NOTES AND CORRESPONDENCE

On the Role of the Indian Ocean in a Coupled Ocean–Atmosphere Model of El Niño and the Southern Oscillation

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ABSTRACT

The coupled ocean–atmosphere model of Anderson and McCreary is extended to include two oceans. An advantage of the two-ocean system is that it is not necessary to specify externally convection over land.

For a basin geometry that most resembles the Indian and Pacific Oceans, strong permanent convection exists in the eastern Indian Ocean, and there is an oscillation in the Pacific Ocean with a period of about five years. Associated with this oscillation is a patch of convection that develops in the central and western ocean and propagates into the eastern ocean before dissipating.

1. Introduction

In a recent paper, Anderson and McCreary (1985) developed a coupled ocean–atmosphere model to study El Niño and the Southern Oscillation (ENSO). The model atmosphere was a linear, "first-baroclinic-mode" atmosphere driven by convection, similar to those used previously by Webster (1972), Egger (1977) and Gill (1980). The model ocean was a nonlinear, reduced-gravity model generalized to include thermodynamic processes, and so it was able to generate a temperature field T. The two systems were coupled together as follows: atmospheric convection was taken to be proportional to $T - T_c$ for T greater than a critical temperature T_c, and the wind stress forcing the ocean was assumed to be proportional to the wind velocity generated by the atmospheric model. For all the solutions the atmosphere was cyclic in longitude, with a circumference of either 15 000 or 30 000 km. One set of solutions was found when the ocean was also cyclic in longitude, and another set in a domain consisting of a bounded ocean and a land mass, each 15 000 km wide. When land was present, convection there was an externally specified forcing function.

For realistic choices of model parameters, solutions exhibited low-period, eastward-propagating coupled oscillations. These oscillations occurred both when the ocean was cyclic and when it was bounded, provided that convection over land was located to the *west* of the ocean. This latter configuration was likened to the situation in the Pacific Ocean, with land convection representing the strong Indonesian heat source. When land convection was located to the *east* of the ocean, however, the model locked into a stable, nonoscillatory mode. This configuration was likened to the Indian Ocean, with land convection again representing the Indonesian heat source. In this stable situation, the ocean was slightly warmed in the east, somewhat similar to what is observed in the Indian Ocean. These results demonstrated a fundamental difference between the model Pacific and Indian Oceans: the former exhibits low-period oscillations while the latter does not.

Two limitations of the above model are that it involves only one ocean and that convection over land is externally specified. In this note we overcome both of these limitations by including a second ocean in the basin geometry. The convection that develops over the second ocean allows oscillatory solutions to exist without the necessity for any convection over land, and so land convection is set to zero throughout. Equations of motion for the model atmosphere and the two oceans are otherwise exactly as described in the Anderson and McCreary study, and parameter values are the same as for their control runs. For this reason, a detailed description of the model is not repeated here; the interested reader should consult the earlier paper.

2. Results

This section contrasts the model response for the three basin configurations shown in Fig. 1. In each case, coupled oscillations develop that involve all of the oceanic and atmospheric variables. For convenience, Figs. 2–4 show only the time development of the ocean temperature field T and of atmospheric convection, with convection occurring wherever T is greater than

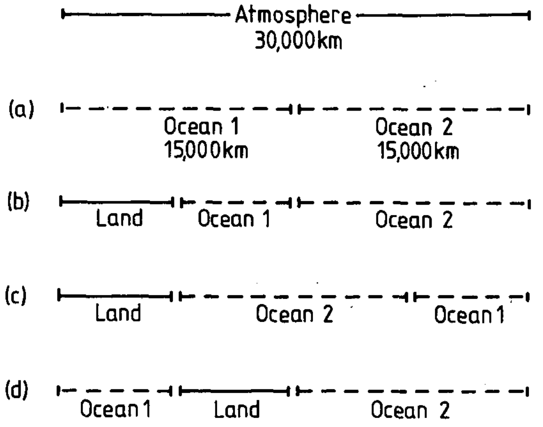

FIG. 1. A schematic diagram showing the location of land and ocean in the three experiments discussed in the text. (a) corresponds to Fig. 2, (b) to Fig. 3 and (c) to Fig. 4. Case (d) is essentially the same as (c). In all cases the atmosphere is cyclic with a circumference of 30 000 km. The oceans are separated by thin barriers or by extensive (7500 km) areas of land. Over land there is no convection. Over the ocean convection depends on SST as described in Anderson and McCreary.

$T_c = 8.5$°C. The behavior of the other variables is similar to that in the solutions of Anderson and McCreary (see their Figs. 4, 6 and 9).

The temperature field T is not sea surface temperature (SST). It is the temperature excess of the surface-layer water over the deeper water that is entrained by the layer. In the tropics, a realistic value for the temperature of entrained water is 20°C, so that SST is given by $T + 20$°C.

a. Two ocean basins without land

In this subsection we consider the case of two independent oceans of width 15 000 km that are separated by land barriers of zero width, as shown in Fig. 1a. The atmosphere is 30 000 km wide and is cyclic. The oceans extend latitudinally to 4500 km, and solutions are symmetric about the equator. The model is forced for the first 100 days by a wind stress that converges on the barrier at $x = 15\,000$ km, and is then allowed to run freely.

Figure 2 shows the time development of T along the equator in both oceans. Initially, a region of warm temperature (and enhanced convection) develops near $x = 15\,000$ km. Subsequently, a slow eastward-propagating disturbance drifts eastward to the eastern edge of ocean 2, and establishes a region of warm temperature near $x = 30\,000$ km. A similar eastward propagation then proceeds in ocean 1, and the oscillation continues in this manner.

Although the oceans are not physically connected in any way, there is a connection via the atmospheric wind field. When a warm patch approaches the eastern edge of ocean 1, say, the easterly wind field to the east of the warm patch extends over the western part of ocean 2, depressing the thermocline in the west and generating a warm patch there as well; eventually, this warm patch separates and propagates eastwards across ocean 2. Because of this strong atmospheric connection, the response in Fig. 2 is similar to that for the cyclic ocean case of Anderson and McCreary (see their Fig. 4); the propagation of the disturbance is retarded by the thin barriers, but not completely blocked.

b. Two ocean basins with land separation

Here, ocean 1 and ocean 2 are separated by a thin barrier on one boundary and by an extensive land mass on the other. Since the Indian Ocean is smaller than the Pacific, we consider one large ocean 15 000 km wide, a small ocean 7500 km wide and a land separation that is also 7500 km wide. The atmosphere remains cyclic with a circumference of 30 000 km. Over land there is no convective forcing of the atmosphere. Two configurations are possible, shown in Figs. 1b and 1c; the configuration in Fig. 1d is effectively the same as that in Fig. 1c. The configuration in Fig. 1b more closely resembles the observed Indian–Pacific Ocean configuration. The land region acts to break the atmospheric connection between the model eastern Pa-

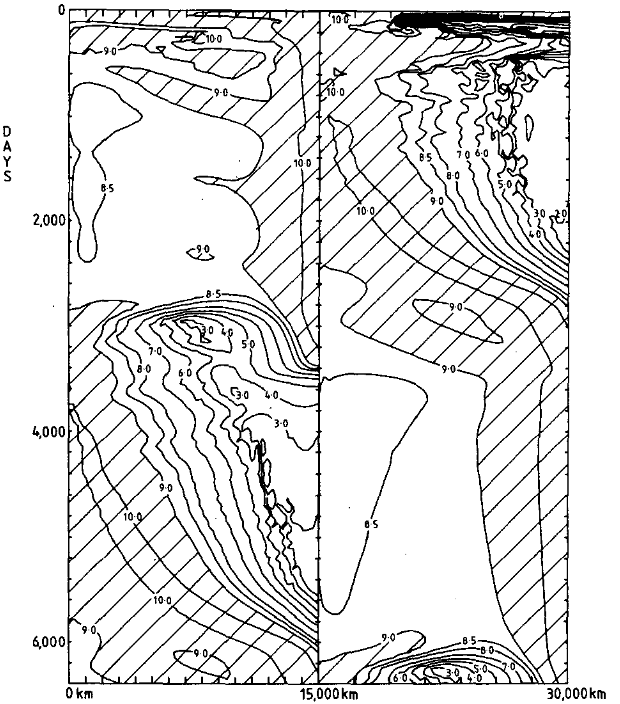

FIG. 2. Contours of T vs time for the configuration of Fig. 1a. There are low-frequency oscillations. A region of warm temperature develops in one ocean, and then propagates eastwards. When it approaches the eastern boundary, it begins to affect the second ocean via the wind field. Another disturbance subsequently develops in the second ocean, then propagates eastwards, and so on. Convection occurs in the atmosphere wherever $T > 8.5$°C.

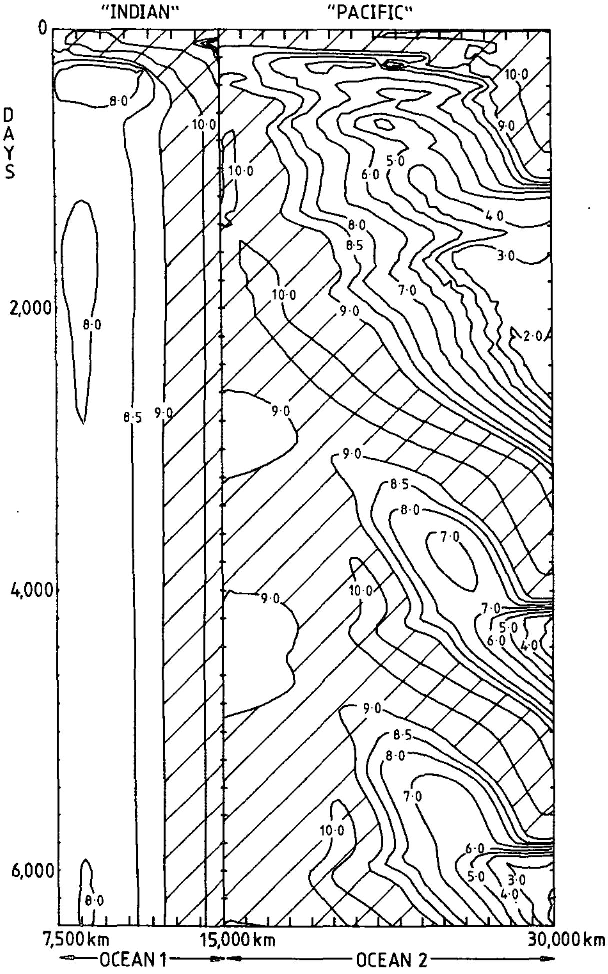

FIG. 3. Contours of T vs time for the configuration of Fig. 1b. The "Indian Ocean" is stable and stays in a state with warm water in the east. In contrast, the "Pacific Ocean" undergoes low-frequency oscillations.

cific (ocean 2) and the model western Indian Ocean (ocean 1). Thus, land simulates the effects of the Andes, Atlantic Ocean and East African Highlands, which together prevent a direct atmospheric coupling between the eastern Pacific and western Indian Ocean wind fields.

Figure 3 shows the time development of equatorial SST for the configuration of Fig. 1c. Ocean 1 (the "Indian Ocean") soon locks into a warm state with winds blowing from west to east. This state is stable, with no oscillations occurring. In contrast, ocean 2 (the "Pacific Ocean") exhibits low-frequency oscillations with a period of about 5 years, similar to the bounded-ocean solution of Anderson and McCreary (see their Fig. 6). This solution has several features in common with observations. For example, there is permanent convection over "Indonesia", the system oscillates at the long periods associated with ENSO, and a region of anomalous convection, SST and westerly winds propagates eastward across the "Pacific Ocean" during an El Niño event.

Figure 4 shows the time development of equatorial ocean temperature for the configuration of Figs. 1c and 1d. In this case, a warm patch develops initially in the west of ocean 1 and then propagates to the east. Thereafter ocean 1 remains locked into a stable state with warm water in the east. Ocean 2 exhibits a weak oscillation with a very long period, a response considerably less realistic than that in Fig. 3.

3. Summary and discussion

The model discussed here is an extension of the Anderson and McCreary model that includes two oceans. One advantage of having two oceans is that it is no longer necessary to specify convection over land. Therefore, land convection is always set to zero.

Solutions are found for various ocean–land configurations. When there is no land present, as in the configuration of Fig. 1a, eastward-propagating disturbances pass from one ocean to the other in a manner much

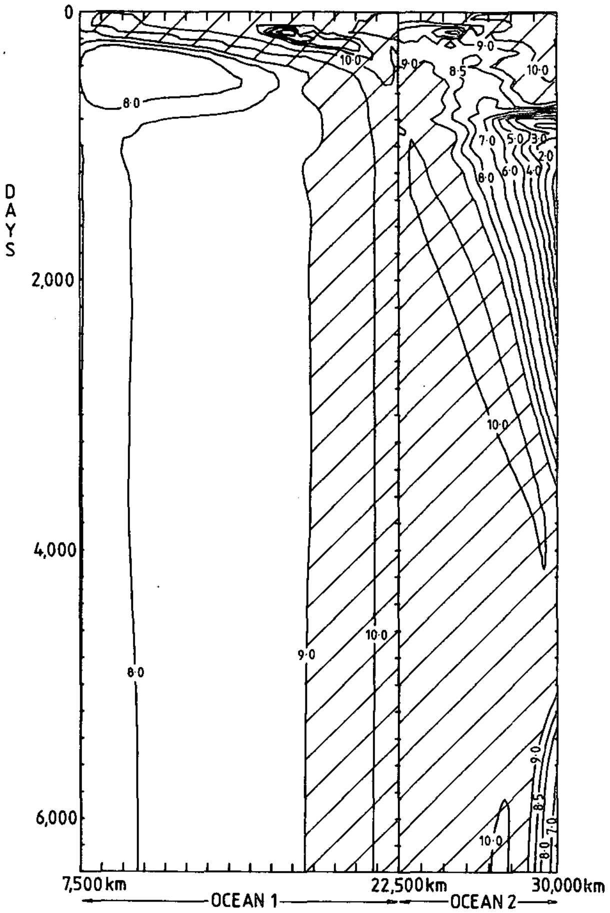

FIG. 4. Contours of T vs time for the configuration of Fig. 1c. The western ocean remains stable, but the smaller eastern ocean undergoes a weak oscillation.

like that in the cyclic-ocean case of Anderson and McCreary; this similarity occurs because there is strong coupling between both oceans via the wind field, even though the oceans are completely separated by barriers. Figure 1b shows the geometry most similar to that of the real Pacific and Indian Oceans. In this configuration the smaller "Indian Ocean" quickly moves to a stable state with warmest water in the east. Convection becomes strong there in association with the warm water, and remains so throughout the integration. In contrast, the larger "Pacific Ocean" exhibits low-period, eastward-propagating oscillations. For the configurations of both Figs. 1b and 1c, the western ocean is stable with warm water in the east, while only the eastern ocean shows oscillations; these oscillations are stronger and faster when the larger ocean lies to the east of the smaller ocean.

In an earlier paper McCreary and Anderson (1984) obtained oscillations at long periods using a model that had two stable states of equilibrium and a trigger (the annual cycle of the trades) that prevented the model from ever attaining either state. At the start of this work, we hoped that having two independent oceans would permit two stable states of equilibrium to exist, and hence that there would be a dynamical similarity with the McCreary and Anderson model. In fact, for no choices of model parameters did two steady solutions exist.

This study and the one done by Anderson and McCreary show that a key ingredient for the low-period oscillations in the model "Pacific Ocean" is convection located to the west. This convection can be achieved either by a specified forcing function as in the Anderson and McCreary study, or by warm SST in the "Indian Ocean" as in the present study. The oscillations, however, are too regular, and so do not exhibit the rapid onset and intermittency of El Niño events. We are currently improving the dynamics of the coupled system in several ways in an effort to overcome this deficiency.

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