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Interactions between the seasonal cycle and the southern oscillation - frequency entrainment and chaos in a coupled ocean-atmosphere model

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Abstract. Nonlinear interactions between the seasonal cycle and interannual variations in the coupled ocean-atmosphere system have recently been proposed as the cause of irregularity of El Niño - Southern Oscillation (ENSO). We investigated such a hypothesis using a coupled ocean-atmosphere model which allows coupling between total sea surface temperature (SST) and total surface winds. Numerical simulations indicate that the model is capable of capturing the essential SST variability on seasonal-to-interannual time scale. Furthermore, it is shown that, as the seasonal forcing amplitude is gradually increased from zero, the coupled model undergoes several transitions between periodic (frequency-locking) and chaotic states before it finally 'gives up' its intrinsic ENSO mode of oscillation entirely and acquires the frequency of the seasonal forcing. Chaotic response is found as the forcing amplitude approaches the observed value and the route to ENSO chaos is identified to be the period-doubling cascade. The study suggests that the response of a coupled system, coupled General Circulation Models of the ocean and atmosphere for example, can be very sensitive not only to changes in the internal model parameters but also to changes in the external forcing conditions.

Introduction

Studies have shown that the seasonal and interannual oscillations in the tropics not only have comparable amplitudes, but also are intimately related. Rasmusson and Carpenter [1982] showed that the evolution of ENSO episodes appears to be phase locked with the seasonal cycle. On the other hand, the strength of the SST annual cycle in the eastern Pacific is regulated by ENSO [Gu and Philander,1994]. Recent investigations [for example, Latif and Graham, 1992] have further suggested that the seasonal cycle is a critical and inseparable component of interannual variability and thus may have an important bearing on the predictability of interannual variability.

Many models of ENSO are coupled ocean-atmosphere models that the specify seasonal cycle and that allow only coupling between anomalous sea surface temperature and surface winds [for example, Zebiak and Cane, 1987]. The oscillatory behavior of ENSO in these models can be understood as a delayed oscillator mechanism in which equatorially trapped waves play a crucial role in maintaining the continual oscillation of the system by delaying the oceanic response to local wind forcing [Suarez and Schopf, 1988, Battisti and Hirst, 1989]. Although the delayed oscillator theory provides a plausible explanation for the cyclic nature of the phenomenon, it fails to explain its irregular characteristics. Recently, two independent studies [Jin, et al., 1994 and Tzipermen, et al., 1994] have proposed that the irregularities can be viewed as a low-order chaotic process driven by the seasonal cycle. Although the two studies use different models, they take a similar approach to examine the transition to chaos as the nonlinearity of the system is increased while the seasonal cycle is specified. Both studies have discovered a quasiperiodic route to chaos that depends on the overlap of phase locking resonance.

In this study, we examine ENSO irregularity with a more complete coupled ocean-atmosphere model that itself determines the seasonal cycle in response to forcing. The coupled model is forced by surface heat fluxes primarily controlled by the annual variation of solar radiation. Total, rather than anomalous, surface winds and SST fields are coupled. This coupling approach allows full interaction between the seasonal cycle and interannual oscillations. Thus, the model includes more realistic physics and is one step closer to more sophisticated coupled GCMs. We explore the dynamical behavior of the coupled system as a function of the intensity of the seasonal forcing.

Model Description

The coupled atmosphere-ocean model used in this study consists of a new atmospheric component recently developed by Li and Wang [1994]. When forced with the observed SST, the model realistically simulates both interannual and annual variations of the surface winds. The oceanic component is a Cane-Zebiak type model [Zebiak and Cane, 1987] which has been modified by Chang [1994] to include surface heat flux forcing for predicting changes in total SST field. The model is shown to be capable of capturing the essential seasonal SST variability in the tropical Pacific when forced with the climatological surface winds and heat fluxes [Chang, 1994].

The atmospheric and oceanic components are coupled using a nonlinear relation between surface wind stresses and wind speeds, i.e., $(\tau_x,\tau_y)=\rho_0 C_d|V|(U,V)$, where C_d is the drag coefficient of value 1.3×10^{-3}, and $|V|$ is the total wind speed. The external forcing of the model is from the monthly mean surface heat flux climatology of Esbensen and Kushnir [1981] (EK heat flux), which consists of short wave radiation, long wave radiation, and latent heat and sensible heat fluxes. The total surface heat flux is decomposed into six Fourier components so that their values at each time step can be precisely determined. Therefore, the heat flux forcing can be written as $Q=Q_m+A\sum_{n=1}^{6}Q_n$, where Q_m is the annual mean EK heat flux, Q_n is a Fourier component of seasonally varying

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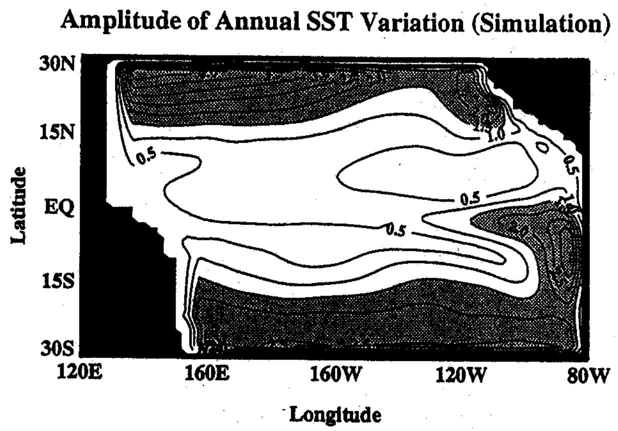

Figure 1. Amplitude of annual SST variation derived from a 130-year integration of the coupled model forced by the EK surface heat flux. The contour interval is 0.5°C and the regions where amplitudes are larger than 1.5°C are shaded.

EK heat flux and A is an adjustable coefficient which controls strength of the seasonal heat flux forcing. To prevent the model from drifting from its climatological mean state in long-term integrations, a constant annual mean heat flux correction was used. Its value is determined by integrating the coupled model for five years with the annual mean surface heat flux plus a Newtonian damping term $-\gamma(T-T_{mean})$, where γ is taken to be 1/30 days^{-1} and T_{mean} is the observed annual mean SST. A detailed description of the coupled model can be found in Chang et al. [1994].

Figure 1 shows the amplitude of the SST annual cycle derived from a 130-year integration of the coupled model with the EK heat flux, i.e., A=1. The amplitude of SST annual cycle in the model compares favorably with observations. In particular, the pronounced annual cycle of SST in the eastern Pacific cold tongue region is clearly captured by the coupled model. Figure 2 depicts two leading empirical orthogonal function (EOF) modes of the simulated SST anomaly. These modes which represent spatial structure of the model ENSO cycle bear a striking similarity to the observed modes (not shown), except that they appear to be too narrowly confined near the equator. A more detailed assessment of the model performance is given in Chang et al. [1994]. In general, the coupled model gives a satisfactory description of the seasonal cycle and ENSO variability in the tropical Pacific.

Numerical Experiments

To explore nonlinear interactions between the seasonal cycle and interannual oscillations, we conducted a large number of numerical experiments in which we gradually increased the amplitude A of the seasonal forcing. Each simulation consists of a 130-year integration commencing from an equilibrium state obtained by integrating the model for five years with the observed annual mean heat flux. Power spectra and the phase portraits of SST are based on the daily SST time series of the last 90 years model integration taken from 0°, 120°W in the model ocean.

In the absence of the seasonal forcing, i.e., A=0, the coupled model exhibits a regular, but non-sinusoidal oscillation with a period of 40 months. The power spectrum of SST (figure 3a) shows this fundamental frequency

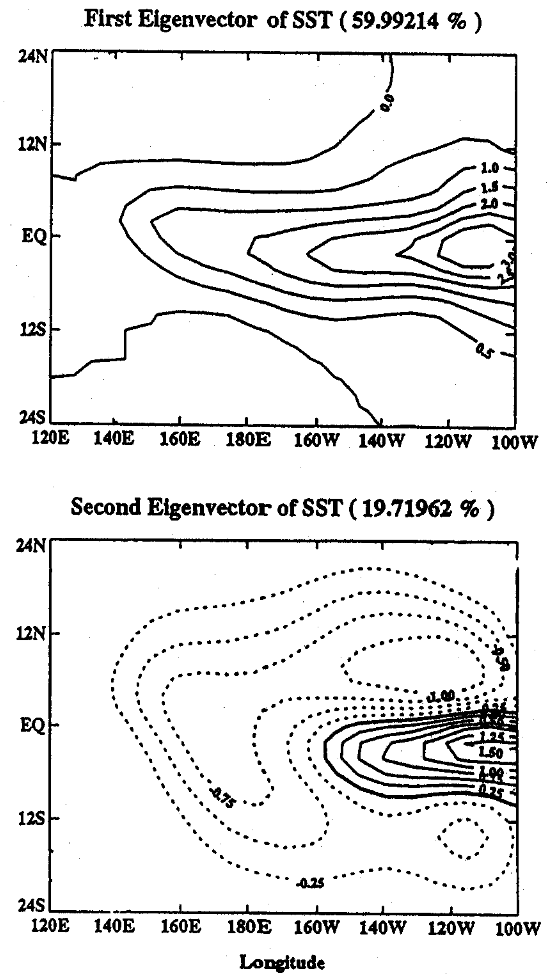

Figure 2. First two leading EOFs of simulated SST anomaly derived from a 130-year integration of the coupled model forced by the EK surface heat flux. Contour interval is 0.5°C in the first EOF and 0.25°C in the second EOF.

f_0=0.025 (months^{-1}) along with higher harmonics at integral multiples of the fundamental. The SST phase portrait reconstructed by the method of time delays [Pachard, et al., 1980] reveals a single period limit cycle. The physical mechanism responsible for maintaining the regular ENSO cycle of the model appears to be the "delayed-oscillator" which has been studied extensively by a number of investigators [Suarez and Schopf, 1988, Battisti and Hirst, 1989].

When the forcing amplitude is very small (A<0.025), the seasonal cycle has little effect on the model ENSO cycle. The model maintains its regular oscillation with a period of 40 months. As the forcing amplitude is increased to above 0.05, the periodicity of the model ENSO cycle doubles and a frequency component of $f_0/2$ peaks in the power spectrum (figure 3b). Increasing the forcing amplitude causes the subharmonic peak at $f_0/2$ to grow until a second period doubling occurs when A reaches about 0.064 (not shown). Higher values of A lead to further bifurcations and eventually to chaotic behavior (figure 3c). This route to chaos through a sequence of period doublings is clearly illustrated in terms of phase portraits of the model SST and the corresponding power spectra in figure 3a-c.

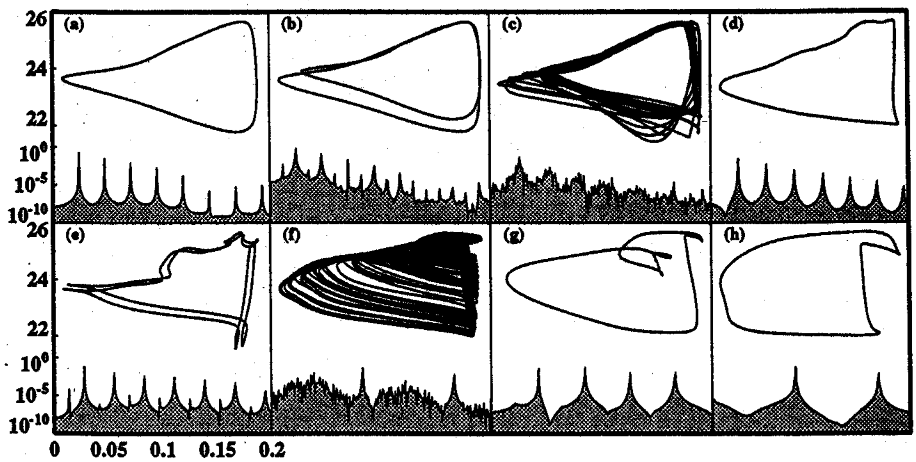

Figure 3. Phase portraits (upper) and power spectra (lower) of the model SST in the eastern equatorial Pacific (0°, 120°W) for various values of the seasonal heat flux forcing amplitude A. The phase portraits are reconstructed using the method of time delay. The delayed time is determined by auto-correlation analysis. The power spectra are shown in log-linear plots and the frequency is in units of cpm.

As the forcing amplitude is further increased to above A=0.1875, the model SST oscillation abruptly becomes regular again. However, the period of the oscillation shortens to 3 years (36 months) and the model ENSO cycle appears to be frequency locked with the seasonal cycle, in the sense that the model ENSO frequency remains unchanged while the forcing amplitude is varied over a limited range of 0.1875 <A<0.5. Within this frequency locking regime, the frequency ratio of the model ENSO cycle and annual cycle keeps a low order rational number of 1/3. Figure 1d gives an example of the power spectrum in the frequency locking regime (A=0.2). In contrast to figure 3c, sharp spectral peaks with no background noise and a single period limit cycle are observed.

A further increase of the forcing amplitude leads to another sequence of period doublings and eventually to chaos (Figure 3d-3f). The chaotic oscillations occupy a relatively wide range of 0.575 <A<1.05. Within this large chaotic region, power spectra of SST all display broadband structures and contain substantial power at low frequencies. In particular, when the forcing amplitude takes the observed value, i.e., A=1.0, the peaks of interannual oscillations are so broadened and the spectrum contains so much noise that it becomes nearly featureless, as in figure 3f. The only distinguishable peaks are at annual and semi-annual frequencies which correspond to the two dominant forcing frequencies. The existence of a strange attractor at A=1 is revealed by the phase portrait shown in figure 3f.

Beyond the large chaotic region, an interval (1.05 < A < 1.27) of frequency locking regime appears again. The regular oscillations manifest themselves as sharp peaks in the power spectra (figure 3g), but the dominant frequency of interannual oscillations shifts once again from 1/36 (months^{-1}) in the previous frequency-locking regime to 1/24 (months^{-1}). For A>1.27, the model interannual oscillation frequency is completely "entrained" by the forcing frequency and the system acquires the frequency of the seasonal forcing (figure 3h). The regular annual cycle is represented by a single-period limit cycle in the phase diagram. The phenomenon by which a self-exciting oscillator 'gives up' its intrinsic mode of oscillation in the presence of strong external forcing is known as "frequency entrainment". The frequency entrainment phenomenon found in this coupled system, in many ways, resembles the characteristic of some self-exciting systems, such as the forced van der Pol oscillator [see Jackson,1990, for an overview], even though the physics involved is much more complicated.

Discussion

This study demonstrates that the coupled ocean-atmosphere system is not only sensitive to changes in conditions that determine the internal processes of the system, but also sensitive to changes in the external forcing condition. Depending on the parameter regime, the coupled system could change from a periodic state to a chaotic state or completely abandon the natural mode of oscillation for a small change in the external forcing condition. Whether our coupled ocean-atmosphere model reflects the sensitivity of the real ocean-atmosphere system is an open question that will require calculation with more realistic models, specifically coupled GCMs. A few such models are being developed and at present they behave in perplexingly different ways. Some reproduce a reasonable seasonal cycle but have practically no interannual variability. Others perform reasonably well when forced with the annual mean, but not when forced with the seasonally varying solar radiation. Our results shed light on the difficulties being encountered with these coupled GCM's. What matters is the relative amplitudes of the interannual and seasonal oscillations. Suppose that a coupled GCM is in a parameter range where, with steady forcing, it reproduces only a weak Southern Oscillation. In that case the introduction of strong seasonal forcing could completely inhibit the interannual variations. Alternatively, if a model reproduces clouds poorly then it misrepresents the albedo of the earth and in effect misrepresents the amplitude of the seasonal forcing. In this respect the low stratus clouds off the coast of Peru and California pose a problem because they reflect a considerable amount of sunshine but are difficult to capture in models because they form in a thin layer near the surface. It is conceivable that a change in the treatment of clouds in a model could change its behavior from that of one of the panels in figure 3 to another panel.

The present study along with previous works by Jin et al [1994] and Tziperman et al [1994] have proposed that the ENSO irregularity can be viewed as a low-order chaotic process driven by the seasonal cycle. Others [see Penland and Sardeshmukh, 1994 for references] have argued that irregular recurrence of ENSO could be primarily due to stochastic processes in the coupled atmosphere-ocean system. Clearly, there is a need for further investigations to understand the relative importance of chaotic versus random processes in the evolution of ENSO. Because of the nonlinearity of the system involved, the familiar tool of Fourier analysis has little use in distinguishing between chaotic and stochastic processes from observed time series. Identifying chaos from observation requires evaluating invariant properties of the dynamics such as dimensions, Lyapunov exponents, and topological characteristic. This may pose a difficult task simply because the available instrumental record of the real ENSO data currently is too short to be accurately used with the techniques developed to analyze chaotic behavior of a system directly from time series. However, further understanding of the dynamic properties of the ENSO system can be gained by experimenting coupled ocean-atmosphere models of different complexity with and without random forcing. Such a modeling effort is being undertaken and the results will be presented in subsequent papers.

This study represents a first step to properly address the interaction between the seasonal cycle and the ENSO variability by forcing a coupled ocean-atmosphere model externally to generate both a seasonal cycle and the ENSO mode. Although this study represents a more rigorous examination of the interaction between the seasonal cycle and the ENSO variability than the previous works by Ji et al. [1994] and Tziperman et al. [1994], the problem is yet to be completely solved. In the present study, only the dynamic feedbacks are included and the thermodynamic feedbacks are excluded by specifying the latent and sensible heat fluxes in the surface forcing. These fluxes depend crucially on the air-sea boundary conditions which ought to be predicted by the model. At present, the role of the thermodynamic feedback processes on seasonal-to-interannual variability is not clear. To address this issue, future works are needed to improve the model heat flux formulation.

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