Two Different Simulations of the Southern Oscillation and El Nino with Coupled Ocean-Atmosphere General Circulation Models [and Discussion]

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Two different simulations of the Southern Oscillation and El Niño with coupled ocean–atmosphere general circulation models

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Two different coupled ocean–atmosphere models simulate irregular interannual fluctuations that in many respects resemble El Niño Southern Oscillation phenomena. For example, the spatial structure of various fields at the peaks of the warm El Niño and cold La Niña phases of the oscillation are realistic. This success indicates that the models capture certain aspects of the interactions between the ocean and atmosphere that cause the Southern Oscillation. The principal difference between the models, namely the prominence of oceanic Kelvin waves in one but not the other, causes the two models to differ significantly in the way El Niño episodes evolve, and in the mechanisms that cause a turnabout from El Niño to La Niña and vice versa. It is possible that the different processes that determine the properties of the simulated oscillations all play a role in reality, at different times and in different regions. Each of the models captures some aspects of what is possible. However, reality is far more complex than any model developed thus far and additional processes not yet included are also likely to have a significant influence on the observed Southern Oscillation.

1. INTRODUCTION

The interannual atmospheric fluctuations referred to as the Southern Oscillation are caused primarily by sea surface temperature changes in the tropical Pacific Ocean. This hypothesis of Bjerknes (1969) has been confirmed by numerous studies with models of the atmosphere. For instance, Lau (1985) has used the observed sea surface temperature anomalies to force a general circulation model of the atmosphere and was able to simulate the observed Southern Oscillation over a period of 15 years, from 1962 to 1976.

The interannual oceanic variations in the tropical Pacific, including those in sea surface temperature that induce the Southern Oscillation, are caused by the atmospheric variations that accompany the Southern Oscillation, especially the variations in the surface winds over the tropical Pacific Ocean. A general circulation model of the ocean forced with the observed winds succeeds in reproducing the oceanic variability associated with both the warm El Niño and cold La Niña phases of the Southern Oscillation (Philander & Seigel 1985; Leetmaa & Ji 1989).

The circular meteorological and oceanographic arguments presented above indicate that interactions between the ocean and atmosphere are of central importance to the Southern Oscillation. These interactions are unstable because it is possible for the oceanic response to a certain change in the winds to reinforce that change. For example, a weakening of the westward trade winds that drive warm surface waters to the western tropical Pacific while exposing cold waters to the surface in the east, will permit some of the warm water to flow back eastward and the associated change in sea surface temperatures can lead to a further weakening of the winds. Coupled ocean–atmosphere models that capture these unstable interactions succeed in simulating the Southern Oscillation (Cane & Zebiak 1985; Schopf & Suarez 1988; Anderson & McCreary 1985; Battisti 1988). The models reproduce interannual fluctuations with a realistic timescale, and at the peaks of the warm (El Niño) and cold (La Niña) phases of the simulated Southern Oscillations certain fields in the models have realistic spatial structures. The simulations, however, can also differ significantly, from each other and from reality, in the way El Niño (or La Niña) evolves and in the mechanisms that cause a turnabout from the warm to the cold phase of the Southern Oscillation. This paper illustrates these differences in the case of two different simulations of the Southern Oscillation.

2. The models

A spectral general circulation model (GCM) of the atmosphere, which has an equivalent horizontal resolution of 4.5° latitude and 7.5° longitude approximately and which has 9 levels in the vertical (the R15 model described by Lau (1985)), has been coupled to two different versions of a general circulation model of the ocean. In one case, the oceanic GCM is global and has a relatively coarse resolution (approximately 4.5° in latitude and 3.8° in longitude and 12 levels in the vertical). In the other set of calculations the oceanic GCM has a very high resolution (1° longitude, $\frac{1}{3}$° latitude between 10° N and 10° S but gradually increasing further poleward, and 27 levels in the vertical) but it is a model of the tropical Pacific Ocean only. Elsewhere in the high-resolution model, the observed time-mean sea surface temperatures are specified as lower boundary condition for the atmosphere. Figure 1 shows the different geometries of the two models. The forcing function for both sets of calculations is the annual mean solar radiation. The radiative forcing was chosen to be steady in order to determine what variability the coupled system will produce in the absence of the seasonal cycle.

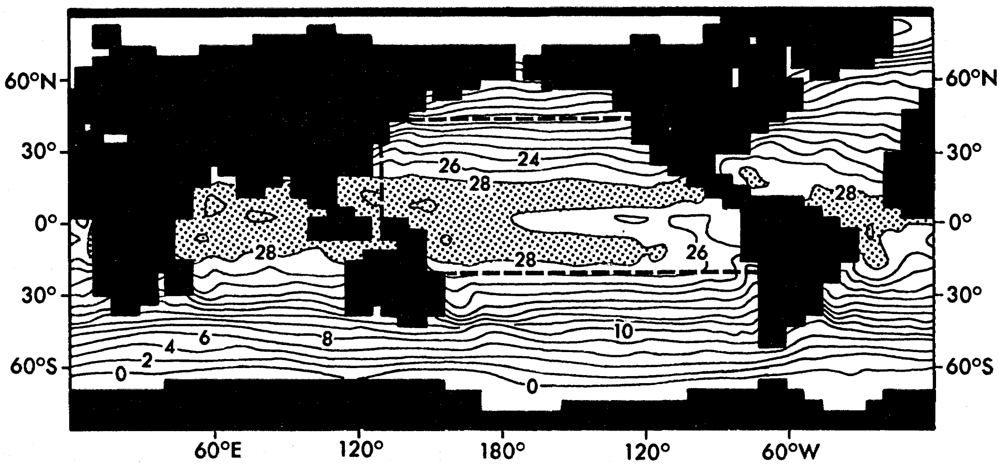


Figure 1. The geometry of the global ocean model, and indicated by broken lines, the domain in which the high-resolution Pacific model calculates sea surface temperatures. Outside this domain the observed annual mean sea surface temperatures are specified in the Pacific model except for a smooth transition from the calculated to the specified values across the broken lines. The mean sea surface temperatures, in degrees celsius, as calculated by the global model are indicated and regions warmer than 28 °C are stippled.

The principal differences between the coupled models are in the resolution and geometries of the oceanic components. The coarse resolution model is the more diffusive of the two. Its coefficient for the horizontal mixing of momentum is 2.5×10^9 cm^2 s^{-1} as opposed to 2×10^7 cm^2 s^{-1} in the high-resolution model. (The coefficients for the vertical mixing of momentum are more comparable.) High diffusivity will damp certain waves that are important in the adjustment of the ocean to changes in the winds. The coarse resolution will further distort, and possibly eliminate some of these waves. This could happen to the equatorial Kelvin wave, for example, because its latitudinal scale, of the order of 300 km, is such that is is barely resolved in the coarse resolution model. Another feature of the coarse resolution model that will inhibit waves is the reasonably realistic western boundary of the Pacific Ocean that reflects waves poorly. The high-resolution model, on the other hand, has an idealized boundary that reflects waves perfectly. The differences between the two models are therefore likely to result in differences in the roles that oceanic waves play in the variability of the coupled ocean–atmosphere system.

The computer requirements are far greater for the high- than the low-resolution model. It is for this reason that simulations in one case cover a 28 year period and in the other case a 100 year period. (The principal goal of the calculations with the coarse resolution global model was a study of climate changes caused by increased CO_2 levels in the atmosphere.)

3. RESULTS

Both models exhibit interannual fluctuations that in many respects resemble the Southern Oscillation. In figure 2, which depicts sea surface temperature variations in the eastern equatorial Pacific Ocean in the two models, the timescales of the oscillations are reasonably realistic. Spectra of different variables in the coarse-resolution model have pronounced peaks at periods of 36 months and 80 months. The spatial structures of various fields at the peaks of the warm and cold phases of the simulated Southern Oscillations in both models are also realistic. Figure 3 gives an example of how extreme the differences between warm and cold conditions can be in the high-resolution model. The pronounced equatorial tongue of cold surface waters, which is associated with spatially uniform intense westward winds during the cold La Niña phase, practically disappears during El Niño when the westward winds along the Equator relax, and in places reverse direction. These changes are in agreement with what is observed, as are the zonal movements of the convective zone which, in the mean, is over the

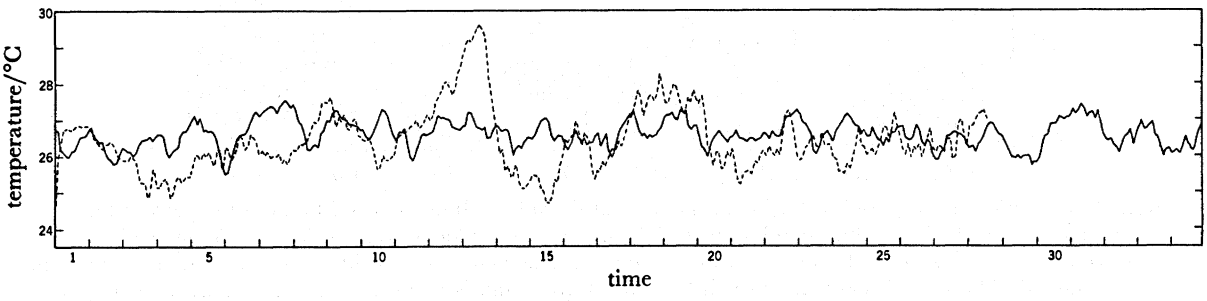
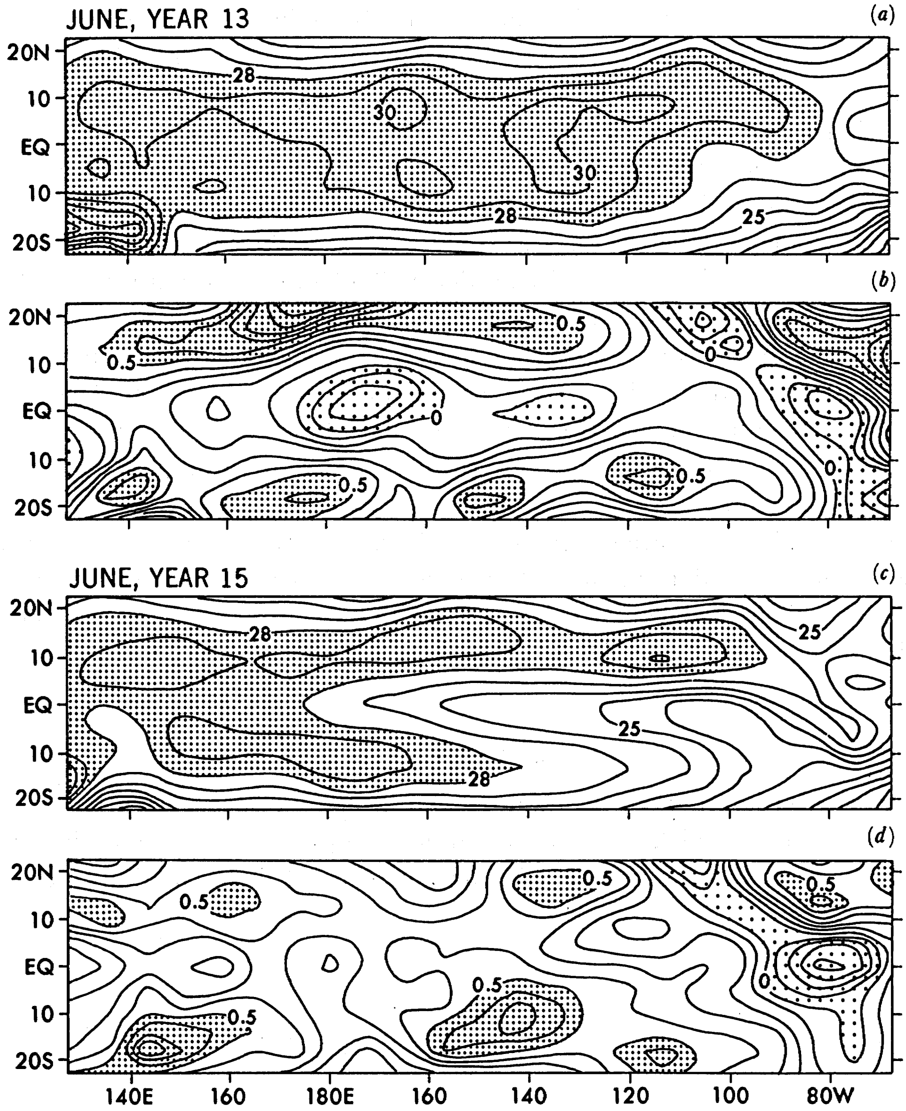


FIGURE 2. Sea surface temperature variations in the eastern equatorial Pacific Ocean. The curves show averages over the region 2.5° N–2.5° S, 150° W–112° W as simulated by the two models. The broken curve is for the high-resolution model, the solid curve shows variations between years 37 and 71 in the coarse-resolution model.


JUNE, YEAR 13

JUNE, YEAR 15

FIGURE 3. Conditions in the tropical Pacific at the peak of El Niño in June of year 13 and at the peak of La Niña in June of year 15 in the high-resolution model. Sea surface temperatures, in degrees Celsius with regions warmer than 28 °C stippled, are shown in (*a*) and (*c*). The zonal component of the wind stress is shown in (*b*) and (*d*). The wind is eastward in lightly stippled areas and is westward with an intensity greater than 0.5 dyn cm^{-2}† in heavily stippled areas.

western tropical Pacific. This region of low surface pressure and heavy rainfall moves eastward during El Niño, westward during La Niña. The occurrence of the simulated El Niños is accompanied by above normal sea-level pressure over the western Pacific, and below normal pressure over the eastern Pacific. The polarity of this east–west pressure seesaw is reversed during La Niña. Such fluctuations in the surface tradewinds, precipitation and sea-level pressure characterize the interannual fluctuations of both models.

The cause of the interannual oscillations in the models is unstable interactions between the tropical Pacific Ocean and the atmosphere. Persuasive evidence in favour of this hypothesis is the very high correlation, at zero lag, between low-frequency variations in surface winds – the meteorological parameter that most affects the ocean – and in sea surface temperature, the

† 1 dyn = 10^{-5} N.

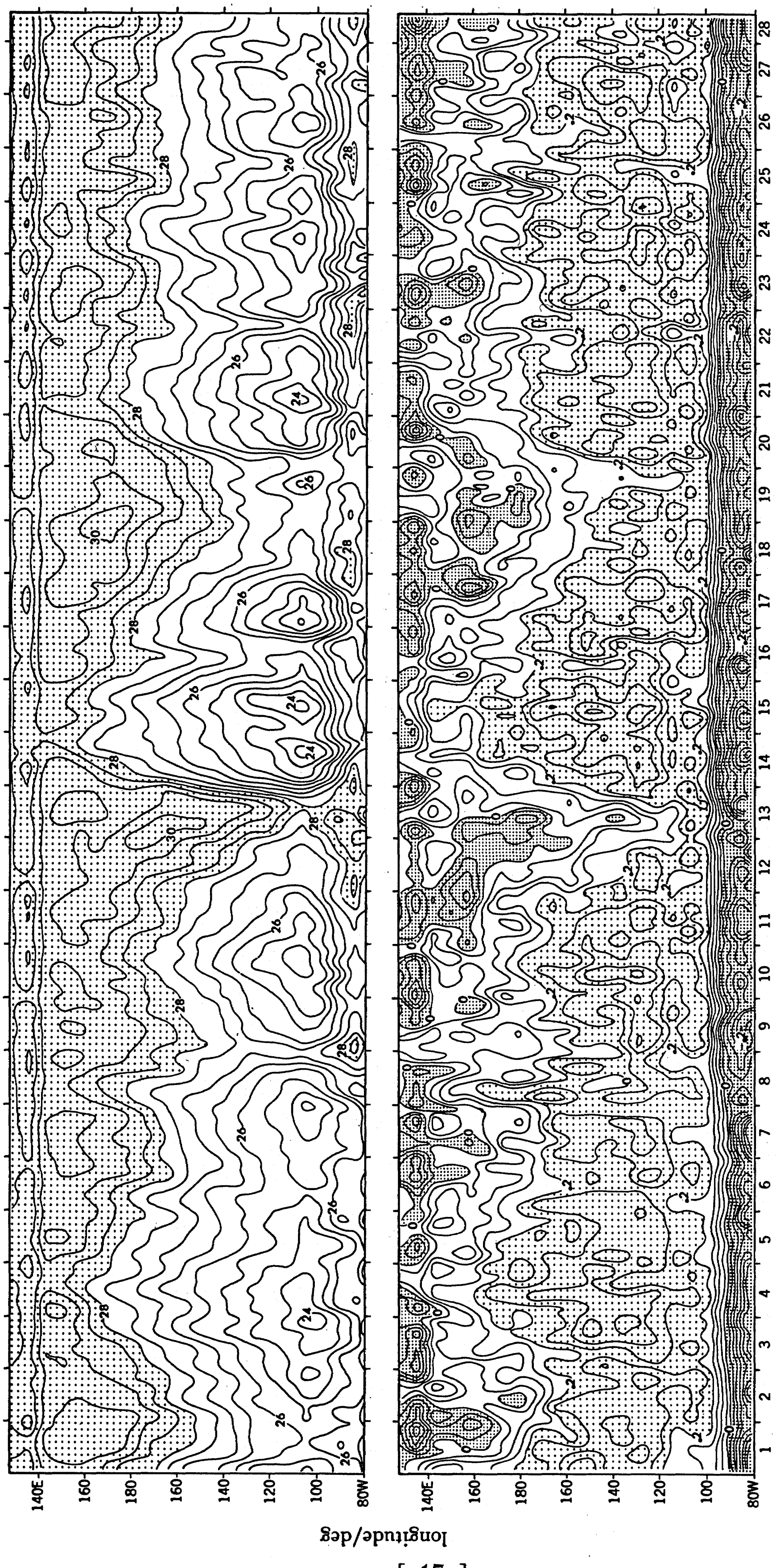


FIGURE 4. Sea surface temperature (in degrees Celsius) and the zonal component of the windstress (dynes per square centimetre) along the equator. Areas warmer than 28 °C, and areas where the intensity of westward winds is greater than 0.2 dyn cm^{-2} are lightly stippled. In heavily stippled regions the winds are eastward. The data shown are 13 month running means so that high-frequency fluctuations have been filtered out.

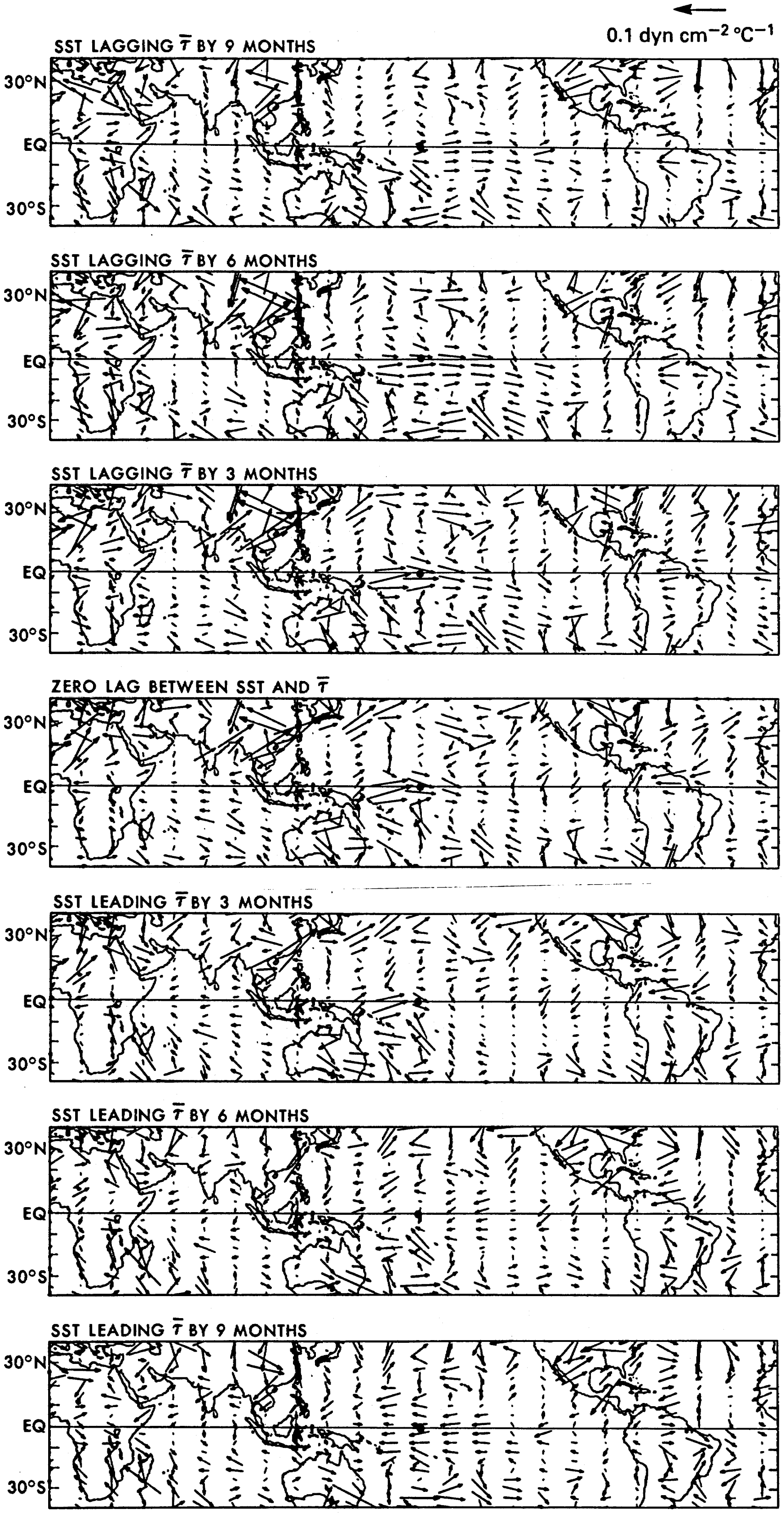


FIGURE 5. For description see opposite.

only oceanographic parameter that affects the atmosphere. Neither the ocean by itself, nor the atmosphere by itself, but interactions between the two media cause the simultaneous oscillations in sea surface temperature and surface winds illustrated in figure 4.

Although the Southern Oscillations simulated by the two models have many similarities, they also have significant differences. In figure 2 the fluctuations are seen to be more energetic in the high-resolution model, presumably because it is less dissipative. In the two models El Niño evolves in strikingly different ways: in the coarse-resolution model the individual events are rather regular, with anomalous conditions first appearing in the eastern tropical Pacific and then migrating westward as illustrated in figure 5 for the surface winds; in the high-resolution model the different events do not follow a definite pattern, with anomalous conditions either starting in the west and expanding eastward or appearing in the central part of the basin and growing in place. The manner in which El Niño evolves depends on the processes that determine sea surface temperature changes. Hirst (1986) for the case of a very simple coupled ocean–atmosphere model, has demonstrated that anomalous conditions migrate eastward if variations in thermocline depth control the sea surface temperature, and westward if advection of a mean zonal temperature gradient has the dominant effect. In the coarse-resolution model, advection of anomalous sea surface temperature gradients by a mean zonal current is important. The mean current along the Equator is westward so that anomalous conditions tend to drift westward. In the high-resolution model, on the other hand, the upwelling of anomalous temperatures has a strong influence on sea surface temperatures. This is so because oceanic Kelvin waves, which affect vertical temperature gradients, are prominent in this model. They are practically absent from the other, presumably because these waves are poorly resolved by the coarse horizontal and vertical grids. It is because a different physical process controls sea surface temperatures in the high-resolution model that its El Niño episodes evolve differently.

The mechanisms that cause a turnabout from El Niño to La Niña, and vice versa, are different in the two models. In the coarse-resolution model the continual oscillations correspond to a westward-travelling unstable ocean–atmosphere mode with a zonal scale smaller than the size of the Pacific. (Ocean–atmosphere interactions in the Atlantic and Indian Oceans do not seem to play a role; the very small sea surface temperature variations in those oceans are not correlated with the variations in the Pacific.) In figure 5, which illustrates this mode, it is seen that by the time El Niño develops to its mature phase, when westerly wind anomalies prevail over most of the central and western tropical Pacific, the atmospheric response to the sea surface temperature pattern includes easterly wind anomalies over the eastern tropical Pacific. The easterlies subsequently amplify as they migrate westward and develop into La Niña, which, in its mature phase, includes the seeds for the next El Niño in the form of westerly winds over the eastern tropical Pacific.

In the simplest models the interannual oscillations associated with a migrating instability are perfectly periodic (Hirst 1988). The introduction of 'weather' or 'random' atmospheric

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FIGURE 5. Maps showing the development of typical El Niño conditions over an 18 month period in the coarse resolution model. Spectra of fluctuations in the model have a peak at 36 months so that a bandpass filter, centred on 36 months and with a half-width of 12 months, was applied to the data. Linear regression coefficients between the surface windstress at individual grid points and the sea surface temperature at 0° N 180° W (see solid dots) were calculated, separately for the zonal and meridional components. These coefficients at the indicated time lags are displayed here in a vectorial format. The scale for the arrows is shown at the top right corner.

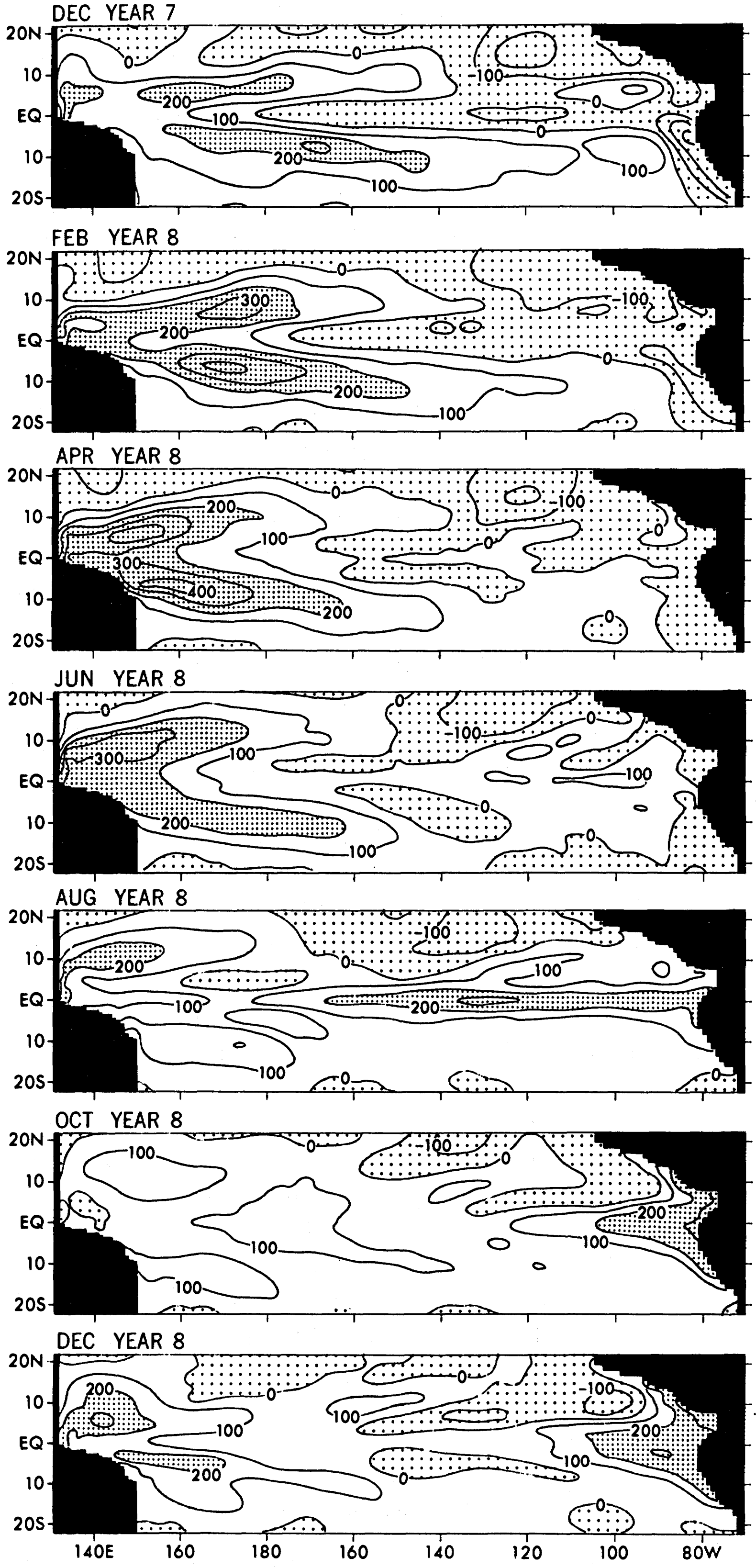

Figure 6. For description see opposite.

disturbances, unrelated to sea surface temperature variations, make the oscillations irregular. Such disturbances are present in the model atmosphere and cause the irregularity of the oscillations in the coarse-resolution model by interfering with the seeds that develop into the next phase of the oscillation. In the high-resolution model, these 'random' disturbances are of even greater importance. In that model the continual interannual oscillations do not seem to be associated with a migrating unstable mode; there are no discernable, consistent atmospheric precursors for the various simulated El Niño episodes. Instead, 'random' atmospheric disturbances seem to initiate and terminate the different episodes. The success with which they do this varies so that some El Niño episodes are relatively brief, those of years 8 and 16 in figures 2 and 4 for example, whereas others are prolonged, the one that lasted from year 17 to 20 for example. Apparently disturbances are more effective on some occasions than others in causing a turnabout from El Niño to La Niña.

One factor that sometimes determines whether a disturbance will cause a turnabout is the presence of a quasi-resonant oceanic mode in the high-resolution model. This mode has a period of 14 months, involves equatorial Kelvin and Rossby waves that reflect off the eastern and western walls respectively, and is maintained, in the face of dissipation, by 'random' atmospheric disturbances. It is absent from the coarse-resolution model presumably because its grid resolves Kelvin waves poorly. Whether this mode is a realistic feature is unclear. The actual western boundary of the tropical Pacific is extremely irregular and is a poor reflector of waves whereas the model has a perfectly reflecting wall. But if such a mode none the less is present in the ocean then it will be difficult to distinguish it from the annual cycle because its period is close to 12 months. At any rate, this resonant mode seldom affects sea surface temperatures. However, when it does, it can initiate ocean–atmosphere interactions. This happened during the modest El Niño of year 8 in figure 4. The associated thermocline displacements, depicted in figure 6, show features of the reasonant mode during that period: a westward-moving disturbance is seen to reflect off the western coast as an equatorial Kelvin wave. The latter wave coincides with a sudden relaxation of easterly winds that amplify it sufficiently to affect (increase) sea surface temperatures in the central equatorial Pacific. This leads to a further weakening of the winds and a further warming of the surface waters so that El Niño develops. In this case the westward-travelling disturbance at the top of figure 6 can be viewed as a precursor of El Niño. There are, however, numerous other occasions when such disturbances are present but no El Niño ensues.

In some models (Schopf & Suarez 1988; Battisti 1988), westward-travelling Rossby waves always precede El Niño. In these models the off-equatorial deepening of the thermocline that accompanies its elevation along the Equator during La Niña disperses into Rossby waves. Upon reaching the western boundary of the Pacific the waves give rise to equatorial Kelvin waves that deepen the thermocline and that cause the termination of La Niña and the onset of El Niño. In the coarse-resolution model the westward-moving off-equatorial depressions are clearly evident but they do not result in equatorial Kelvin waves. In the high-resolution model the off-equatorial deepening during La Niña is primarily west of the dateline near 10° N. It is

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FIGURE 6. Maps of anomalies in the vertically integrated temperature from the surface to 300 m in the high resolution model. These maps effectively show changes in the depth of the thermocline. The thermocline is elevated in lightly stippled regions. In heavily stippled areas the deepening of the thermocline exceeds 200×10^3 cal cm^{-2}. (1 cal = 4.184 J.)

clear in figure 3 that the curl of the wind varies considerably in that region and, during El Niño, elevates the thermocline. This elevation extends to the Equator where it migrates eastward. The speed is far slower than that of equatorial Kelvin waves, however, and the waves fail to counter the deepening of the thermocline in the eastern equatorial Pacific. In fact the deepening in the east continues while the thermocline shoals in the west. There is no evidence that Kelvin waves attributable to off-equatorial thermocline disturbances effect turnabouts from El Niño to La Niña. The result is confirmed by numerical experiments in which the neighbourhood of the western boundary of the Pacific is made highly diffusive in order to inhibit wave reflection there. Such a change does not alter the character of the oscillations significantly. Unstable ocean–atmosphere interactions, initiated and terminated by 'random' atmospheric disturbances, cause the interannual oscillations in the high-resolution model.

4. Discussion

Both coupled ocean–atmosphere models described here succeed in simulating reasonably realistic Southern Oscillations. El Niño and La Niña develop differently in the two models because different processes control sea surface temperature variations in the two models. In the tropical Pacific Ocean the dominant processes vary with time and location. There are likely to be occasions when the zonal advection of anomalously cold surface waters along the Equator determines sea surface temperatures. La Niña could then develop the way it does in the coarse-resolution model. On other occasions, when thermocline movements associated with propagating waves change sea surface temperature, El Niño is likely to develop the way it does in the high-resolution model. Each model captures some of the processes important in reality but neither these models, nor any of the coupled models constructed thus far, approach the complexity of reality. Further improvements to the models are necessary because they lack some of the processes that strongly influence the Southern Oscillation, the factors that control the seasonal and interannual movements of the intertropical convergence zone for example.

If the two coupled models described here were given certain initial conditions and then used to predict the further development of the Southern Oscillation, then they will give different results. The models have the same atmospheric component but the high-resolution version describes oceanic conditions, in response to specified surface winds, more accurately than does the other. It is therefore possible to conclude that predictions with the high-resolution model are preferable to those with the coarse-resolution model. This, however, is a sophistical argument. Both models are flawed because of their atmospheric component which provides surface winds that are too weak in response to a specified sea surface temperature pattern. (In figure 4 the wind stress over the equatorial Pacific ranges between 0.2 and 0.3 dyn cm^{-2}, whereas the typical observed climatological values for this region are significantly higher.) Because of this, advection in the ocean is underestimated. In the high-resolution model this defect causes oceanic waves to play too dominant a role in controlling sea surface temperature changes. The high dissipation of the coarse-resolution model can therefore be viewed as a correction towards a better balance between advection and wave processes. It is conceivable that predictions with that coupled model will be more accurate than predictions with the high-resolution model. A coupled model should not be judged on the basis of how its components perform separately.

A model that is a poor predictor can none the less be of enormous value for other types of climate studies. In the same way that most climate models are inappropriate for weather prediction but none the less resolve weather disturbances in order to incorporate their gross effect, their poleward transport of heat for example, so models that resolve the Southern Oscillation without capturing all its details, could be useful for studies of climate change on a timescale of several decades. The models would have to capture the effect, if any, of the Southern Oscillation on lower-frequency variability. It is possible that the poleward transport of heat in the ocean is strongly influenced by the Southern Oscillation but this matter will be discussed on another occasion.

S. Manabe, R. Stouffer and M. Spelman generously made available data from their coupled model. We are indebted to Dr Held for numerous fruitful discussions. Ms Marshall and Mr Tunison provided expert technical assistance.

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Discussion

J. B. WILLIAMS (*LRD: ODNRI (ODA), Chatham, U.K.*). I would like to ask Dr Philander about the predictability of an El Niño Southern Oscillation (ENSO) warm event. Does the likelihood (the propensity or potential) of a warm event increase during the course of the cold phase, as the ocean stored (not transported) energy increases? There do not appear to be long periods without warm events in published ENSO sequences over the past 100 years.

If the potential for a warm event increases with time, then less-likely modes of warm-event initiation may occur more easily. Is there any evidence of relations between mode of initiation and subsequent intensity and duration of the warm event?

S. G. H. PHILANDER. Model studies, specifically those of Zebiak & Cane, indicate that El Niño cannot occur until the spatially averaged depth of the thermocline near the Equator exceeds a certain critical value. Hence the likelihood of El Niño increases steadily during the cold La Niña phase of the Southern Oscillation as the heat stored in the equatorial ocean increases. When El Niño does occur the oceanic transport of heat away from the equatorial zone is unusually large so that the event eliminates the conditions that give rise to its occurrence.

At this time models have some skill in predicting whether or not El Niño will occur but are unable to predict the manner in which an event will evolve. There has been no identification of precursors that indicate how intense an event will be.

K. Hasselmann (*Max Planck Institute for Meteorology, F.R.G.*). Dr Philander made the point that the Southern Oscillation may be as important to the mean oceanic circulation as the weather disturbances are to the mean atmospheric climate, in the sense that both fluctuations have a strong impact on the equator-to-pole heat transfer. Can he elaborate?

S. G. H. Philander. The northward heat transport in the ocean increases during El Niño and decreases during La Niña (when the heat exported from the equatorial zone into the Southern Hemisphere can increase). If a coupled ocean–atmosphere model, designed to study climate variability on timescales of centuries, fails to simulate a Southern Oscillation but reproduces realistic mean conditions then there is no problem. If, however, mean conditions correspond to either a warm El Niño or a cold La Niña then the meridional heat transport of the model is likely to be inaccurate. The oceanic heat transport to the south is likely to be too high if La Niña prevails; the transport to the north is likely to be too high if El Niño conditions prevail. If the model does reproduce a Southern Oscillation then it may not matter whether the detailed evolution of El Niño events is correct, in the same sense that a climate model need not be good at weather prediction.