Discussions and Conclusions

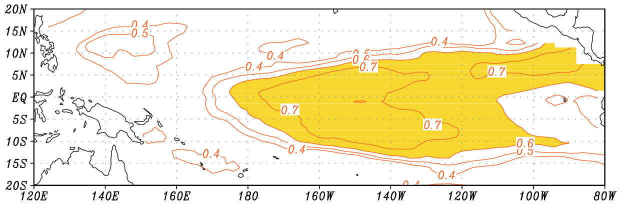
[15] We have developed a new ICM for El Niño simulation and prediction over the tropical Pacific. The most distinguishing features of this new ICM are realistic simulations of

Correlation: Tau(Mon)−Te(Mon); 1980−97

(a) Lead time 3 Months



(b) Lead time 6 Months



(c) Lead time 9 Months

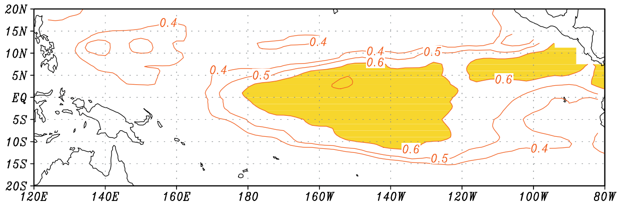


Figure 3. Horizontal distributions of anomaly correlations between observed and predicted SST anomalies at 3-, 6-, and 9-month lead times, respectively. The results are obtained for all predictions made during the period 1980–97. The contour interval is 0.1.

equatorial currents and the empirical parameterizations of subsurface entrainment temperatures, Te, that affect SST variability most importantly in the region. For the given SST model, the inverse modeling of Te, by giving a balanced treatment of various terms in the heat budget of the mixed layer, yields an optimized estimate of Te anomalies for use in simulating SST. A statistical relationship is then constructed from a regression analysis of dominant variability patterns of SSP and Te interannual anomalies in a reduced EOF space. This non-local scheme is able to better parameterize Te anomalies than other local schemes, including the phase lag relationship between Te and SSP variability over the central equatorial Pacific. An improved Te parameterization naturally leads to better depiction of the subsurface effect on SST. As such, SST simulations are significantly improved in the tropical Pacific.

[16] The improved ocean model is coupled to a statistical atmospheric model that estimates wind stress anomalies based on an SVD analysis. With reasonable selections of physical parameters and model setting, the coupled system produces interannual variability that is in good agreement with observations, including a dominant standing pattern of SST anomalies along the equator and a major 3-year oscillation period. Retrospective El Niño predictions have been extensively conducted with this intermediate coupled system and demonstrated encouraging results. The hindcasts are initialized using an initialization procedure that only uses observed SST anomalies. As compared to other prediction systems, our coupled model has significantly small systematic errors in predicted SST anomalies. One striking feature is that the model skill beats persistence at all lead times (out to 12 months) over the central equatorial Pacific. To our knowledge, this has not been achieved previously. The system has been cross validated in the sense that empirical Te models constructed from one period can be successfully used for other independent periods for SST simulation and prediction; the artificial skill introduced by constructing the statistical Te model from historical model data appears not to be significant.

[17] The results described in this paper represent preliminary attempts to develop and improve an intermediate coupled system for better El Niño forecasting. Further refinement and extension are underway. For example, the effects of the statistical atmosphere on variability and predictability need to be examined further, including cross validation for the atmospheric model. The Te scheme we developed empirically works best in the tropical central and western Pacific. In the eastern equatorial basin, where the ZC87 scheme seems to work better, there is a clear room for improvement. More comprehensive ocean data assimilation and coupled initialization should be developed and incorporated into the system.

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