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The Rossby soliton: a robust non-linear structure in the equatorial ocean

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Abstract

A non-linear reduced gravity model of the equatorial Pacific ocean is used to study the characteristics of one special solution: the first baroclinic Rossby soliton. We have found it to travel westward and lose 25% of its energy in the reflection at the west coast. It returns as a non-linear Kelvin wave which steepens as it travels eastward. Reflection of this structure at the east coast generates a new Rossby soliton. Again about 25% of the energy is lost. Interaction of the non-linear Kelvin wave with a Rossby soliton leaves both structures unchanged. Finally, a temporal westerly wind patch in the centre of the basin generates a same kind of non-linear Kelvin wave, which returns after reflection as a Rossby soliton.

1. Introduction

This research is part of the NOP project 853110, entitled: "Non-linear dynamics of the coupled equatorial ocean-atmosphere system". In particular we are looking for the physical mechanisms that determine the behaviour of the tropical coupled system on interannual time scales of 2-9 years (El Niño/Southern Oscillation). Focus is on persistent oscillatory structures in the coupled equatorial Pacific ocean-atmosphere system, developing through non-linear interaction of unstable coupled modes.

As a first approach we study these structures in a non-linear model of the ocean only. The coupling to the atmosphere is to be added later. Then we will study how weak coupling affects the solutions as found for the ocean model. Boyd (1980) has already made a rigorous study of the non-linear development of equatorial waves in an uncoupled homogeneous ocean model. This study shows that for dispersive Rossby waves eventually a balance between dispersion and non-linearity (inertia) develops, resulting in equilibrium structures like solitons. The importance of these Rossby solitons for ENSO is also stressed by Kindle (1983). He showed that temporal relaxation of trade winds can generate an internal Kelvin wave front, which reflects at the eastern oceanic boundary as one or more solitons.

In this study we want to take another look at these Rossby solitons by means of a direct numerical time integration. We want to know what happens when the Rossby soliton reflects at the western boundary. What kind of structure results? What happens to the energy of the system? How is it redistributed, how much energy is absorbed by the boundary? Can a Rossby soliton be generated by an arbitrary initial disturbance?

2. Model

We use a reduced gravity model on an equatorial beta plane to describe the ocean dynamics. In this 1.5-layer model, the upper layer is bounded from above by a rigid lid. The lower layer is infinitely deep and inert. The interface between the two layers lies at a depth of about 100m and models the tropical thermocline.

The set of partial differential equations describing the ocean dynamics consists of two momentum equations describing the time evolution of the zonal *(u)* and meridional *(v)* flow velocities, and the continuity equation describing the time evolution of the thermocline depth *(h)*.

At the eastern and western boundary we apply no-slip boundary conditions. The northern and southern boundary of the domain of calculation are open. To avoid any reflection from these artificial boundaries we apply a sponge filter, which damps out any signal approaching them.

3. Results

We initialise the dynamical fields *u*, *v* and *h* with the first baroclinic Rossby soliton given by Boyd (1980), in a basin extending from 140°E to 280°E and from 20°N to 20°S (fig. 1). Following the soliton as it travels westward, we find that the isolated structure moves across the basin without changing its shape. We can therefore conclude that in our numerical code the right balance between non-linear and dissipative effects, necessary for the existence of soliton solutions, is maintained.

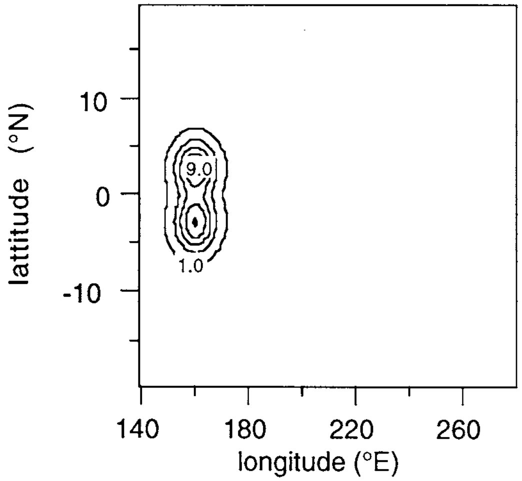

Fig. 1 The thermocline depth perturbation h at day 0: the Rossby soliton.

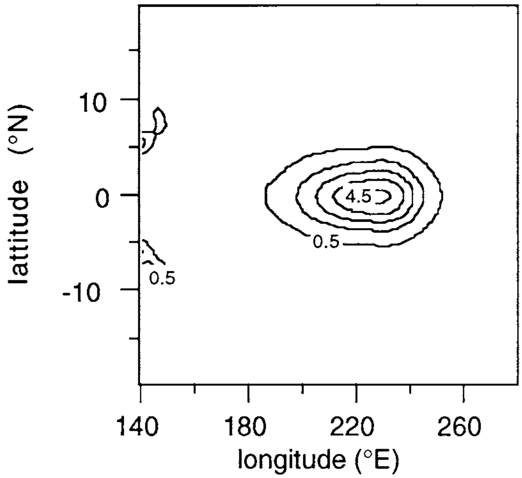

Fig. 2 The thermocline depth perturbation h at day 120: the non-linear Kelvin wave.

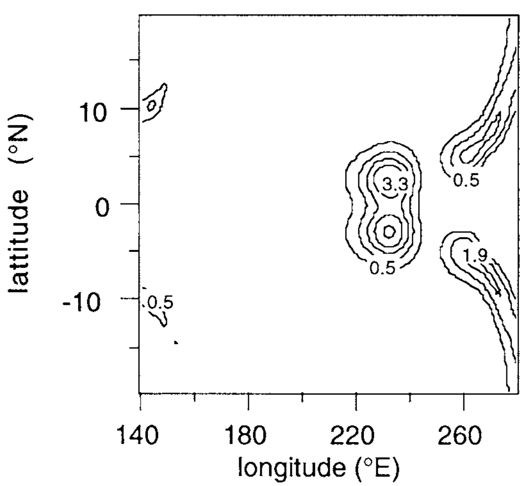

Fig. 3 The thermocline depth perturbation h at day 200.

After some time the Rossby soliton reflects at the west coast. The reflected signal is clearly a non-linear Kelvin wave (fig. 2) with its maximum at the equator. Its meridional velocity is two orders of magnitude smaller than the zonal velocity, so practically zero. A second product of the reflection are high frequency Rossby waves which are visible along the west coast. However, the wavelengths of these waves are too small to be properly resolved on the numerical grid that is used.

Calculating the sum of the total kinetic and potential energy, we find that about 25% of the total energy is lost in the reflection. As the non-linear Kelvin wave travels eastward, it steepens because of non-linear effects.

After reflection at the east coast we see that a new Rossby soliton appears (fig. 3). Furthermore we see coastal Kelvin waves travelling poleward along the east coast, leaving the basin. Again, about 25% of the energy is found to be lost in the reflection.

In a second simulation we let the Kelvin wave which appeared in our first simulation interact with a second Rossby soliton, initialised in the east part of the basin. We find that the two structures add up almost as if the superposition principle were valid, although we are dealing with non-linear waves. After interaction the two structures separate again and regain their initial shape. This behaviour is typical for solitary waves. But as the non-linear Kelvin wave is not a soliton, for it changes shape as it propagates, this behaviour was not expected.

In a third simulation we let a patch of westerly winds blow between 200°E and 220°E for three months. This generates an eastward travelling Kelvin wave, which reflects at the east coast and returns as a Rossby soliton. This result is the same as was found by Kindle (1983).

4. Conclusions

Rossby solitons turn out to be robust solutions in a non-linear 1.5-layer equatorial ocean model. Not only are they maintained when explicitly initiated, but they can also be caused by reflection of any Kelvin wave, irrespective of how it was generated. In particular, a temporal weakening of easterly trade winds, modelled here by a temporal patch of westerly winds, generates such a Kelvin signal. As weakening of trade winds tends to coincide with the initiation of El Niño events, we might expect to detect Rossby solitons a few months after the onset of an El Niño, as the Kelvin wave has reflected at the coast of Peru. They have however never been observed so far. It might be that the signal is so weak in the real ocean that it disappears in other wave signals. Another explanation may be that nobody has ever attempted to extract a Rossby soliton signal from observational data.

References

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Kindle, J.C., 1983: *On the generation of Rossby solitons during El Niño.* In: J. C. J.Nihoul (editor), Hydrodynamics of the equatorial ocean, Elsevier Oceanography Series, 36, pp. 335-351.