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Rossby waves: synergy in action

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Rossby waves are an important phenomenon, linking processes in the west of ocean basins with forcing that occurred earlier in the east. We show evidence for such features in satellite-derived datasets of sea-surface height, temperature and ocean colour, using a section of the south Indian Ocean as an example. We discuss the possible mechanisms for an effect on chlorophyll, and we investigate this by comparing the ocean colour signal with the other datasets. In this region, the primary mechanism for a Rossby-wave signal in ocean colour appears to be meridional advection of water across a strong chlorophyll gradient. However, this cannot fully explain the observations in the westernmost basin.

Keywords: Rossby waves; sea-surface height; sea-surface temperature; chlorophyll concentration; Indian Ocean; synergy

1. Introduction

Rossby waves are an important process by which signals are transmitted from one side of an ocean basin to another. They correspond to a solution of the equations of motion of a fluid on a rotating body in response to some initial perturbation. In the south Indian Ocean, Birol & Morrow (2001) found both wind forcing and eastern boundary processes to be important mechanisms for generating Rossby waves. Oceanic Rossby waves have a large wavelength (of the order of 1000 km) and slow propagation (of the order of 1–10 km per day). They are not just a surface phenomenon, but may affect the full depth of the water column and have the intriguing property that for long wavelengths the group velocity is predominantly westward. This means that they can only convey information (on changes in forcing) from east to west. Further details on the transmission and vertical structure of Rossby waves can be found in Gill (1982). Although the concept of Rossby waves was proposed more than a century ago, and they have been observed in the atmosphere for more than 50 years, there were limited observations of oceanic Rossby waves until the advent of satellite sensors able to provide accurate basin-wide observations every few days. In this short paper we illustrate the observations of Rossby waves in sea-surface height (SSH), temperature and ocean colour datasets, and discuss the challenges in interpretation that have arisen.

One contribution of 25 to a Theme 'Science and applications of the space environment: new results and interdisciplinary connections'.

2. Satellite observations and filtering

Tokmakian & Challenor (1993) first showed that Rossby waves could be detected from space. Subsequently, Chelton & Schlax (1996) have demonstrated that Rossby waves are present in all ocean basins at many different latitudes. Hill *et al*. (2000) were the first to show the near ubiquity of these signals in sea-surface temperature (SST) and, even more recently, Cipollini *et al*. (2001) and Uz *et al*. (2001) noted the chlorophyll signature of Rossby waves in all the main ocean basins. To illustrate the signature of Rossby waves within various datasets we show longitude–time sections (figure 1) of SSH, SST and chlorophyll concentration (CC) at 34° S in the Indian Ocean, as this is a location where the signals for all three are particularly clear.

For the temperature dataset we use measurements from the along-track scanning radiometer (ATSR-2), which has a stated accuracy of 0.3 K for point measurements (Mutlow *et al*. 1994). Although a Hovmöller plot of SST (figure 1*a*) is dominated by the seasonal cycle of warming and cooling, hints of westward-propagating features can be discerned. To enhance these we apply a high-pass filter in the spatial domain. This is simply a matter of differencing the value at a location with respect to a 550 km running mean. This enhances the shorter scale features at the expense of the basin-wide consistent changes (see figure 1*b*). The typical amplitude of these resolved features is 0.5 K, with positive and negative anomalies being equally pronounced.

The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) provides information on ocean colour, from which chlorophyll concentration can be calculated. The stated accuracy for 1 km^2 pixels is of the order of 30% (Hooker & McClain 2000) but, provided that some of the errors are not systematic, the overall uncertainty of the monthly averages used here will be smaller. As the distribution of CC values is approximately lognormal (Campbell 1995), it is sensible to perform our analysis on the logarithms of the values. This means that our filtering returns the *ratio* of CC at a location to the value of the running mean. Again westward features can be discerned, with their peak amplitude being in December–January and the peak occurring slightly earlier in the west than the east. The peak in the CC signal of Rossby waves occurs at the *end* of the spring bloom, which occurs earlier in the west than the east. Although the amplitude of the chlorophyll signature of Rossby waves is at times only 10% (e.g. July–August in the east), there is still a coherent pattern of propagation.

Finally, in figure 1*d* we provide the SSH signature of Rossby waves as detected by the TOPEX/Poseidon altimeter. The altimetric dataset usually contains the clearest indicator of Rossby waves, partly because SSH is an integrated quantity over the entire water column, rather than a surface manifestation that can be masked by local conditions. The surface amplitude of Rossby waves here is of the order of 5 cm, which is significantly above the 2 cm measurement error of the instrument (Cheney *et al*. 1994). Assuming a typical density profile, this surface signal would correspond to undulations of the thermocline depth of the order of 50 m.

3. Correlated observations

Westward-propagating Rossby waves involve the meridional (north–south) displacements of water due to geostrophic velocities associated with the waves themselves. Gill (1982) explains how this relates to changes in currents and thus generates an

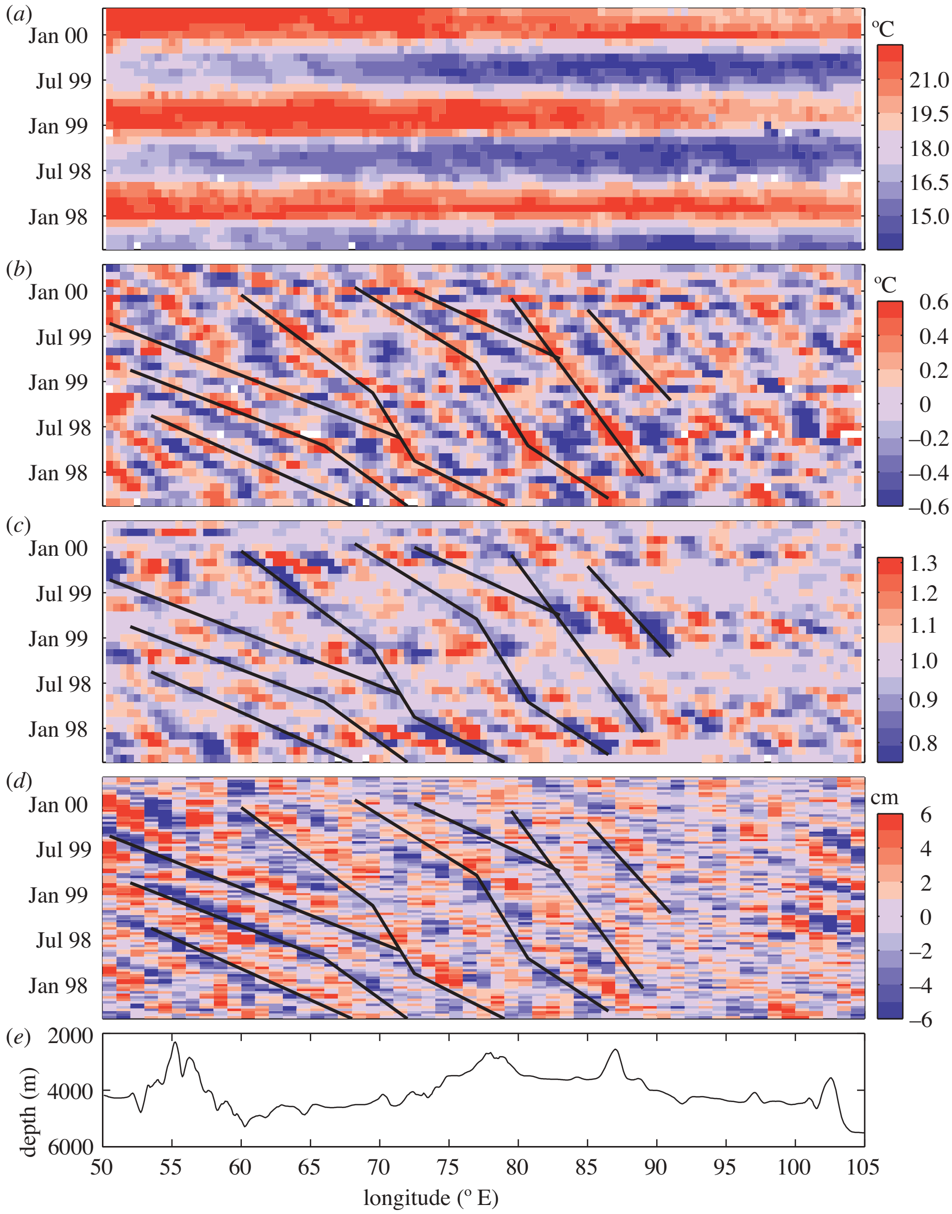

Figure 1. Hovmöller diagrams of various water properties at 34° S in the Indian Ocean. (*a*) SST; (*b*) SST anomalies; (*c*) CC anomalies; (*d*) SSH anomalies (see text for further details); (*e*) bathymetry for the section. (The solid lines are discussed in § 3*a*.)

SSH signal. In the 'waveguide' at 34° N in the North Atlantic, Cipollini *et al*. (1997) noted that the SSH and SST signatures of Rossby waves were in phase, which was explained in terms of a pressure balance through density changes. White (2000), however, found that the SSH signal lags the SST signal by *ca*. $\pi/2$. He explained this predominantly in terms of an advective effect; however, the thermal signal may affect the surface wind, leading to a different phase relationship through ocean–atmosphere coupling.

Three mechanisms have been advocated to explain the signal in ocean colour. First, that the colour signature is simply due to north–south movements of water, which advects the phytoplankton horizontally in a region of marked meridional gradient of CC. Second, that vertical adjustments within the water column have brought the deep phytoplankton up into the surface layer sensed by the satellite. However, simple calculations of the vertical advection of the phytoplankton cells suggest that this effect should be negligible. Third, and most intriguingly, that the Rossby wave has affected the nutrient supply, leading to a genuine increase in biomass. (This is akin to phytoplankton growth in the core of an eddy, which was suggested by McGillicuddy *et al.* (1998) to be due to upwelling of nutrients.) To test these hypotheses, we review the CC observations in light of those from other sensors.

(*a*) *Correspondence of individual events*

In figure 1*c* we have highlighted a number of the westward-propagating local reductions in CC, and replicated these lines in figure 1*b*, *d*. The propagation speeds of these features (given by the slopes of the lines) vary from 1.2 to 4.2 km per day. Some of the features appear to undergo marked changes in speed or else generate secondary features of a different speed to the original. The different speeds are associated with different modes of Rossby waves, each with their own depth structure, and the changes in speed (and generation of new modes) occur where the bathymetry is varying most rapidly. Subrahmanyam *et al.* (2001) have shown that the first three modes of Rossby waves can be found in SSH data for the Indian Ocean, once a number of different latitudes is considered.

The majority of the highlighted features can be found as local increases in SST. Corresponding signals in SSH are not so readily apparent. Most of the *fast* features match a change in SSH such that the SST anomaly leads the SSH by $\pi/2$; the SSH in turn leads the CC by the same amount. In the east, the slower signals (with the more complex depth structure) appear to have no analogue in SSH.

(*b*) *Correlations in phase and changes in amplitudes*

As the closest agreement in the Hovmöller plots appears to be between SST and CC, we performed a lagged cross-correlation of the two. For the signals at 34° S, the strongest agreement was at zero lag, with a correlation of -0.45. Similar results are found for analyses of other sections at latitudes between 31° and 36° S, whereas further north the peak correlation (again at zero lag) is positive (see figure 2). As the SST always increases towards the Equator (figure 3*a*), whereas the CC has a minimum at mid-latitudes, the latitudinal change in sign of correlation coefficient (figure 2) may be thought to be consistent with where the SST and CC meridional gradients are of opposite or same sign. However, the very broad minimum in the annual CC distribution does not produce significant gradients between 21° S and 29° S, whereas in that band there is sufficient CC signal to correlate positively with SST.

Clearly, annual averages do not reveal the whole picture, and figure 1*c* illustrates the strength of seasonal modulation of the CC signal of Rossby waves at 34° S. The

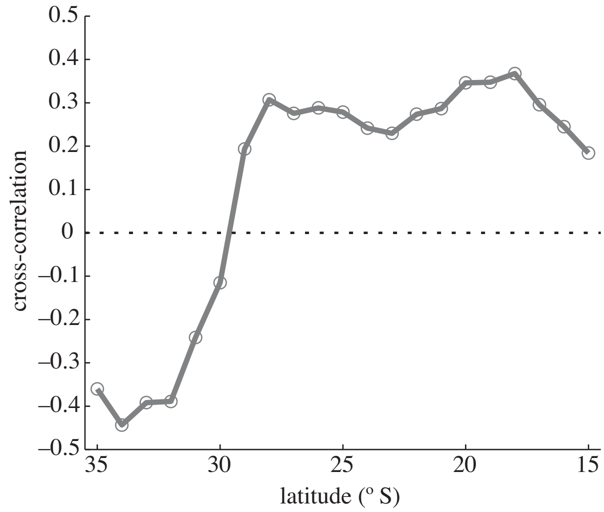

Figure 2. Correlation of chlorophyll and temperature anomalies in the Indian Ocean as a function of latitude.

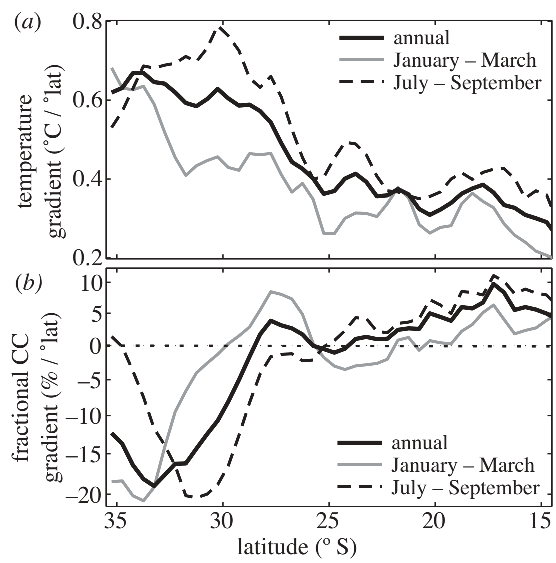

Figure 3. Mean meridional gradients between 50° E and 105° E. (*a*) SST (°C per degree of latitude). (*b*) CC (percentage change per degree of latitude).

majority of the south Indian Ocean has a clear annual cycle in phytoplankton growth, with a peak in CC around September, and the sharp meridional gradient in CC in the south reaches its northernmost position in August (figure 3*b*). However, in the western half of the basin, between 30° S and 20° S, there is a secondary bloom in February and March (Longhurst 2001), giving rise to strong short-lived CC gradients of opposing signs (figure 3*b*). Advection cannot explain why the CC and SST anomalies appear in phase throughout the region north of 29° S (figure 2); thus, other mechanisms must be playing an important role here.

The SST gradient at 34° S is *ca.* 0.65° C per degree throughout the year, and the propagating signal has an amplitude of *ca.* 0.6° C; for January to March, the CC gradient is about −20% per degree, and the propagating amplitude (averaged over 50–105° E) is *ca.* 20%. Thus, the ratio of amplitude to gradient is the same for both CC and SST, giving support to the hypothesis that they are both acting as passive tracers in this region. Cipollini *et al.* (2000) compared the amplitudes and speeds of the various propagating features observed in the SSH and CC datasets. Neither showed significant eastward propagation. The strongest signature of Rossby waves in SSH was between 20° S and 28° S, whereas that region had weak signals in the ocean colour. The ocean colour signal was most marked in the bands 11–17° S and 31–33° S, which is consistent with the strong meridional gradients in figure 3*b*. South of 20° S, the two datasets agreed on the dominant speed of signals but, further north, the ocean colour signal corresponded to a slower (higher order) mode than the SSH. Here, we note a similar mismatch at 34° S in the eastern side of the basin (figure 1*c*, *d*).

4. Conclusions

Rossby waves are known to be present in all ocean basins at most latitudes, but there are still many questions being raised concerning their propagation rates and the interchange of energy between the different modes. Our observations in the south Indian Ocean have shown a strong correlation between the signals in SST and CC. In the band 15–29° S the signals are in phase, whereas for 31–35° S they are in opposition. This is roughly in accord with the signs of their meridional gradients. The relationship with SSH is less clear. At 34° S in the western half of the basin, the first-mode Rossby waves are apparent in all three data sets, with the SSH lagging the SST by $\pi/2$, but leading the CC by $\pi/2$, whereas at the same latitude in the eastern half of the basin there is no SSH analogue of the slower, higher order modes observed in SST and CC. Although the mechanisms behind the ocean colour signal of Rossby waves are still being propounded and tested, the combination of different observing techniques appears to be a promising approach to answering these questions.

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