Annual ENSO simulated in a coupled ocean–atmosphere model

Tomoki Tozuka\textsuperscript{a,*}, Jing-Jia Luo\textsuperscript{b}, Sebastien Masson\textsuperscript{b}, Swadhin K. Behera\textsuperscript{b}, Toshio Yamagata\textsuperscript{a,b}

\textsuperscript{a} 21st Century Earth Science COE Program, Department of Earth and Planetary Science, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

\textsuperscript{b} Frontier Research System for Global Change, Yokohama, Kanagawa, Japan

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Abstract

Using an output from 200-year integration of the Scale Interaction Experiment of EU project-F1 model (SINTEX-F1), the annual ENSO reproduced in the coupled general circulation model is investigated, suggesting the importance of reproducing an annual cycle in realistically simulating ENSO events. Although many features of the annual ENSO are reproduced, the northward expansion of sea surface temperature anomaly (SSTA) in the eastern tropical Pacific stays south of the equator. It is suggested that this model bias is due to the excitation of the too strong Rossby waves in the southeastern tropical Pacific, which reflect at the western boundary and intrude into the eastern equatorial Pacific. The zonal wind stress anomaly along the equator also plays an important role in generating the equatorial Kelvin waves. The amplitude of SSTA for the annual ENSO mode is reproduced, but its variance is only 20% of the observation; this is again due to the lack of northward migration of seasonal SSTA in the equatorial region and weaker coastal Kelvin waves along South America. Remedies for the model bias are discussed.

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* Corresponding author.
E-mail address: tozuka@eps.s.u-tokyo.ac.jp (T. Tozuka).
1. Introduction

Since no coupled general circulation models (CGCMs) to date have succeeded in reproducing the seasonal cycle in the eastern equatorial Pacific to full extent (Delecluse et al., 1998; Latif et al., 2001; Davey et al., 2002), modeling the seasonal cycle in the tropical Pacific is still a great challenge. In this context, Tozuka and Yamagata (2003, hereafter TY03) have investigated the seasonal cycle in the tropical Pacific in detail and presented a basin-scale view of seasonal air–sea interaction; they have called this phenomenon ‘annual ENSO’. The annual ENSO consists of the seasonal air–sea interaction in the eastern tropical Pacific with an east–west seesaw in atmospheric pressure anomaly and the westward propagation of heat content anomalies generated in the off-equatorial region by the zonal wind anomalies associated with the air–sea interaction. However, past CGCM studies are mostly concerned with simulating the annual cycle of SSTA (sea surface temperature anomaly) rather than simulating the air–sea interaction in the eastern equatorial Pacific.

Since Rasmusson and Carpenter (1982) showed in their pioneering work that most ENSO events are phase locked to the annual cycle, the importance of the annual cycle in understanding ENSO events (see Neelin et al. (1998) for a review) has long been recognized. Wang (1994) also recognized the importance of the annual cycle in analyzing ENSO, as the symmetric equatorial annual cycle is coupled with ENSO. More recently, TY03 have shown that ENSO may be interpreted as an interaction between the ‘interannual ENSO’ mode and the ‘annual ENSO’ mode. Based on this, they have suggested that the decadal change in ENSO characteristics may be explained by relative importance of these two modes in amplitude and phase. The annual cycle is also believed to play a key role in chaotic nature and phase-locking of ENSO (Tziperman et al., 1994; Jin et al., 1994; Chang et al., 1994). Thus, to reproduce the seasonal cycle in the tropical Pacific seems to be the first step toward reproducing and predicting ENSO. Of course, there is a debate over this issue; Latif et al. (2001) has suggested that the quality of simulating annual cycle may not be related to that of interannual variability in the tropical Pacific.

As a step toward simulating the realistic seasonal cycle in the tropical Pacific and possibly ENSO, we investigate an output from 200-year integration of a high-resolution CGCM without flux correction from the viewpoint put forward in TY03. The content is organized as follows. A brief description of the CGCM is given in the next section. In Section 3, the simulated annual ENSO and model biases are discussed. The interannual and decadal variation in the tropical Pacific is described in Section 4. In particular, a detailed discussion of the interaction between the annual ENSO and the interannual ENSO, and their decadal variation are given there. The final section summarizes the main results with possible remedies of the model biases.

2. Model

The model data used in this study are obtained from an atmosphere–ocean–land coupled GCM, called Scale Interaction Experiment of EU project-F1 (SINTEX-F1) model (Luo et al., 2003), which is an upgraded version of the SINTEX model (Gualdi et al., 2003; Guilyardi et al., 2003) and integrated on the Earth Simulator. The atmospheric component
ECHAM-4 (Roeckner et al., 1996) is coupled to the oceanic component OPA-8.2 (Madec et al., 1998) using the coupler OASIS 2.4 (Valcke et al., 2000). The horizontal resolution of atmosphere general circulation model (AGCM) is T106 (about 1.1° × 1.1°), which is very fine compared with other CGCMs. In the vertical, a hybrid sigma–pressure vertical coordinate with 19 levels is adopted for the AGCM. The horizontal resolution of the ocean general circulation model (OGCM) is 2° × 2° with an increased meridional resolution of 0.5° near the equator. There are 31 levels in the vertical with 19 levels in the upper 400 m for the OGCM. The monthly mean output from the last 200 years of the total 220-years model integration is used for analysis after removing a linear trend from the model output using a least-square fit. The model has shown a good ability in reproducing variability in the tropical region (Behera et al., 2003; Luo et al., 2003), and details of the CGCM can be found in the above references.

For comparison, we use Rayner et al. (2003) for SST data, NCEP/NCAR reanalysis data (Kalnay et al., 1996) for outgoing longwave radiation (OLR), J-OFURO (Kubota et al., 2002) for wind stress data, Xie and Arkin (1996) for rainfall data, and Topex/POSEIDON data and Simple Ocean Data Assimilation (SODA; Carton et al., 2000) for sea surface height (SSH) data.

3. Annual mean field and annual ENSO

Using the model output, we first calculate seasonal anomaly fields by subtracting annual mean field (Fig. 1) from the corresponding monthly mean climatology. As seen in Fig. 1, the annual mean SST is characterized by a cold tongue in the eastern equatorial Pacific and a warm pool in the western Pacific. The model reproduces the observation well in general. However, the modeled cold tongue is narrow and extending too far to the west. This results in too strong westward expansion of high-OLR and less precipitation region, and may have an influence on the cloud--radiation--SST feedback of ENSO (Li et al., 2003). The SSH pattern shows troughs and ridges as in the observation, but the equatorial trough extends too far westward. The modeled northeast (southeast) trade winds in the North (South) Pacific are slightly stronger compared with the observation. This bias in the zonal wind along the equator changes the thermocline tilt and thus the sensitivity of the model to ENSO (Li et al., 2003).

Despite the above limitation in the model climatology, the model reproduces the annual ENSO relatively well (Fig. 2). The SST off the coast of Peru starts warming toward the end of the year as a northerly wind stress anomaly starts blowing along the coast, leading to a deepening in thermocline depth and a decrease in latent heat loss along the coast. Compared to other models, the improved simulation of the seasonal coastal warming, or the classical El Niño (Wyrtki, 1975), is partly due to the high-horizontal resolution of the atmospheric component; low-resolution spectral models have difficulties especially near a steep topography and suffer from weaker coastal upwelling owing to underestimated alongshore winds off South America (Mechoso et al., 1995). Subsequently, anomalous winds converge on the western flank of the warm SSTA. Since the direction of the anomalous wind is opposite to the mean wind (Fig. 1), it suppresses the latent heat loss, and further enhances the SST warming as in the observation. However, the northward expansion of
the warm SSTA is hampered in the model and it remains south of the equator. Nigam and Chao (1996) suggest that this warm SSTA expansion to the north of the equator is induced by the latent heat anomaly. However, the latent heat flux in the coastal region is well reproduced in the model; we find a smaller (larger) latent heat loss to the north of the equator when the warm (cold) SSTA develops (Fig. 3). Then, what is the origin of the model bias?

It has turned out that the lack of northward expansion is due to intrusion of strong upwelling Kelvin waves; they arrive at the eastern equatorial Pacific in the first half of the year (Fig. 4b). The negative sea surface height anomaly (SSHA) is originally generated in the eastern Pacific by a cyclonic wind stress curl anomaly in the southeastern Pacific during
February (Fig. 5), and propagates westward along 9°S as Rossby waves (Fig. 4d). Although its amplitude decays as it propagates westward, it is reinforced to the west of the dateline in the South Pacific Convergence Zone (SPCZ). The negative SSHA generated in the Southern Hemisphere is much stronger compared with the observed signal (Fig. 4c). When it impinges the western boundary, it reflects as equatorial upwelling Kelvin waves. Furthermore, the zonal wind stress anomaly along the equator plays an important role in forcing the equatorial upwelling Kelvin wave. Finally, the Kelvin waves reach the eastern equatorial Pacific just when the warm SSTA is about to expand both northward and westward. The simulated variation along the equator (Fig. 4b) is much stronger compared with observed variation (Fig. 4a). Consequently, no westward expansion of warm SSTA is seen along the equator (Fig. 6a) although it is seen along 3°S (Fig. 6b).

The above scenario is further confirmed by calculating annual heat budget. We here consider an artificial box (105°–115°W, 0–2°N) in the upper 50 m just to the north of the equator, where the northward expansion of the SSTA is hampered (Fig. 7). The averaged temperature decreases from November to February, where the maximum cooling occurs in
January. The cooling is associated with the divergence of heat transport as the surface heat flux shows largest warming during this time of the year.

Since the double Intertropical Convergence Zone (ITCZ) and the subtropical high in the Southern Hemisphere have a direct influence on the wind stress curl field near the origin of the above Rossby waves, improving the convective scheme seems to be important (Yu and Mechoso, 1999a). Also, better simulation in the formation of the stratus cloud in this region is crucial as suggested by Ma et al. (1996) and Yu and Mechoso (1999b) through sensitivity experiments with different idealized stratocumulus. This is because the Peruvian stratus cloud plays an important role in the feedback off the South American coast and thus the equatorial annual cycle (Nigam, 1997). The effort in this direction is in progress (Luo et al., manuscript in preparation).

The positive feedback inducing the warm phase of the annual ENSO is terminated by the southerly wind stress anomaly along the South American coast during the late boreal spring (TY03). The cold phase of the annual ENSO develops during the latter half of the year and it is almost a mirror image of the warm phase (Fig. 2). All these processes are simulated well in the present model. We note, however, that modeling the cold phase has a similar problem in the northward expansion of the cold SSTA.

Another important feature of the annual ENSO is the off-equatorial Rossby wave propagation along 5°N, and it is well captured by the model (Fig. 8). A negative SSHA, which is generated in the off-equatorial region of the eastern tropical Pacific, propagates westward and reaches the maximum height of about 9 cm in agreement with observation. However,
Fig. 4. Time–longitude diagrams of SSHA along (a and b) the equator, and (c and d) 9°S for TOPEX/Poseidon data and the SINTEX-F1 model data, respectively. Contour interval is 2 cm. Negative anomalies are shaded.
Fig. 5. Annual march of wind stress curl anomaly. Unit is in N m$^{-3}$ and negative anomalies are shaded.
the simulated SSHA signal decays faster as it propagates westward with the peak located in the eastern tropical Pacific. This is partly due to insufficiency of simulating the semi-resonant condition between the westward propagating westerly wind stress anomaly and the off-equatorial ‘cold’ Rossby wave (Yamagata, 1987; TY03), as the modeled seasonal

![Time-longitude diagrams of SSTA along the equator and 3°S for the annual cycle.](image)

**Fig. 6.** Time–longitude diagrams of SSTA along (a) the equator and (b) 3°S for the annual cycle. Contour interval is 0.3 °C. Negative anomalies are shaded.

![Monthly heat budget analysis for the artificial box.](image)

**Fig. 7.** Monthly heat budget analysis for the artificial box (105°–115°W, 0–2°N) in the upper 50 m. The rate of change of heat storage (thick solid line) is determined by the convergence of heat transport (dashed line) and the surface heat flux (thin solid line).
air–sea interaction is mostly confined to the Southern Hemisphere in the eastern equatorial Pacific.

4. Interannual variations

4.1. General description of model ENSO events

We analyze here how ENSO events are simulated in the model to check the model performance. The simulated standard deviation of Niño 3 (90°–150°W, 5°S–5°N) SSTA_{msc} (deviation from the mean seasonal cycle) is about 0.8 °C, which is comparable to the observation. This model performance ranked high compared to models participated in the ENSIP (El Niño Simulation Intercomparison Project), where about half of the models are characterized by too weak variability (Latif et al., 2001).

The nature of ENSO events approximately locked to the annual cycle is also well reproduced. As shown in Fig. 9a, more than 50% of warm events reach the maximum strength on December and January. Here, warm events are selected according to a criteria that Niño 3 SSTA_{msc} with 3 months running mean exceeds 0.8 °C (1 S.D.) for at least five consecutive months. The phase-locking, however, is still loose compared with the statistics based on the extended reconstructed sea surface temperatures (ERSST; Smith and Reynolds, 2003), where about 60% of warm events reach the maximum on either November or December.
during 1903–2002 period (Fig. 9b). Since the seasonal cycle is known to play an important role in the phase locking of ENSO, the loose phase-locking may be attributed to the model bias in the annual ENSO. In particular, the bias in the seasonal cycle of wind and oceanic upwelling seems crucial (cf. Tziperman et al., 1997).

To extract common features of simulated warm events, composite diagrams are constructed by averaging 10 strongest warm events. To define its strength, we use the maximum Niño 3 SSTA$_{m}$ during a warm event, and changing number of events used in constructing composites does not change the qualitative result presented here. Fig. 10 shows various anomaly fields thus obtained for Dec. (+0) when many El Niño events reach the maximum strength. For observation, eight warm events (1965/66, 1969/70, 1972/73, 1976/77, 1982/83, 1986/87, 1991/92 and 1997/98) are used. Since the positive SSTA$_{m}$ extends too far to the west as seen in other CGCMs, the negative OLRA$_{m}$ also extends far into the western Pacific. The westerly wind stress anomaly is seen along the equator, indicative of the weakened Walker circulation. Finally, the SSHA$_{m}$ is positive in the eastern and central equatorial Pacific, and negative in the off-equatorial western Pacific, suggestive of a deeper thermocline to the east and a shallower thermocline to the west. In summary, many features during the mature phase of warm events are relatively well reproduced in the CGCM.

4.2. Interaction between two modes of ENSO

An important suggestion obtained from the data analysis in TY03 is that ENSO may be interpreted as the interaction between the ‘annual ENSO’ mode and the ‘interannual ENSO’ mode. Here, we investigate whether this feature is simulated in our CGCM. After subtracting the annual mean field shown in Fig. 1, we apply both complex EOF (CEOF) and composite methods to various fields of interest. We applied CEOF to the Pacific basin between 20°N and 20°S to encompass the annual ENSO, but to make the effect of SSTA variations associated with annual solar forcing as small as possible. We also note that changing the meridional boundary by few degrees does not change the qualitative result.
Fig. 10. Composite diagrams of (a and b) SSTA, (c and d) ZWSA, (e and f) OLRA, and (g and h) SSHA for Dec. (0) for observation/reanalysis/assimilation and SINTEX-F1 model, respectively. Units are °C, N m⁻², W m⁻², and cm, respectively. The statistical significance of the anomalies was estimated by the two-tailed t-test. Shading for left and right column indicates anomalies exceeding 90 and 95% significance, respectively.

and all CEOF modes discussed in this section have statistically significant separations from other modes (North et al., 1982).

It is found that the variation associated with the interannual ENSO mode is captured by the second CEOF mode for SSTA and SSHA (Fig. 11). Composite diagrams of El Niño years are constructed as in Fig. 10. During an early stage of El Niño, a downwelling Kelvin wave associated with positive SSHA is generated in the western equatorial Pacific and propagates eastward. This results in a deepening in the thermocline depth and an SST warming in the eastern and central equatorial Pacific, which peaks toward the end of the El Niño year 0. Meanwhile, a negative SSHA or a cold Kelvin wave is generated in the western tropical Pacific and propagates eastward as upwelling Kelvin waves, terminating the SST warming in the eastern Pacific by the next summer of the year +1. The evolution of the warm event is in agreement with observational study of TY03. After the decay of El Niño condition, La Niña condition with negative SSTA in the eastern equatorial Pacific develops toward the end of the year +1.

The evolution of the annual ENSO mode, which is captured by the first CEOF mode of SSTA and SSHA, takes a normal course during the first half of El Niño year 0, but the cold phase in the latter half of year 0 is slightly weaker than normal and the warm
phase in the following year is slightly stronger than normal (Fig. 12). The change in the amplitude of annual ENSO mode is due to changes in the background fields caused by the interannual ENSO mode. As is clear from Fig. 11, the interannual ENSO mode results in a deeper thermocline depth in the eastern tropical Pacific, leading to less effective upwelling of subsurface water. The maximum change in the amplitude of the simulated annual ENSO mode during the El Niño year is about 0.2 °C near the coast (Fig. 13), which is statistically significant at 95% confidence level with the two-tailed t-test. The amplitude change in annual ENSO mode during the El Niño year seems to be a robust feature. However, the simulated value is much smaller compared with the observed value of about 0.7 °C during 1958–1975 and 1.4 °C during 1980–1999. We attribute this defect to the resolution of the OGCM; the zonal resolution of 2° of the present ocean model is too coarse to resolve coastal Kelvin waves. As a result, the maximum change in the thermocline depth (defined by the depth of 20 °C isotherm) off the South American coast during El Niño is less than 50% of that in the SODA (Carton et al., 2000) (figures not shown).

The interannual amplitude modulation of the simulated annual ENSO mode associated with warm events is almost nonexistent in the Niño 3 region (Fig. 14). This is in contrast with observation, where the amplitude of the annual ENSO mode in the Niño 3 region

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Fig. 11. El Niño composite of reconstructed fields for the second CEOF mode of (a) SSTA, and (b) SSHA. Variance contributions are 16 and 20%, respectively. Contour intervals are 0.5 °C and 3 cm. Negative anomalies are shaded.
Fig. 12. As in Fig. 9 but for the first CEOF mode of (a) SSTA and (b) SSHA. Variance contributions are 70 and 45%, respectively.

varies by about 0.5 °C during ENSO events. Since the interannual variation in the simulated thermocline depth along the equator is comparable to that of observation, this result appears to be strange. The model bias that the seasonal variation of SSTA associated with the annual ENSO mode is mostly restricted to the south of the equator may explain this, as the change associated with the interannual ENSO mode is strongest along the equator. This again suggests the importance of improving the spatial distribution to reproduce the realistic interaction between the annual ENSO mode and the interannual ENSO mode. On the other hand, the amplitude of the simulated interannual ENSO mode is in accord with observation, although the simulated one is superposed with stronger semi-annual signal.

We note that the variance contribution of two modes is different between SSTA and SSHA (Table 1). For the SSTA, the first CEOF mode that corresponds to the annual ENSO mode explains 70% of the total variance, whereas the second mode that corresponds to the interannual ENSO mode explains only 16% of the total variance. This is in accord with data analysis using HADISST (Rayner et al., 2003); the annual ENSO (interannual ENSO) mode explains 74% (14%) of the total variance during 1980–1999 (see TY03). For the SSHA, the annual ENSO mode appears as the first CEOF mode in the model and explains 45% of
The total variance, whereas the interannual ENSO mode explains 20% of the total variance as the second CEOF mode. This shows quite a contrast with the analysis using the SODA, where the first (second) CEOF mode is the interannual (annual) ENSO mode and explains 44% (15%) of the total variance for the period of 1980–1999 (see TY03). The interannual ENSO mode is also the first mode even for the period of 1958–1975, during which the amplitude of ENSO was much weaker compared to the recent period. The result presented here suggests that ocean dynamics has too much influence on the simulated annual ENSO, as expected from the large seasonal SSHA variations revealed in Fig. 4.

The above interaction between annual ENSO mode and interannual ENSO mode also varies decadely. The ratio of the former to the latter, which is calculated by applying CEOF analysis to the SSTA of different 20-year period varies from 3.1 to 6.7 (Table 2). Periods with low ratio are associated with strong ENSO events, and two strong El Niño events that are comparable in strength with the 1997/98 El Niño occurred during the period showing
Fig. 14. Time-series of the Niño 3 SSTA reconstructed from the first CEOF mode (thin solid line) and the second CEOF mode (thick solid line) for (a) HADISST and (b) SINTEX-F1 model.
Table 1

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Table 2

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the lowest ratio. A similar feature was discussed in TY03, but its robustness was limited by the short duration and sparseness of the observation. The present model suggests that the decadal change in two modes of ENSO can occur as a result of natural variability. In contrast to observation (e.g., Wallace et al., 1998; Wang and An, 2001), however, no significant change in the propagation characteristics of ENSO is detected in the model. This is partly due to too weak equatorial SSTA associated with the annual ENSO. This further stresses the importance of simulating the annual cycle in CGCMs to reproduce the ENSO events.

5. Conclusions

Using the output from 200-year integration of the SINTEX-F1 ocean–atmosphere coupled model, we have investigated how the annual ENSO is simulated in the model. Many features of the annual ENSO, such as the classical El Niño that initiates the air–sea interaction in the eastern equatorial Pacific, the westward expansion of the SSTA, the westward propagation of SSHA along 5°N, are reproduced well in the model. However, the meridional expansion of the SSTA to the north of the equator in the eastern tropical Pacific is not well reproduced. The semi-resonant condition between the westward propagating zonal wind stress anomaly and the off-equatorial Rossby wave is not well simulated. We have suggested that this model bias is due to the excitation of the too strong Rossby waves in the Southern Hemisphere, which reflects at the western boundary as the Kelvin waves and intrudes into the eastern equatorial Pacific. One possible remedy is to improve convective scheme and the stratus cloud effect. Either resolving or parameterizing the tropical instability waves (e.g., Legeckis, 1977; Masina and Philander, 1999) may provide us with another possible remedy by enhancing the horizontal mixing along the northern flank of the SSTA.
The amplitude of SSTA of the simulated annual ENSO mode changes with the maximum difference of only 0.2°C. Although the modulation is statistically significant, it is about 20% of the observation. This weaker amplitude modulation is due to not only the lack of northward migration of the seasonal SSTA in the equatorial region, but also the weaker coastal Kelvin wave propagating along the coast of South America. The model is successful in reproducing decadal change in the relative contribution of the two modes as well as the amplitude of ENSO events. However, no significant change in the ENSO propagation characteristics is simulated. This again seems to be due to too weak equatorial SSTA associated with the annual ENSO. Finally, more ENSOs in the model reach their maximum during boreal spring in contrary with observation. We suggest that the model bias in wind and oceanic upwelling associated with the annual ENSO is one of the main reasons for this loose phase-locking. Therefore, the present analysis suggests the importance of reproducing the annual ENSO realistically and its interaction with interannual ENSO to simulate the ENSO variability. Future models resolving the annual ENSO more faithfully will enhance ENSO predictability; the present work is the first step toward the goal by analyzing a CGCM result with the new viewpoint presented in TY03.

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References