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The characteristic oscillation induced by coupled processes between oceanic vertical modes and atmospheric modes in the tropical Pacific

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Abstract. An intermediate coupled model (ICM) based on an ocean model with three vertical modes and a statistical atmosphere model was used to investigate the relationship between the dominant modes of variability in the ocean and the atmosphere in the Tropical Pacific. Tests on sensitivity to the oceanic vertical structure of the ocean show that the time scale of variability in the sea surface temperature anomaly (SSTA) mainly depends on the relative contribution of the baroclinic modes. The first two atmospheric modes, i.e. the central and 'off-equatorial' modes, play different roles in modulating the impact of oceanic baroclinic modes on SST changes through coupled processes. In the model, the central mode excites the second oceanic mode which drives the observations-like interannual variability in the model. The atmospheric off-equatorial mode, on the other hand, favors the gravest baroclinic mode through the forcing of Rossby waves and consequently shortens the frequency of SSTA variability in the tropical Pacific. This suggests a possible mechanism governing time modulation of the El Niño events characteristics in the tropical Pacific.

1. Introduction

From recent modeling and observational studies, there is increasing evidence that the vertical structure of the low frequency variability found in the tropical Pacific ocean cannot be reduced to a single mode, i.e. the first baroclinic mode [*McPhaden*, 1999; *Delcroix et al.*, 2000]. From a forced OGCM simulation, *Dewitte et al.* [1999] showed that the zonal current anomaly in the eastern Pacific is mostly controlled by the second baroclinic mode whereas the first baroclinic mode is the largest in the west Pacific. Both contributions are also quite weakly correlated over most of the basin. *Delcroix et al.* [2000] compared observations with multi-mode linear simulations and note a much better agreement for sea level and zonal current anomalies derived from altimetry when more than one baroclinic mode is used. In a coupled context, *Dewitte* [2000] (Hereafter D0) showed that the ocean's vertical structure could also determine the time-scales of the variability in sea surface temperature anomalies [hereafter, SSTAs] in the tropical Pacific. To demonstrate this, he used an intermediate ocean-atmosphere coupled model including three oceanic vertical modes for the oceanic component and a dynamical *Gill* [1980]'s atmospheric model. Such a result is model-dependent and his study focuses on the oceanic part only knowing the limitations implied by the use of a dynamical atmosphere such as *Gill* [1980] [cf. *Dewitte and Périgaud*, 1996]. Further investigation of such sensitivity in other coupled models is required. It also raises the issue of the specific role of atmospheric variability modes in these models. This is what we aim to address in this paper through an intermediate ocean-atmosphere coupled model of similar complexity to the one used in D0, except that the atmospheric component is a statistical model. With a statistical atmosphere, one can differentiate the dominant modes of variability in the atmosphere and assess their role in the coupled model variability.

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2. Model description

The model developed in this study (named ICM) can be regarded as an extension of the *Cane and Zebiak* [1987] model (hereafter ZC model). It includes three vertical baroclinic modes with characteristics of phase speed C_n (n=1,2,3), projection coefficient P_n (see Table 1 for definition) and frictional time scale γ_n. We chose $\gamma_n \sim C_n^{-q}$ with q=0.5, which allows vertical separation [*Gent et al.*,1983]. The parameter values for this model are given in Table 1. The values for C_n and P_n are derived from the vertical mode

Table 1. Parameter values for the ocean model. $F_n(z)$, the vertical structures for the baroclinic modes, are derived from a density profile of Levitus data along the equator (0°N,160°E-140°W).

	n=1	n=2	n=3
Phase speed(m/s): C_n	2.68	1.6	1.1
Projection coefficient: P_n	0.58	0.52	0.17
$P_n = \frac{150}{\int_{-H}^{0} F_n^2(z)dz}$			
Frictional coefficient (in months): γ_n	30	23	18

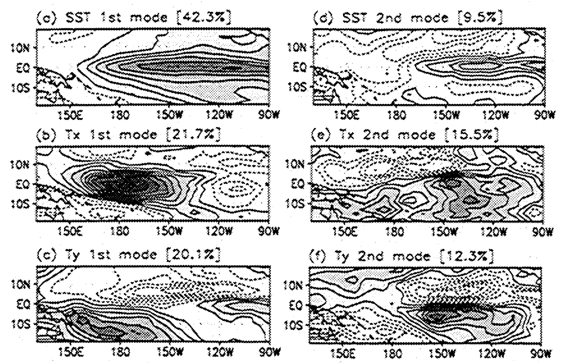

Figure 1. First (a), (b), (c) and second (c), (d), (e) SVD eigenvectors for SST, zonal wind stress and meridional wind stress anomalies. Values are standardized by their respective variance. The variance is indicated on top of each panel. The contour interval is 0.01. Shading indicates anomalies higher than 0.

decomposition of a mean density profile in the central equatorial Pacific from Levitus data. These values are very close to the value chosen in D0 (see Table 1). Also, ICM has a parameterization for the temperature of the subsurface water entrained into the ocean mixed layer following *Dewitte and Périgaud* [1996]. The basic state of the ocean current is obtained by spinning up the ocean model using the Florida State University monthly-mean wind stress averaged for the 1979-1998 period.

The atmosphere part is a statistical model based on the singular value decomposition (SVD) of SSTAs and wind stresses over 37 years from January 1961 to December 1997. The model is the one used by *Kang and Kug* [2000] for El Niño predictions. Fig. 1 shows the first and second modes of SVD vectors between SSTAs and zonal stress. The first (second) mode explains 80.8% (10.1%) of the covariance between the SST and the winds. The first (second) mode explains 42.3% (9.5%) of the SST variance over the domain, 21.7% (15.5%) for the zonal stress and 20.1% (12.3%) for the meridional stress. As expected, the spatial structure of the first mode has the largest variability in the central and eastern Pacific and that of zonal wind stress reveals its maximum variability near the dateline (Fig. 1a, b). We shall call this mode the 'central mode'. The second SVD mode has a SST pattern trapped near the equator. For the zonal wind stress, it is a combination of symmetrical and antisymmetrical patterns about the equator in the central Pacific because amplitude is larger in the North (~7°N) than in the South (~7°S) with a passing to zero at the equator. The projection of this mode onto a gaussian curve with meridional scale of the order of $L \sim (c_1/\beta)^{1/2}$ km with $c_1 = 2.68$ ms^{-1} (i.e. the Kelvin wave structure of the first baroclinic mode) is very weak in the central Pacific (not show) indicating that this mode mostly forces Rossby waves (of uneven and even meridional mode numbers). In the eastern basin, the Kelvin wave contribution is larger. This will be further discussed in the last section. Note that the pattern associated to the meridional wind second SVD mode is mostly antisymmetrical about the equator. We shall refer to the wind stress second SVD mode as the 'off-equatorial mode' although, in the literature, it is usually called 'the coastal mode' because of the SSTA pattern. The reader is invited to refer to the study by *Cassou and Périgaud* [2000] for an other estimation and description of these SVD modes.

3. Model variability and sensitivity to the oceanic vertical structure

In this section, we briefly describe the model's variability and sensitivity to the configuration of the oceanic vertical structure. A 100-year extended simulation was carried out starting from the initial condition obtained in a forced mode (corresponding to January 1967). We arbitrarily selected the 40-year period after the first 10 years of the simulation to derive the dominant frequency of SSTAs. Figs. 2a and 2b show the equatorial SSTAs from NCEP for 1980-1994 and those of ICM for an arbitrarily selected 15-year period. ICM supports free oscillations of SSTAs with features resembling the interannual variability observed in the equatorial Pacific climate system: it reveals oscillations at a 4-year period with large amplitude in the 140°W-110°W range during each warm and cold event. As pointed out in D0, the location of the SSTA variability peak is further west than that of the coastal-type El Niño simulated by the ZC coupled model. This is closely related to the difference in the setting of subsurface temperature parameter as discussed in D0. Note that the location of the SSTA variability maximum along the equator depends also on the statistical atmospheric model. The spatial and temporal characteristics of SSTAs are very similar to those found in D0 because of the similarity of the oceanic component. To further investigate the sensitivity of the model's variability to oceanic vertical structure, we carried out three experiments according to D0. The experiments differ in the way the mean upwelling of the anomalous temperature term is controlled by thermocline displacement $\delta\xi$. In Exp1, $\delta\xi$ is estimated from the contribution of the first baroclinic mode only. Similarly, Exp2 and Exp3 correspond to simulations where the contributions of the second and third baroclinic mode are included respectively (Table 2). The other terms of the SST equation are dynamically determined by the horizontal currents, themselves driven by the contribution of the three baroclinic modes. The three experiments led to SSTA oscillations with different periods: Fig. 3a shows the timeseries for the NINO3 SST index (SSTA averaged over the region of 150°W-90°W and 5°S-5°N). The spectral analysis of these timeseries indicates that Exp1 has a spectral peak at 2.0yrs and Exp2 at 4.0yrs. Exp3 presents periods longer than 10 years. Thus the period of the oscillations increases with the order of the baroclinic mode. Although the atmosphere model was different, this result is similar to D0 which shows that the vertical modes control the time scales of variability of its model. The vertical structure determines the relative

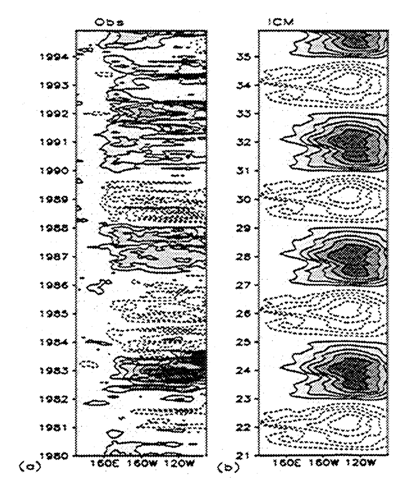

Figure 2. Time-longitude contours of simulated equatorial SST anomalies for (a) the NCEP reanalysis, (b) ICM (Unit is °C, contour interval of 0.5°C). Shading indicates anomalies higher than 0.

Table 2. Experiment summary.

Name	Ocean configuration (baroclinic mode)	Atmosphere configuration (SVD mode)
Control Run	3 modes	2 modes
Exp.1	1st mode	2 modes
Exp.2	2nd mode	2 modes
Exp.3	3rd mode	2 modes
Exp.4	1st mode	1st mode
Exp.5	3 modes	1st mode
Exp.6	3 modes	2nd mode

contribution and timing of the zonal and vertical advections to SST changes and consequently determines the relative strength of the positive coupled instability feedback and the delayed oscillator negative feedback (cf. D0). Note that Exp2 produces the oscillation time scale of NINO3 SST in a frequency band close to that of the observations.

4. Experiment on sensitivity to the modes of atmospheric variability.

It is interesting to see how atmospheric modes can affect coupled processes through the contribution of the baroclinic modes. A recent study by *Cassou and Perigaud* [2000] suggests that the modes of variability in the atmosphere could drastically impact the tropical Pacific coupled system. In particular, in their intermediate coupled model that also uses a statistical atmosphere, the second SVD mode is necessary to sustain oscillations. Following their approach, we carried out Exp4 which is the same as Exp1 (the thermocline depth anomaly is only controlled by the contribution of the first baroclinic mode in the ocean) except that the off-equatorial mode (Fig. 1d) in the atmosphere is removed. Interestingly, and in keeping with their results, the model is not able to sustain oscillations, and the simulated SSTAs decay over time (see Fig3a). This, in particular, suggests that the off-equatorial mode has a specific effect on the first baroclinic ocean mode. In the next series of experiments, the ocean model included the contribution of the three-baroclinic modes. In Exp5, only the central mode was retained in the statistical atmosphere (Table 2). On the other hand, only the off-equatorial mode was used for Exp6 (both central and off-equatorial modes were used in the control run). The results of these experiments are presented in Figure 3b for the SSTAs averaged over the NINO3 region. Whereas Exp6 results in no oscillation, SSTAs for Exp5 reveal oscillations at a dominant 5-year period. This indicates that the first SVD mode is needed to induce ENSO-like variability in the model and that the second SVD mode is not by itself able to sustain oscillations. This is due to the fact that the off-equatorial mode cannot force energetic Kelvin waves in the central Pacific because of its meridional structure, unlike the central mode. Note that in the eastern basin, there should be a contribution from Kelvin waves because SVD mode 2 is relatively large along the equator. However this contribution is weaker than the one induced by SVD mode 1. Secondly, the results of Exp4 and Exp5 suggest that the central mode excites the higher-order baroclinic modes. As a consistency check, we carried out two experiments where the atmosphere is solely determined by the central mode and thermocline displacements are determined by the contribution of the second and third baroclinic modes, respectively. Unlike Exp4, where the model is not able to sustain oscillations, these experiments reveal ENSO-like

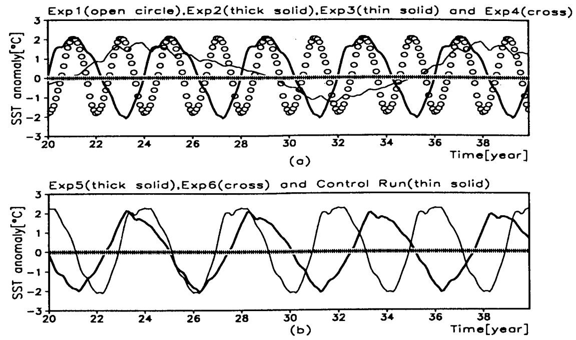

Figure 3. Time series of SSTAs averaged over the NINO3 region for (a) Exp1(thin solid), Exp2(thick solid), Exp3(closed circle) and Exp4(cross), (b) Exp5(thick solid), Exp6(thin solid) and the Control run(cross).

oscillations at different periods (not shown). Fig4 displays the differences in amplitude of the spatial structures for the first EOF modes of baroclinic contributions to thermocline displacements between Control run and Exp5. The associated timeseries for the EOFs were standardized so that the amplitudes of the spatial structures are comparable. The figure shows that the second and third baroclinic mode contributions are of a similar amplitude for both simulations. On the other hand, for the first baroclinic mode, we find relatively large differences in amplitude between the Control Run and Exp5 over the whole basin. After investigation, it was revealed that they mostly correspond to differences in the Rossby wave component. These results indicate that the central mode (SVD1) in the atmosphere preferentially excites the second and third baroclinic modes. The off-equatorial mode increases the Rossby wave contribution of the first baroclinic mode. Note that the EOF analysis also reveals the 9-month resonant mode associated with the first baroclinic mode contribution (see *Périgaud and Dewitte* [1996] for a detailed description of this mode). It explains 6.3% of the variance in the Control Run and 4.2% in Exp5, indicating that it is fostered by the off-equatorial mode. These results can be interpreted in terms of ocean wave dynamics: the central mode with a symmetrical structure to the equator favors the forcing of Kelvin waves and first-meridional mode Rossby waves. In addition, the higher the oceanic mode order, the finer the meridional scale. Thus, for the same input of wind stress forcing, the larger the amplitude of the forced Kelvin

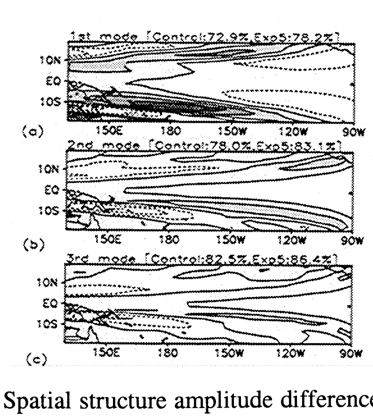

Figure 4. Spatial structure amplitude differences for the first EOF modes of (a) the first (b) the second and (c) the third baroclinic contributions to thermocline displacements. The modes are standardized so that the maximum of the associated timeseries is 1. The percentage of explained variance is indicated on top of each panel for the Control Run and Exp5. The contour interval is 0.01. Shading indicates anomalies higher than 0.

wave in the ocean. On the other hand, the off-equatorial mode tends to force the Rossby wave component because of its meridional structures (symmetrical and antisymmetrical about the equator) in the central Pacific. In the eastern Pacific, forcing of Kelvin waves rapidly give birth to Rossby waves through reflections at the eastern boundary. Such forcing favors the dominance of the first baroclinic mode over the second baroclinic mode because the higher-order modes propagate slower and consequently dissipate faster. In particular, the 9-month resonant mode associated with the first baroclinic mode is enhanced. In keeping with the results of section 3, increasing the relative contribution of the first baroclinic mode tends to change the period of SSTA variability in the tropical Pacific towards higher frequencies.

5. Discussions and conclusions

In this study, an intermediate coupled model for the tropical Pacific was developed on the basis of the ZC model. The ocean component is a three-mode model and includes changes in the parameterization of subsurface temperature and the basic states according to D0. In addition, the atmosphere part is replaced by a statistical model based on the SVD of SST and wind stress anomalies. ICM reproduces free oscillations at a dominant 4-year period, which resemble observed inter-annual variability over the tropical Pacific. Results of tests on the model's sensitivity to oceanic vertical structure are consistent with the results of D0, namely that the vertical structure affects the variability time scales in the model, with a power spectrum for SSTAs in the tropical Pacific shifting towards longer periods when the contribution of the higher-order baroclinic modes increases. In the present model, the baroclinic modes impose specific frequencies (f) for SSTAs, i.e., biennial ($(2\text{yrs})^{-1}<f<(3\text{yrs})^{-1}$) for the first baroclinic mode, interannual ($(3\text{yrs})^{-1}<f<(5\text{yrs})^{-1}$) for the second mode and interdecadal ($f<(10\text{ yrs})^{-1}$) for the third one. We investigated the impact of variability modes in the atmosphere on the oceanic baroclinic modes. This is possible using a statistical atmosphere which includes the first two SVD modes: the central mode and off-equatorial mode. The central mode favors the dominance of the second baroclinic mode in coupled processes, which will then tend to set the dominant period of variability between 4 and 5 years, like the observations. Because of its spatial characteristics, the atmosphere's off-equatorial mode does not force energetic Kelvin wave in the central Pacific (it does in the eastern Pacific) and is not by itself able to produce SSTA oscillations. It does, however, favor the contribution of the first baroclinic mode over second baroclinic mode through the contribution of Rossby waves. It consequently tends to change the period of SSTA variability towards higher frequencies. Note that SVD mode 2 is sensitive to the period over which it is calculated (see also Figure 10 in *Cassou and Périgaud* [2000]) which may alter the results about the impact of SVD mode 2 presented in this paper. In particular its ability to force Kelvin wave may be enhanced. Also *Cassou and Périgaud* [2000] find that SVD2 is responsible for lengthening the period of the SSTA variability of their model, because of the westerlies located in the eastern Pacific which grow a coupled mode with the anomalous vertical heat advection more than in the central Pacific (where the SVD1 westerlies are located). So, rather than shortening the period because SVD2 enhances the first baroclinic mode Rossby waves that erode the growing event, SVD2 in their case enhances the growth of the warm events that last longer. Opposite conclusions are reached because the strength of our coupling in the eastern equatorial Pacific is weaker than in the off-equatorial central Pacific unlike their model.

In the light of these results, we propose a mechanism by which the spatial and temporal scales of variability in the tropical Pacific can interact and lead to a broadband spectrum for SSTA fluctuations. The central mode favors the contributions of the second modes in the ocean and is then associated with inter-annual variability. The off-equatorial mode has a much smaller impact on the higher-order ocean modes, presumably because this off-equatorial mode favors Rossby waves which dissipate faster for the higher-order modes. This fosters the coupling of this mode with the gravest baroclinic mode, tending to change the period of SSTA variability towards higher frequencies (i.e., mostly biennial in this model). Considering that atmospheric teleconnections between the midlatitudes and the tropics are more likely to project onto the less 'robust' off-equatorial mode, this study offers a hint on how the tropical variability could be influenced by atmospheric fluctuations of the midlatitudes. This is currently under investigation.

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