Decadal Modulation of ENSO in a Hybrid Coupled Model

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ABSTRACT

Decadal variations in the amplitude of El Niño and the Southern Oscillation have been the subject of great interest in the literature for the past decade. One theory suggests that ENSO is best described as a stable system driven by linear dynamics and that stochastic atmospheric forcing is responsible for the development and modulation of ENSO on interannual as well as decadal time scales. Another theory suggests that ENSO is driven by strong nonlinear coupled feedbacks between the ocean and atmosphere and low frequency changes in ENSO amplitude are driven by decadal changes in the tropical Pacific mean state. Unfortunately, the observed record is too short to collect reliable statistics for such low frequency behavior. A hybrid coupled model composed of a simple statistical atmosphere coupled to the Poseidon isopycnal ocean model has been developed for the study of ENSO decadal variability. The model simulates realistic ENSO variability on interannual and decadal time scales with negligible climate drift over 1000 years. Through analysis and experimentation the authors show that low frequency changes in the atmospheric “weather noise” drive changes in the tropical Pacific mean state leading to changes in the amplitude of ENSO on decadal time scales. Additional model simulations suggest that, while predictability is limited by the presence of atmospheric noise, there are extended periods when the coupled instability, strengthened by changes in the mean state, is insensitive to noise on interannual time scales.

The relationship between decadal modulation of ENSO and mean state changes resides somewhere between the linear damped stochastically forced theory and the strongly unstable theory. Unlike the strongly unstable system, changes in ENSO amplitude on longer time scales are determined by the stochastic forcing. The stochastic forcing is not necessary in this model to sustain ENSO; however, its presence is crucial for low frequency changes in the mean state of the tropical Pacific. The strong relationship between the mean state and ENSO amplitude modulation in the model is in opposition to the linear damped stochastically forced theory. The fact that changes in the tropical Pacific mean state lead directly to changes in ENSO amplitude and predictability has positive implications for predictability.

1. Introduction

El Niño and the Southern Oscillation (ENSO) make up a phenomenon originating in the tropical Pacific that affects the climate over a large part of the globe. While ENSO is the largest climate signal on interannual time scales, there is also low frequency variability in the amplitude of ENSO. Decadal shifts in the amplitude and frequency of ENSO have led to the hypothesis that ENSO statistics have changed over the last 100 years (Gu and Philander 1995; Wang 1995; Nitta and Yamada 1989; Trenberth 1990; Mitchell and Wallace 1996; Wang and Wang 1996). Irregularity in the behavior and predictability of ENSO on decadal time scales has lead to a debate in the climate community as to the processes responsible for ENSO development and variability.

Many scientists argue that ENSO can be characterized as a stable stochastically forced phenomenon and consider the decadal changes in ENSO amplitude...
[ENSO decadal variability (EDV)], frequency, and predictability a sampling issue associated with a random walk process. Others describe ENSO as an unstable self-sustained oscillation where decadal variability is due to changes in the underlying mean state in the tropical Pacific caused by dynamical processes in the tropics and/or the midlatitudes. For clarification, we define mean state changes in this study as the low-pass filtered (11-yr running average) of the state variable of interest (i.e., SST, wind stress, or thermocline depth), while ENSO decadal variability is defined by the 11-yr running variance of the SST anomalies in the Niño-3.4 region. To better understand both sides of this argument it is important to understand the different theories for ENSO growth and irregularity (variability).

The first theory relies on the importance of internal nonlinearity in the tropical coupled system and places little importance on stochastic processes (Zebiak 1989; Tziperman et al. 1994; Jin et al. 1994; Webster and Yang 1992). This nonlinearity arises from strong ocean–atmosphere feedbacks that cause a dynamically unstable coupled mode. This unstable mode can then interact with other modes, resulting in low-order deterministic chaos.

The second theory relies primarily on the stochastic forcing generated by the internal dynamics of the atmosphere (Penland and Sardeshmukh 1995; Ping et al. 1996). Here it is assumed that the coupling strength of the atmosphere–ocean system is weak and the system is stable. In this case not only does the external stochastic forcing from the atmosphere cause the irregularity of ENSO, it is the source of ENSO growth as well. Moore and Kleeman (1996), Kleeman and Moore (1997), and Moore and Kleeman (1999a,b) showed that there were so-called stochastic optimals, which represent the spatial patterns on which the stochastic forcing most efficiently causes variance growth within a dynamical system. Growth occurred owing to the nonnormality of the coupled system, which allowed for a limited-time superexponential growth.

The third theory relies on weak nonlinearity to sustain ENSO with stochastic forcing acting to disrupt an otherwise regular oscillation (Schopf and Suarez 1988; Battisti and Hirst 1989; Goswami and Shukla 1991; Eckert and Latif 1997; Blanke et al. 1997; Kirtman and Schopf 1998; Latif 1998). When ENSO is viewed as a weakly unstable mode, noise can be viewed as the limiting factor on an otherwise good prediction potential. The behavior of the system in this case is governed by the temporal characteristic of the single most dominant mode plus the stochastic forcing. While sufficient ocean wave dynamics and boundary reflection properties are required for self-sustained oscillations of the “delayed oscillator” mode, irregularity comes from the inclusion of stochastic wind forcing generated in the atmosphere (i.e., external to the coupled equatorial Pacific system). Irregularity in this case comes from the inclusion of stochastic wind forcing generated in the atmosphere (i.e., external to the coupled equatorial Pacific system) that interferes with the dominant mode leading to the type of irregularity seen in observations.

The debate concerning the decadal variability in ENSO amplitude can be understood when we consider these differing views for ENSO development and variability. Some researchers argue that the linear damped stochastically forced ENSO mechanism should be regarded as the null hypothesis for ENSO decadal variability (Flügel 1999; Thompson and Battisti 2001; Yeh et al. 2004; Flügel et al. 2004). Thompson and Battisti (2001) argue that a damped stochastically forced model does the best job of reproducing the observed ENSO statistics, though it is unclear how the result is affected by the simplified model physics in their intermediate coupled model (ICM). Flügel et al. (2004) found that the linear damped stochastically forced model of ENSO could not only reproduce the types of “shifts” observed in the mid-1970s but could also produce decadal variability in the predictability of ENSO. Since stochastic processes contain variability on all frequencies, it is consistent to conclude that the low frequency variability of ENSO is a response to the low frequency component of the noise forcing on the optimal growth patterns. Flügel et al. state that “the low frequency variations in ENSO prediction were not associated with any change in the underlying dynamics, but are only due to changes in the statistical characteristics of the spatial structure in the noise forcing.”

When we view ENSO as a system driven by unstable processes leading to regular or chaotic self-sustained oscillations, changes in the mean state become more important. That is, if we consider that there are low frequency changes taking place in the tropical Pacific where these unstable interactions take place, the ocean–atmosphere interactions may be influenced in such a way as to change the character of ENSO on longer time scales. The nature of these decadal changes in the tropical Pacific has been the subject of much research in recent years (Zhang et al. 1997; Garreaud and Battisti 1999). While the mechanisms responsible are still unclear, there are several theories that rely, to varying degrees, on the influence of ocean and atmospheric processes in the tropics and extratropics (Gu and Philander 1997; Kleeman et al. 1999; Barnett et al. 1999; Pierce et al. 2000).

Several studies have shown that purely tropical pro-
cesses can shift or influence the tropical Pacific mean state. Jin (2001) suggests that there are very low frequency modes associated with tropical decadal variability due to ocean–atmosphere interactions. If the internal coupled dynamics associated with ENSO is chaotic, then it will have decadal and longer time-scale variations (Münnich et al. 1991). Several authors have proposed that the inclusion of higher vertical and horizontal modes in the delayed oscillator can contribute to the decadal signal (Knutson and Manabe 1998; Jin 2001; Kirtman 1997). Schneider et al. (1999) showed that local wind may be factor in the low frequency variability in the tropical Pacific. An and Wang (2000) argued that the spatial structure of the “coupled mode” has low frequency changes that can lead to variations in the frequency and amplitude of ENSO events, although why the structure of the coupled mode changes is unclear. Again, how these low frequency changes relate to the secular changes in the amplitude and frequency of ENSO is unanswered. The literature suggests three theories concerning the relationship between ENSO decadal variability and decadal changes in the tropical Pacific mean state.

Kirtman and Schopf (1998) argued that the decadal variability of ENSO predictability in their intermediate coupled model was due to the fact that ENSO resides near the neutral stability boundary and external stochastic forcing can move it across this boundary. If the ocean dynamics move ENSO below the neutral stability boundary, the system is damped and predictability is reduced due to the increased sensitivity to the stochastic forcing. If the ocean dynamics move the model above the neutral stability boundary, the system is self-sustained and predictability is increased. The authors attributed the decadal variability in ENSO amplitude and predictability to relatively low frequency and small amplitude changes in the decadal average ocean state, but the source of these low frequency changes was unclear. Fedorov and Philander (2001) also attributed changes in ENSO frequency to small amplitude changes in the mean state. They analyzed how changes in the mean state could alter the properties of the most unstable mode. The authors found that, by changing the thermocline depth or the mean strength of the zonal wind stresses, the dominant coupled mode can migrate between a SST-mode regime, where entrainment of cold water across the thermocline is the controlling factor, to a delayed-oscillator-mode regime where thermocline fluctuations induced by equatorially trapped waves are a major factor in controlling SST change.

Using a coupled general circulation modeling strategy called an interactive ensemble strategy (Kirtman and Shukla 2002), Yeh and Kirtman (2004) found two important modes of tropical decadal variability. The first mode explains 41.6% of the tropical low-frequency variability, has the same structure as tropical Pacific decadal variability (TPDV), and is unrelated to low frequency variations of ENSO amplitude. The authors suggest that the first mode appears to be forced by the atmospheric noise, although precisely how the noise preferentially excites this mode remains undetermined. The second mode explains 10.6% of the variance and was found to be unambiguously related to the low frequency changes in ENSO variance, suggesting that there is a component of the ENSO variability that cannot be explained by the damped linear theory (assuming the linear operator remains fixed). Whether this mode is driven by the tropical Pacific mean state or is simply producing a nonlinear residual in the mean state is unclear.

The probability distribution function of ENSO-related SST anomalies is skewed to the positive (Burgers and Stephenson 1999; Jin et al. 2003; An and Jin 2000), which cannot be explained by linear theory with Gaussian white noise. The preference for stronger and larger warm events in recent decades (Fedorov and Philander 2000) supports this skewness in ENSO statistics. If we view ENSO as a nonlinear phenomenon, we must consider that decadal changes in ENSO may be an artifact of these nonlinearities. Timmermann et al. (2003) propose that ENSO events can grow until they reach a maximum intensity of El Niño, at which point a quick reset takes place and then small ENSO variations grow again. An and Jin (2000) argued that nonlinearities in the tropical heat budget and vertical and zonal advection act to increase the amplitude of warm events and decrease the amplitude of cold events. These asymmetries can lead to apparent changes in the tropical Pacific mean state by way of residuals in the statistics (Rodgers et al. 2004). Schopf and Burgman (2006) present a purely kinematic argument to explain the ENSO asymmetry and residual effect on the mean state without invoking changes in the stability of the coupled system. It is intended as an illustration of the kinematic effect of oscillating a nonlinear temperature profile with finite amplitude excursions that will cause the Eulerian time-mean temperature to rise (fall) where the curvature of the temperature is positive (negative) as the amplitude of the oscillations increases. They report that larger ENSO cycles lead to statistics that show a flatter, more diffuse, looking time mean thermocline purely by kinematic effects. The mechanism is extremely simple, relying on nonlinearity in the temperature field and an oscillating advective mechanism. It shows that a change in the statistics of the long-term mean temperature may be found even in the absence of diabatic effects.
In this study we reexamine the relationship between decadal changes in the tropical Pacific mean state and changes in ENSO amplitude. In the context of this study, “mean state changes” in the tropical Pacific are defined by the slowly varying (11-yr running average) state variable of interest while decadal changes in ENSO amplitude are defined by the 11-yr running Niño-3.4 variance. A tropically forced hybrid coupled model (HCM) comprising an empirical atmosphere and a complex global ocean model is presented. The advantages of using a hybrid coupled model include control of the “weather noise” forcing as well as a more complex oceanic response in multicentury integrations. Analysis of the control simulation establishes a relationship between changes in the tropical Pacific mean state and changes in ENSO amplitude. Next, experiments are conducted to test the relationship between mean state changes and changes in ENSO amplitude and simultaneously remove the uncertainty associated with ENSO residuals. The question of primary interest is, What is the nature of the relationship between the mean state and ENSO variability in the hybrid coupled model? One of the main conclusions of this study is that changes in the tropical Pacific mean state are responsible for changes in ENSO amplitude on decadal time scales, while the mechanism for these low frequency changes is the weather noise forcing.

The paper is organized as follows: In sections 2 and 3 we describe the hybrid coupled model used for this study and examine the behavior of the model with and without prescribed weather noise. In section 4 we establish a relationship between the mean state and changes in ENSO amplitude in the control simulation. In section 5 we conduct experiments with the hybrid coupled model to elucidate the nature of the relationship between the mean state and ENSO decadal variability and mechanisms responsible for mean state changes in the tropical Pacific. Conclusions and discussion are found in section 6.

2. Coupled model description and performance

Hybrid coupled models have been a valuable diagnostic tool in the study of ENSO for many years in that they allow the user to monitor the changes in model response to changes in simple empirical model forcings. Because we are interested in the ocean response to changes in atmospheric forcing, the model developed for this study incorporates a simple statistical atmospheric model coupled to the Poseidon isopycnal ocean model. The choice of a simple atmospheric model also reduces the computational expense in the multicentury simulations necessary to examine ENSO behavior on decadal time scales. The atmospheric component has no systematic internal variability, leaving all of the memory of the coupled system in the oceanic component. Coupling of the statistical atmosphere to the ocean is through the sea surface temperature anomaly in the Niño-3.4 region (10°S–10°N, 190°W–120°E); wind stress adjusts instantaneously in the atmospheric boundary layer. While this assumption holds for low frequency variability in the tropics, recent studies indicate that addition modes are important in defining the coupled part of the wind (Zavala-Garay et al. 2003). Our intent is to closely follow the methodology of the Kirtman and Schopf (1998) study for direct comparison of results. The incorporation of a more complex ocean model is meant to include important physical processes that are neglected by simpler models such as cold tongue physics, ventilated thermocline processes, and meridional overturning processes.

a. The atmospheric model

There are many ways to design a statistical atmosphere for the study of ENSO phenomena, with differing levels of sophistication. The purpose of the statistical atmosphere is to capture as much of the observed seasonal-to-interannual wind stress variability as possible while remaining highly simplified. The atmosphere is modeled as in Kirtman and Schopf (1998):

\[ \tau_x = \alpha(x, y)(\text{NINO3.4}); \quad \tau_y = \beta(x, y)(\text{NINO3.4}), \]

where Niño-3.4 is the sea surface temperature anomaly in the coupled model averaged over the Niño-3.4 index region (10°S–10°N, 190°W–120°E), and \( \tau_x \) and \( \tau_y \) are the zonal and meridional wind stress anomalies, respectively. The structure functions \( \alpha \) and \( \beta \) are independent of time and are externally prescribed in the coupled model simulations. The structure functions \( \alpha \) and \( \beta \), shown in Fig. 1, are determined by linearly regressing the observed time series of Niño-3.4 sea surface temperature anomalies from 1986 to 1996 onto monthly wind stress data derived from the European Centre for Medium-Range Weather Forecasts (ECMWF). The assumption of a spatially fixed atmospheric structure is supported by observations of the zonal wind stress anomaly, which is largely dominated by a standing oscillation.

The monthly mean wind stress data was computed from 4-times-daily ECMWF 1000-hPa wind analysis by the method described in Trenberth et al. (1990), though a constant drag coefficient \( C_D = 1.4 \times 10^{-3} \) was used. The use of surface winds stresses derived from ECMWF 1000-hPa winds and other data analysis systems over the ocean have been widely used in ocean
modeling studies (Huang and Shukla 1996; Carton and Huang 1994; Huang et al. 1995) with results similar to observations. The seasonal cycle of the ECMWF wind stress is applied globally to the ocean, while coupling is limited to within 30° of the equator in the Atlantic and Pacific basins using an 80-min time step and piecewise parabolic interpolation of the monthly fields. To avoid drastic differences in wind stress curl in the extratropics, a mask is applied to the coupling coefficient that decreases linearly from one at 20° to zero at 30°.

b. Weather noise

To create the atmospheric weather noise forcing in the model we use the same approach as Kirtman and Schopf (1998). This choice is motivated by the fact that we want isolate the impact of a more complex ocean model while using similar forcing. The purpose of using observed data is to capture atmospheric noise that has the temporal and spatial variability found in the observed wind stress. After removing the annual cycle from the ECMWF wind stress data, a 9-month running mean is applied to capture the interannual, ENSO scale, variability of the wind stress. We then remove this 9-month running mean anomaly from the total wind stress anomaly to capture the variability on subseasonal time scales—what we will refer to as weather noise. Figure 2 shows a time–longitude plot along the equator of the monthly ECMWF zonal winds stress anomaly, the zonal wind stress anomaly with a 9-month running mean applied, and the difference between total wind stress anomaly and the low-pass wind stress data or weather noise, respectively. The wind stress associated with individual ENSO events is evident in the first two plots, while the third plot is characterized by higher frequency variability and patchy spatial structure.

The procedure for applying the weather noise in the HCM is as follows. Every 10 model years in December, a random start date is chosen from the 120 monthly weather noise fields. The components of this field (zonal and meridional), along with the annual cycle components for the current month, are interpolated from month to month using piecewise parabolic interpolation and are prescribed at each time step (every 80 min) with the coupled components of the wind stress. For the following 119 months, the noise fields are applied in this manner serially. For example, suppose month 54 is initially randomly selected. We then apply month 55..., 120, 1, ... 53 in the subsequent months. The purpose for this methodology is to retain the high frequency variability of the high-pass filtered noise. If the fields were chosen at random every month, the noise would be temporally white, introducing a low

FIG. 1. Structure functions of HCM (a) zonal and (b) meridional wind stress anomalies determined by linearly regressing the observed time series of Niño-3.4 sea surface temperature anomalies on ECMWF winds. Units are N m⁻².
frequency component to the forcing to which we could expect a robust low frequency response (Hasselmann 1976; Eckert and Latif 1997; Thompson and Battisti 2001). After 10 years, the noise fields have cycled completely and another random start month is chosen. The prescribed noise forcing fields are passed through the same latitudinal mask function as the coupled wind stress components described above.

One concern, which arises from the weather noise sampling procedure described above, is the inclusion of an artificial decadal signal through the abrupt change in the noise sequence every 10 years. Figures 3a–c shows the power spectrum for the zonal component of the wind stress noise at three different latitudes at 160°W. While there is power at periods longer than a year, there is no sign of an artificial decadal signal in the noise fields. The lack of power at lower frequencies distinguishes the noise used in this study from the white noise commonly used in stochastically forced model studies (Penland and Sardeshmukh 1995; Thompson and Battisti 2001). Notice, however, that there is some power at lower frequencies; this small low frequency component of the noise is an important forcing for changes in the tropical Pacific mean state.

c. The ocean model

The ocean component of the hybrid coupled model is a reduced-gravity version of the Poseidon isopycnal global ocean model (Schopf and Loughe 1995; Yu and Schopf 1997). The model uses a generalized vertical coordinate to represent a well-mixed turbulent surface layer and nearly isopycnal deeper layers. The surface mixed layer in the Poseidon ocean model is treated as a bulk turbulent well-mixed layer with all of the mixing effects prescribed through a cross-coordinate mass flux at the base of the first layer. A reduced-gravity treatment is made in the model for reasons of computational expediency; the inclusion of bottom topography would make this a full ocean circulation model. Schopf and Loughe (1995) used a reduced-gravity version of the model in their study of the interannual-to-interdecadal variability of ENSO and found that the model pro-

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**Fig. 2.** Time–longitude cross section along the equator of (a) observed ECMWF zonal wind stress, (b) the 9-month running average ECMWF zonal wind stress, and (c) the difference between the zonal wind stress in (a) and (b). Contour interval is 0.02 N m⁻².
duced reasonable results and provided significant computational savings over a full OGCM. The model has 14 isopycnal layers with the deepest residing at a mean depth of 2300 m. The model extends from 70°S to 60°N with horizontal resolution of 1.25° longitude by 1° latitude, except in the tropics between 10°S and 10°N where it is stretched to 0.5°.

In the control and experimental simulations the wind and SST climatology remains the same and only the anomalies change. The model is also forced with a Haney (1971) surface heat flux boundary condition derived using the method of Schopf and Loughe (1995), which gives a weak restoration of model SST to observed climatological SST values, from (Smith et al. 1996). Net heat flux in the model is composed of three parts: the annual cycle of heat flux derived by the method above and two damping terms. The first is a linear damping term to observed SST of 10 W m⁻² K⁻¹ and the second is a cubic damping term that damps large SST anomalies stronger than smaller anomalies, and is similar to the cubic damping used in the Schopf and Suarez (1988) delayed oscillator. Solar radiation is needed for the mixed layer turbulent kinetic energy equations and was prescribed by a linear interpolation of the Pinker all-sky surface shortwave net irradiance data (Whitlock et al. 1995).

3. Hybrid coupled model performance

When the hybrid model was run for 300 years without prescribed noise forcing, the model settled into regular oscillations. Figure 4a shows a time–longitude cross section of SSTA along the equator. The SST anomalies are defined as the deviation from the mean annual cycle calculated over the entire (300 yr) integration. The regular period of the ENSO events is apparent as is the tendency for stronger cold events. Analysis of the Niño-3.4 SSTA shows a skewness of −0.20 with a standard deviation of 0.985°C. This negative skewness contrasts with the observed behavior of ENSO where there is a tendency for stronger warm events. There is also a westward propagation of the SST anomalies along the equator as the warm and cold events develop. Spectral analysis of the Niño-3.4 SSTA (not shown) shows a sharp spike at 48 months with little power at other frequencies. Drastic changes in ENSO variance on decadal time scales are not present in the run without noise; instead, the persistently high ENSO variance varies by only 10% with a period of 60–80 yr. Based on these results we conclude that the ENSO prediction skill in the hybrid model without noise is unrealistically high with little change from one epoch to another.

For the control run (i.e., with noise forcing) the ocean is forced between 30°N and 30°S using the mask function described in section 2 to remove direct forcing of the extratropical ocean. Climatological values of wind stress are derived from observations and applied over the entire ocean. With the model parameters set to control values the hybrid coupled model was integrated for 1000 years, during which time the ocean underwent very little drift. This lack of drift throughout the Pacific basin makes analysis of the ocean response on longer time scales less difficult and allows for more reliable statistics when looking for sensitivity in the model ENSO to potentially small changes in the background mean state. Analysis of the control run was performed on the last 800 years of the simulation.

Figures 4b,c show a time–longitude cross section of sea surface temperature anomalies for 20 yr along the equator from the control simulation and observations.
The observed and HCM SSTA are defined as the deviation from the mean annual cycle calculated over the entire record of observations (1950–2000) and the HCM (200–800), respectively. The model period was chosen for its general agreement in ENSO characteristics with the chosen observed period. The period of model ENSO is similar to that of the observations at 42 months, though the model period shown is more regular than observations. The amplitude of warm and cold events are within the same range of values; however, the location of the largest anomalies in the model is generally found in the eastern part of the basin while the observed events show less of a preference. Analysis of the Niño-3.4 SSTA over 800 yr shows that the skewness has shifted to a positive value in the presence of prescribed noise (skewness = 0.19) and the standard deviation has decreased to 0.82°C, which is closer to observed values. The model ENSO events during this period show a westward propagation of anomalous temperatures, while in the observations ENSO is generally dominated by a standing oscillation.

To highlight the decadal variability of ENSO, we use

![Fig. 4. Time–longitude cross section along the equator of the sea surface temperature anomalies from the hybrid coupled model (a) without prescribed noise forcing and (b) with prescribed noise forcing, and (c) observations: shading is 0.5°C.](image)
an 11-yr running Niño-3.4 SSTA variance. The use of a multiyear moving variance to characterize the low frequency variability of ENSO amplitude is a standard technique and is particularly relevant in comparing results to the recent literature (Kirtman and Schopf 1998; Rodgers et al. 2004; Yeh and Kirtman 2005), unpublished manuscript), and we find similar results using 7-yr and 21-yr windows. Figure 5 shows the time series of the Niño-3.4 variance calculated over an 11-yr moving window for the Smith and Reynolds extended reconstructed SST (Fig. 5a) and a comparable period of time from the HCM (Fig. 5b). The time period shown in the HCM time series was chosen to illustrate the similarity in the range and low frequency changes in ENSO variance. Similar to the observed time series, the simulated Niño-3.4 SSTA variance in the hybrid coupled model shows irregular variability. The amplitude and frequency changes in the 11-yr running variance from the model are reasonable, with decadal fluctuations and signs of century-scale variability. In the next section, we will investigate the relationship between tropical Pacific decadal variability and low frequency changes in ENSO in the context of our hybrid coupled model and search for the mechanisms behind these two modes of variability.

4. ENSO decadal variability and the mean state

To document tropical Pacific decadal variability in the HCM, an 11-yr running mean is applied to the boreal winter season [December–February (DJF)] sea surface temperature anomaly fields in the hybrid model output. We first find the seasonal-averaged SST for all of the boreal winter seasons in the model and remove the mean value. The 11-yr running mean is calculated by averaging winter season SST anomalies using an 11-yr moving window; results are not particularly sensitive when the 11-yr running mean is taken with monthly data. Next, EOF analysis was performed on the low-pass filtered data to determine the internally generated decadal variability in the model control run. Figure 6 shows the leading EOF and the leading principle component (PC) time series based on the 11-yr running mean SST from the HCM.

The spatial structure of the leading decadal mode in the model is characterized by three centers of action including an area of warming at 120°W on the equator, a zonal band of cooling extending from the central Pacific along 5°N with stronger anomalies near the equator at 90°W, and another area of warming extending along 15°N from the central Pacific to the coast. The leading mode of decadal variability in the observations is generally characterized by a broad meridional scale with a triangular shape in the tropics (Knutson and Manabe 1998; Zhang et al. 1997), with a horseshoe-shaped region of opposite anomalies poleward and to the west. The leading decadal mode in the HCM explains 48% of the variance on decadal time scales, while studies of the observed decadal variability find that the leading mode describes around 36.2% of the variance (Yeh and Kirtman 2005).

Also plotted in Fig. 6 is the 11-yr running Niño-3.4 variance. For comparison, only the boreal winter season values of the 11-yr running variance are plotted. Decadal variations in the two time series representing ENSO decadal variability and tropical Pacific decadal variability are readily apparent as is the similarity in phase between the two time series. When we compare the principal component of EOF1 with the 11-yr running variance, we find a simultaneous correlation coefficient of 0.7. This high correlation suggests that there is a relationship between the dominant mode of decadal variability in the tropical Pacific and the low frequency modulation of ENSO in the control run. This is in contrast to the leading decadal mode found by Yeh and Kirtman (2004), which resembles the TPDV pattern seen in observations but was unrelated to low frequency changes in ENSO amplitude in their model. The second mode of variability in their simulation was strongly correlated to decadal changes in ENSO variance; however, the authors considered this mode to be a nonlinear residual of ENSO. The second decadal mode found by Yeh and Kirtman shared some of the characteristics of the leading mode shown in Fig. 6, which leads to the question, What is the nature of the
relationship between the mean state and EDV in the hybrid model?

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Our next calculation involves deriving the structures associated with changes in ENSO variance directly. To extract the structures associated with the 11-yr running Niño-3.4 SSTA variance we will construct composite averages of the state variables of interest. We choose composite analysis instead of correlation patterns because it preserves physical units and has the virtue of simplicity. The threshold for defining high and low variance periods in the HCM is one standard deviation from the mean 11-yr running Niño-3.4 variance, but the results are not very sensitive to moderate changes in the value of this threshold.

Figure 7 shows the composite winter season SSTA from the hybrid coupled model. For consistency, the composite is constructed using 800 years of winter season sea surface temperature anomalies; however, the results are insensitive when the 11-yr running variance of all monthly data is used. The spatial correlation between the TPDV pattern seen in Figs. 6 and 7a is 0.9. Based on this analysis, we assert that there is a strong relationship in the HCM between the tropical Pacific mean state and decadal modulation of ENSO amplitude. A similar pattern of opposite sign is found during periods when ENSO amplitude is small for extended periods (Fig. 7b). This relationship between the mean state and ENSO amplitude is consistent with the results of Kirtman and Schopf (1998) and in disagreement with the argument of Flügel et al. (2004).

The wind stress associated with the SSTA patterns shown in Fig. 7 is shown in Fig. 8. When the total wind stress anomalies (coupled response + prescribed noise) from the composite analysis are plotted, we are able to see the part of the wind stress that affects ENSO variance on longer time scales. Figure 8 shows the total wind stress anomalies associated with extended periods of high and low variance in the HCM. During periods of high variance (Fig. 8a) we see a large patch of westerlies
along the equator centered at 140°W, convergence from the subtropics, and a region of southwesterly anomalies centered at 20°N, 125°E. During low variance periods of the simulation, easterly anomalies prevail across the equatorial central and eastern Pacific (Fig. 8b).

The composite mean anomalies of total wind stress are in agreement with the mean state changes found by Kirtman and Schopf (1998) in their ICM. The composite analysis suggests that during periods when ENSO variance is high (low) the equatorial Pacific is characterized by anomalously warm (cool) surface temperatures in the central tropical Pacific associated with anomalous westerly (easterly) wind stress over the central equatorial region. Our first experiment is designed to test whether the mean state structures seen in Figs. 8a,b effect ENSO variance in the model in a manner consistent with the results of our composite analysis.

5. HCM experiments

a. Prescribed mean state experiment

By prescribing the mean state patterns of wind stress anomalies in Figs. 8a,b, we intend to test whether these wind stress patterns are consistent with the changes in ENSO variance on longer time scales. We follow a similar methodology of Kirtman and Schopf (1998) and apply the mean state anomalies from the composite analysis to the climatological wind stress forcing in the model and integrate the model for 100 years. The model coupling strength and forcing region are unchanged from the control run; however, the prescribed noise forcing is not included in the prescribed mean experiments.

Figure 9 shows a time–longitude plot of sea surface temperatures along the equator for the two simulations with prescribed mean states. The years shown in Fig. 9 are from an early period in the 100-yr run and were chosen to show the transition of the easterly forced run to one that does not sustain strong ENSO oscillations. When mean westerlies are prescribed (Fig. 9a) the model maintains strong ENSO events with a period of 47 months. The cold bias of the “no noise” run emerges and the amplitude of cold anomalies is larger than that of warm events. The westward propagation of SSTA seen in the no-noise simulation is reduced, and ENSO behaves more like the standing oscillation seen in observations.

Based on the results of these experiments, we find
that the mean state changes in the composite analysis of 11-yr running variance are consistent with changes in ENSO variance. This result supports the findings of Kirtman and Schopf (1998) who found that periods of high (low) variance were characterized by westerly (easterly) wind stress anomalies that had direct effects on ENSO variance in their ICM. The behavior of ENSO changed in their model as the background mean state changed. They determined that during periods of high predictability the delayed oscillator mechanism was the dominant mode of variability and the model was insensitive to noise forcing. During periods when predictability was low the delayed oscillator was not the dominant mode of variability and the model was more sensitive to the noise forcing. They attributed the decadal variability in ENSO amplitude and predictability to relatively low frequency and small amplitude changes in the mean state; however, the source of the mean state changes was unclear. In the following section we expand on the work of Kirtman and Schopf by explaining what causes the mean state changes over decadal time scales.

Several extratropical mechanisms have been proposed to explain decadal changes in the tropical Pacific seen in the observations. These mechanisms focused on either oceanic or atmospheric teleconnections between the midlatitudes and the tropics. Owing to the design of the HCM we can dismiss the effects of wind anomalies generated in the midlatitudes as a source of equatorial wind stress forcing. The confinement of atmospheric forcing to within 30° of the equator was intended to rule out oceanic teleconnections between the midlatitudes and the extratropics proposed by Gu and Philander (1997) and Kleeman et al. (1999); however, recent studies suggest that forcing in the subtropics may play a role in decadal variability (Solomon et al. 2003). To address this possibility we designed an experiment that further confines the forcing region to within 15° of the equator.

Fig. 8. Composite average winter (DJF) wind stress anomalies where Niño-3.4 11-yr running variance is (a) larger and (b) smaller than one standard deviation from the mean. Units are N m⁻²; shading of the zonal component of the wind stress is shown at 0.003 N m⁻² intervals.
Analysis of the 11-yr Niño-3.4 running variance (not shown) for the 200-yr reduced-forcing region integration showed a correlation of 0.95 with the control simulation, indicating that the source of decadal variability is tropical (Burgman 2006).

The role of weather noise research has shown that the ocean can act as a low-frequency filter to stochastic processes in the midlatitudes (Hasselmann 1976), and recent research by Penland and Sardeshmukh (1995), Moore and Kleeman (1999b), and Yeh and Kirtman (2004) suggests that this may also be the case in areas of the tropics. Therefore, it is possible that the noise forcing may lead to decadal mean state changes (in agreement with Flügel et al. 2004, but not Kirtman and Schopf 1998) and these mean state changes impact ENSO variability (in agreement with Kirtman and Schopf 1998, but not Flügel et al. 2004). To quantify the relative contribution of the prescribed noise to the mean total wind stress anomaly seen in Fig. 8, we calculate the boreal winter season composite average of the noise component of the total wind stress using the 11-yr running average of Niño-3.4 variance. Figure 10 shows the winter season (DJF) composite average of the prescribed noise wind stress for extended periods of high (low) ENSO variance. We can immediately recognize the same basic structure as seen in the total wind stress anomaly composites in Fig. 8. To further illustrate the similarities, Fig. 11 shows the composite DJF difference maps of total wind stress anomaly minus the prescribed noise component. The fact that there is almost no contribution to the mean ocean state by coupled wind stress anomalies at the 99% significance level suggests that the noise alone is responsible for the low frequency modulation of ENSO via changes in the mean state. To test the influence of the noise on the low frequency changes in the tropical Pacific mean state we performed a model simulation designed to remove the influence of coupled interactions in the hybrid model.

b. ENSO removed experiment

To test the idea that the ocean component of the hybrid coupled model is acting as a low-frequency filter...
of the stochastic forcing we designed a model simulation to remove the coupled instability associated with the dominant ENSO mode from the model. In this model simulation the coupling strength was set to zero, with all other model parameters set to control values. The purpose of this design is to determine if the ocean response to noise forcing is consistent with the mean state changes seen in the control run. Wind stress response in this simulation is composed of the annual cycle of wind stress and identical prescribed noise forcing from the control run. The model was integrated for 275 years.

To examine the oceanic response to wind stress noise in the control simulation using the model output from the “no coupling” run, we perform a composite analysis using the 11-yr running Niño-3.4 SST variance form the control simulation and the boreal winter season SST anomalies from the no-coupling run. We are interested in the ocean’s response to noise forcing in the control run; however, we cannot a priori discern which part of the spatial structure is noise forced and which is a result of ENSO. By calculating the composite average SST from the no-coupling run during periods when ENSO variance is high in the control run, we can determine which mean state changes in the control run are due to the noise forcing alone.

Figure 12 shows the spatial structure of the noise-forced SST during high (low) variance periods in the control run. The similarity between the patterns from this analysis and those using SST from the control simulation is evident, and the patterns have a spatial correlation of 0.91. Based on this analysis, we conclude that the low frequency changes in the tropical Pacific mean state seen in the control simulation (Figs. 7a,b) are forced by the noise component of the wind stress. It is our contention that the ocean is responding to small
amplitude, low frequency variations in the stochastic forcing and that these mean state changes directly effect the ENSO variance on decadal time scales. The concept of the ocean behaving as a “red filter” of stochastic atmospheric forcing was first applied in the mid-latitudes (Hasselmann 1976) and was later applied to the tropics by Yeh and Kirtman (2004), Penland and Sardeshmukh (1995), and Moore and Kleeman (1999b).

The high correlation between the composite SSTA from the control run and the composite SSTA analysis of the no-coupling run suggests that the mean state changes are not caused by changes in ENSO variance in the control run and thus not subject to the residual argument proposed by Schopf and Burgman (2006). A comparison of the residual patterns calculated from the no-noise and control simulations (see Burgman 2006) with the patterns found in the composite analysis confirm that the low frequency changes in the mean state are, indeed, noise forced and not a residual of changing ENSO variance. The results of this experiment suggest that, while the residual mechanism of Schopf and Burgman (2006) may be consistent with observations, it is not the mechanism responsible for changes in the mean state in the control simulation.

In a recent study by Fedorov and Philander (2001), the authors found that, by altering the mean state of zonal wind stress or thermocline depth in their simple coupled model, the statistics of ENSO changed. Their results suggest that small changes in these parameters can cause the coupled mode to migrate between a delay-oscillator-dominant mode and a SST mode or alter the stability of the coupled system. Using composite analysis we have established that, over decadal time scales, low frequency variability in the prescribed noise wind stress forcing effects the mean state of the tropical Pacific. We now apply that same analysis technique to the equatorial thermocline in search of a mechanism for low frequency changes in ENSO variance.

**FIG. 11.** Composite average winter (DJF) wind stress (total wind stress − prescribed noise) where Niño-3.4 10-yr running variance is (a) larger and (b) smaller than one standard deviation from the mean: Shading of the zonal component of the wind stress is shown at 0.003 N m$^{-2}$ intervals.
Using the 11-yr running Niño-3.4 variance from the control simulation, we calculate composite averages of the winter season thermocline anomalies along the equator (averaged from 2°S to 2°N) in the no-coupling run when the variance is above or below one standard deviation from the mean. We propose a scenario where low frequency changes in the zonal component of the prescribed noise wind stress alter the equatorial thermocline, affecting the behavior of the delayed oscillator mechanism in the model. It is by these changes in the delayed oscillator that ENSO variance is effected. The temperature profiles from the no-coupling run are presented to represent the low frequency, noise-forced response of the equatorial thermocline.

Figure 13a shows temperature anomalies from 120°E to 80°W along the equator for periods where the zonal component of prescribed wind stress noise are westerly and ENSO variance in the control run is high. The equatorial temperatures are anomalously cold from 165°E to 110°W at depths ranging from 100 to 250 m with relatively weak warming at the surface. Figure 13b shows anomalous warming across much of the basin with weak cooling at the surface. Figure 13c shows the difference between Figs. 13a and 13b with several isotherms plotted for direct comparison. In the central Pacific below 100 m there is a distinct shoaling of the thermocline, and above 100 m decreased easterlies (or anomalous westerlies) lead to an eastward shift of the isotherms. We do not know whether it is the shoaling of the thermocline or the change in the tilt that actually is important in impacting the ENSO variance.

6. Discussion

In some sense, we describe a mechanism for decadal modulation of ENSO that resides somewhere between the stochastically driven ENSO of Flügel et al. (2004) and the nonlinear self-sustained ENSO of Kirtman and Schopf (1998). Our results suggest that the low frequency changes in the tropical Pacific mean state are stochastically driven, in agreement with the null hypothesis of Flügel et al. (2004). However, the slowly varying mean state in our HCM drives the changes in ENSO variance on decadal time scales, in agreement with Kirtman and Schopf (1998).

Our strategy is to examine the roles of coupled instability and atmospheric noise in the decadal variations in ENSO amplitude in the context of a hybrid coupled model. The model is composed of a statistical
atmosphere coupled to the Poseidon global ocean model. The wind stress in the model is derived from observations and has three components: an annual cycle, a coupled response based on an empirical relationship between Niño-3.4 SSTA and wind stress, and a noise component derived by filtering the observational estimates of wind stress. In the no-noise simulation ENSO resides in a weakly unstable parameter regime and is characterized by regular self-sustained oscillations in the absence of noise, though the skewness is of opposite sign to that seen in the observations. When the atmospheric noise is prescribed, the ENSO behavior becomes irregular on interannual as well as decadal time scales. In the control simulation the model simulates individual ENSO events in a realistic way and simulates low frequency changes in ENSO amplitude that are similar to those found in observed estimates of SST.

By taking composite averages of the SSTA associated with high and low variance periods of the model simulation we were able to show that the structure associated with these 11-yr running variance was very similar to the pattern of decadal changes in the mean state. In other words, this analysis indicates that there is a strong relationship between changes in the mean state and decadal changes in ENSO amplitude in the model. Changes in ENSO variance are apparently related to changes in the mean state that are directly forced by low frequency variability in the noise. This can be considered consistent with the nonlinear theory of ENSO or the linear theory of ENSO, assuming you allow for the linear operator to change.

The next question then became, what is the source of these mean state changes? To examine this question a composite analysis of the wind stress anomalies was performed. This analysis suggests that periods in the model with high (low) variance are characterized by westerly (easterly) wind stress anomalies along the central equatorial Pacific. A series of prescribed mean experiments showed that these mean state wind stress patterns were effective in altering the ENSO amplitude by changing the efficiency of the coupled feedbacks. While this is a nice consistency relationship, the source of the decadal variability remained unresolved.

Composite analysis was next performed on only the prescribed noise component of the total wind stress anomaly. The composite average of the noise component had the same structure and amplitude as the total wind stress anomaly composite, suggesting that the low frequency changes in the tropical Pacific mean state were forced by low frequency changes in the atmospheric noise forcing. In essence, it appears that the ocean is acting as a highly efficient low-frequency filter of atmospheric noise forcing, despite our attempts to reduce the low-frequency component of the noise.

To test this argument we set the coupling strength in the model to zero and integrated the model for 300 years with only the prescribed noise forcing. By then compositing the SSTA from the simulation with coupling strength set to zero, using the 11-yr running variance from the control run to determine the composites, we were able to characterize changes in the SSTA associated with the prescribed noise that is unaffected by ENSO. The structure of the low frequency composite average from the no-coupling run was highly correlated to the structure found in the control run. There are two points worthy of note here: (i) the ocean model is a

![Composite average winter (DJF) temperature anomalies for no-coupling simulation where Niño-3.4 11-yr running variance from control run is (a) larger and (b) smaller than one standard deviation from the mean: Contour intervals in (a) and (b) are 0.2°C. (c) Temperature difference between high variance temperature composite average and low variance composite average (a) – (b): Contour interval is 0.4°C; selected isotherms from the high variance composite (dashed) and low variance composite (dotted) are shown.

FIG. 13. Composite average winter (DJF) temperature anomalies for no-coupling simulation where Niño-3.4 11-yr running variance from control run is (a) larger and (b) smaller than one standard deviation from the mean: Contour intervals in (a) and (b) are 0.2°C. (c) Temperature difference between high variance temperature composite average and low variance composite average (a) – (b): Contour interval is 0.4°C; selected isotherms from the high variance composite (dashed) and low variance composite (dotted) are shown.
highly effective low-frequency filter of the noise and (ii) the low-frequency mean state changes are driven by the noise with little feedback or influence from ENSO, yet the changes in the mean state influence the ENSO statistics.

The no-coupling run was also very effective in ruling out ENSO residuals as an alternative hypothesis. While it was impracticable to determine the causality between changes in the mean state and changes in ENSO amplitude in the composite analysis of the control simulation, the analysis of the no-coupling run allowed us to directly remove the ENSO signal form the analysis. The ability of the no-coupling simulation to capture the control mean-state pattern effectively removes the residual argument from the current model simulation because the residual argument necessarily relies on the existence of ENSO.

The relationship between decadal modulation of ENSO and mean state changes resides somewhere between the linear damped stochastically forced theory and the strongly unstable theory. Unlike the strongly unstable system, changes in ENSO amplitude on longer time scales is determined by the stochastic forcing. The stochastic forcing is not necessary in this model to sustain ENSO; however, its presence is crucial for low frequency changes in the mean state of the tropical Pacific. The strong relationship between the mean state and ENSO amplitude modulation in the model is in opposition to the linear damped stochastically forced theory. The fact that changes in the tropical Pacific mean state lead directly to changes in ENSO amplitude and predictability has positive implications for predictability.

The results of the model studies presented here must be interpreted within the context of the hybrid coupled model. The statistical atmosphere produces a highly simplified coupled response in the tropical Pacific that cannot represent the complex atmospheric dynamics seen in observations and more complex AGCMs. By coupling the atmosphere to the ocean through the Niño-3.4 SST anomaly we neglect the influence of SST gradients along the equator on the development of ENSO. The forcing boundaries exclude the influence of midlatitude processes that may play a major role in ENSO dynamics and the tropical Pacific mean state and remote climate signals like the monsoons and the North Atlantic Oscillation. In constructing the atmospheric noise component of the hybrid model several assumptions had to be made a priori about the statistics of stochastic processes in the tropical Pacific that are not fully justified.

The caveats aside, the current study does identify some challenges in understanding the observed decadal modulation of ENSO. For example, the linear theory as presented by Flügel et al. (2004) suggests that the appropriate “null hypothesis” is that mean state changes and ENSO modulation are completely independent and uncorrelated. The results presented here could be interpreted as an alternate null hypothesis in examining the observational data, namely that low frequency variability in the noise causes the decadal modulation of the mean state, which in turn modulates ENSO amplitude. One possible approach would be to diagnose the noise in the observational estimates of the wind stress. Just such a procedure has been outlined in Schneider and Fan (2007).

REFERENCES


