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Rossby waves detected in global ocean colour data

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Abstract. We demonstrate for the first time the detectability of mid-latitude Rossby waves in global ocean colour data from the Japanese Ocean Colour and Temperature Scanner (OCTS) and U.S. Sea-viewing Wide Field-of-view Sensor (SeaWiFS) radiometers. By producing longitude-time plots of the merged OCTS and SeaWiFS datasets we observe at some latitudes westward propagating signals. Their signature is much weaker than the annual phytoplankton cycle, but can be highlighted by filtering the plots. The main propagating speed is estimated with the Radon Transform and increases equatorward, as expected for Rossby waves. A comparison with both speeds derived from altimeter data and the zonal mean of the speed predicted by a recent theory of Rossby wave propagation shows a broad agreement. We conclude that Rossby waves are sometimes observable in the ocean colour field and thus have some effects on biology, and we suggest two simple hypotheses for the underlying interaction mechanism.

Introduction

Long-wavelength baroclinic Rossby waves play a fundamental role in atmospheric and ocean dynamics [e.g. *Gill*, 1982]. They are the means by which the ocean responds to disturbances from equilibrium due to wind forcing, they affect western-boundary currents and can transmit across the Pacific some effects of El Niño [*Jacobs et al.*, 1994; *Jacobson and Spiesberger*, 1998].

Knowledge of baroclinic Rossby waves in the oceans has dramatically increased with the advent of satellites. Fields of sea surface height (SSH) observed by satellite-borne altimeters such as TOPEX/POSEIDON (T/P) have given a global picture of the occurrence and characteristics of these waves [*Chelton and Schlax*, 1996] and shown that they propagate faster than was previously expected. Recently, Rossby waves have been unambiguously observed in sea surface temperature (SST) data from the Along-Track Scanning Radiometer on board ERS satellites [*Hill et al.*, 2000]. Sometimes the signals observed in SST and SSH show different propagation speeds, which could point to different baroclinic modes of propagation [*Cipollini et al.*, 1997]. A review of the observational techniques and results is in *Cipollini et al.* [2000].

Having observed Rossby wave propagation in global satellite datasets of SSH and SST, it is a natural step to establish whether they have any effects on biology. We therefore examine whether there are any signatures of Rossby waves in time series of global ocean colour data from satellites. The aim of this paper is to demonstrate that westward propagating features are indeed present in a significant number of locations in all the main ocean basins, and that the speed of these signatures is in broad agreement with the expected propagation speed for Rossby waves.

Datasets and Processing Techniques

With the launch (August 1996) of OCTS on board the Japanese satellite ADEOS (whose operation unfortunately terminated on 30 June 1997) and the subsequent launch (August 1997) of SeaWiFS, the scientific community has access to a 4-year long time series of ocean colour data. This is now being extended by SeaWiFS itself and the recently launched MODIS.

In this study we used data from OCTS and SeaWiFS. For OCTS we used Global Area Coverage (GAC) level 3 Binned Map data (monthly chlorophyll-a composites) available from NASDA-EORC. The data have been processed with version 4 chlorophyll algorithm and cover the period November 1996 to June 1997 (8 months in total). For SeaWiFS, we used GAC level 3 data from NASA-GSFC DAAC, processed by GSFC with version 2 chlorophyll algorithm. This study includes 20 months of SeaWiFS data, from October 1997 to May 1999.

The original OCTS and SeaWiFS data have been rebinned from a $0.0879^\circ \times 0.0879^\circ$ grid, far too detailed for observing large-scale features like Rossby waves, onto a $0.5^\circ \times 0.5^\circ$ grid, still sufficient to detect large-scale propagating signals. This additional binning reduces the noise and the effect of potential remnant cloud contamination on the data. Finally OCTS and SeaWiFS datasets have been merged into a single dataset covering 31 months from November 1996 to May 1999, with a three-month gap in summer 1997.

With the merged OCTS and SeaWiFS datasets we have built longitude-time plots at given latitudes, a technique typically used to look for Rossby waves because of their mainly zonal (east to west) propagation. Propagating waves appear as diagonal features in the plots. Figure 1 a) shows the longitude-time plot at 35.75°S in the Indian Ocean. The most evident feature is the annual phytoplankton cycle with a bloom starting in May and extending to December. On closer inspection there is a hint that, superimposed on the bloom, weak signals are propagating to the west, but it is clear that some filtering is needed in order to make these evident. In figure 1 b) we show the same plot after high-pass filtering along the longitude direction only. The one-dimensional filter adopted has a kernel of 61 samples and its idealized response is 1 for all wavelengths shorter than 40 samples (that is 20°) and 0 elsewhere. The real filter has been designed by windowing the idealized response with a Hanning window (in order to minimize the sidelobes of the

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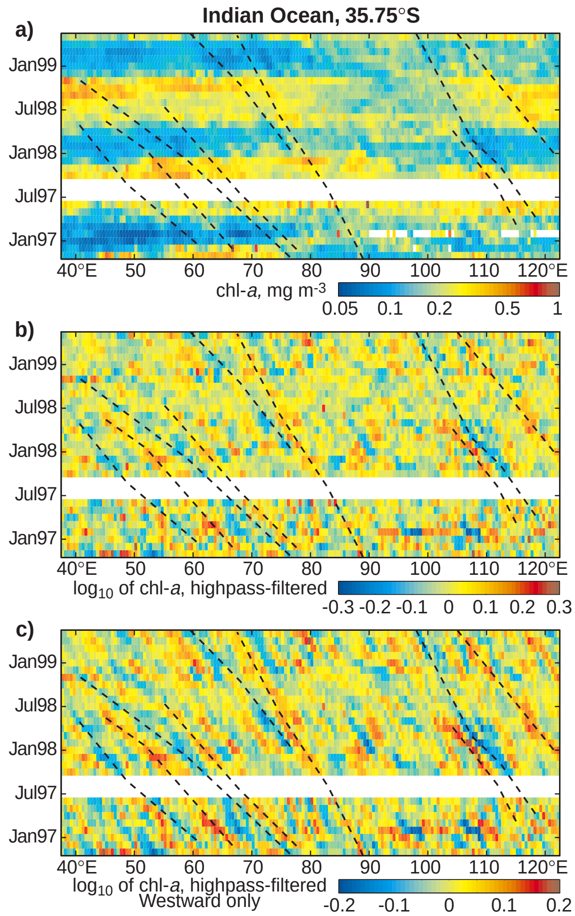

Figure 1. **a)** Longitude-time plot of the combined OCTS and SeaWiFS monthly chlorophyll concentrations at 35.75°S in the Indian Ocean. The colorscale is logarithmic. **b)** same as in a), after high-pass filtering as described in the text. **c)** same as in b), after westward-only filtering as described in the text.

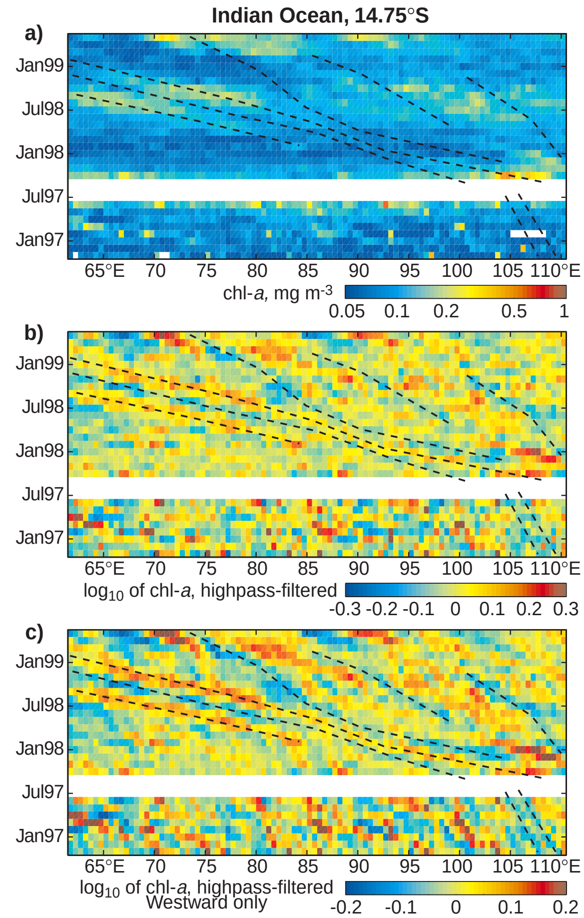

Figure 3. As in fig. 1, for 14.75°S in the Indian Ocean.

real response) hence its response has smoothed sides. To avoid edge effects, the filter was applied to a plot 60 points (30°) wider (30 points on each side) than shown in figure 1 a) and 30 pixels were removed from each side after filtering.

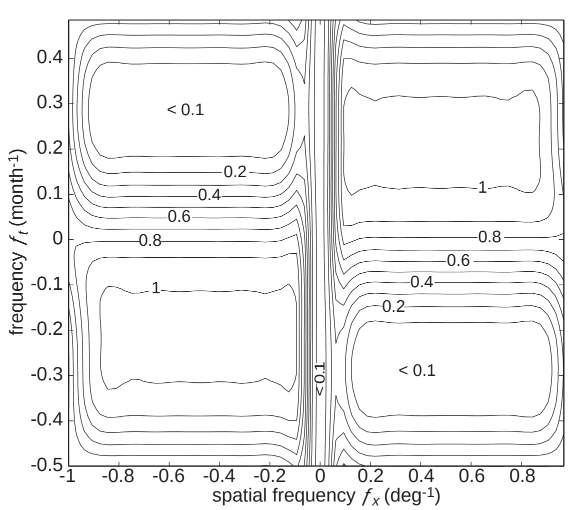

Figure 2. Frequency response of the cascade of two filters employed in the processing.

In figure 1 b) the presence of westward propagating alignments is much clearer than in figure 1 a) and unequivocal. It must be noted that the highpass filter adopted is perfectly symmetric and does not favour westward-propagating features over eastward propagating ones. Nevertheless, we could not detect any unambiguous eastward-propagating features in figure 1 b).

To make the detection of westward propagating features easier, we applied to figure 1 b) a two-dimensional filter whose idealized response is 1 in the first and third quadrants (including the f_x axis) of the f_x, f_t domain and 0 elsewhere. This was implemented as a 21×7 samples kernel windowed with a Hanning window and was applied separately to the OCTS and SeaWiFS regions of figure 1 b). Given that the plot in figure 1 b) has approximately zero mean we could use a zero padding technique at the borders. The results are shown in figure 1 c), while figure 2 shows the cumulative two-dimensional response of the two filters. In figure 1 c) we have highlighted with dashed lines some of the most visible alignments of crests and troughs, corresponding to westward-propagating features. It is worth noting that some of the alignments observed in the OCTS data match those in the SeaWiFS data. The same dashed lines have been copied to figure 1 a) and 1 b) so that it is easier for the reader to appreciate the effects of the filtering technique on the visibility of the features. The speed of the propagating features, which can be directly inferred from the slope of the dashed lines, varies from 2.1 to 5.6 cm/s. This large degree of variability could be partly due to the longitudinal variability of the propagation characteristics (on average the features on the left hand side are going faster). To get an objective estimate of the "mean" propagation speed (or the speed of the strongest propagating signals when more than one speed is present) at this particular latitude, we have applied to the plot in figure 1 c) the same Radon Transform (RT) technique described in *Hill et al.* [2000]. The RT has a peak at 3.7 cm/s.

In order to compare ocean colour with altimetry we also produced longitude-time plots of gridded (1°×1°× 1 cycle of 9.92 days) SSH anomalies from T/P, at any location where we detected unambiguous westward propagating features in ocean colour. We used T/P cycles 1 to 234 (September 1992 to February 1999) and applied the same filtering and RT techniques as for the ocean colour data. At 36°S (the closest latitude to the one in figure 1) the longitude-time plot of T/P data (not shown) has very clear signatures of Rossby waves whose speed (from the RT) is 4.0 cm/s, in good agreement with the result from the ocean colour dataset. A detailed (feature-to-feature) comparison of the propagating features in the colour with those in the altimetry in all those locations where these are present would greatly exceed the scope and the size of this paper. We will limit the present analysis to a comparison of the mean speeds as estimated with the RT.

Results

The scheme described above was applied to ocean colour data worldwide. Northward of 36°N we did not observe any clear propagating signals. Southward of 40°S we still observe alignments in the longitude-time plots but the situation in many places is complicated by the strong advection by the Antarctic Circumpolar current and there are a number of eastward-propagating (or even quasi-stationary) features. Moreover, this study does not investigate equatorial Rossby waves (whose propagation speed may be too fast to be resolved by a monthly dataset), so in the following we limit our analysis to 40°S to 10°S and 10°N to 36°N.

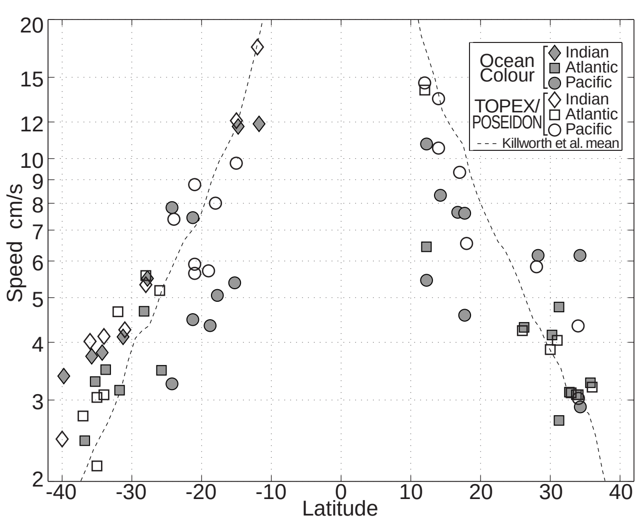

Figure 4. Comparison among ocean colour-derived speeds, T/P-derived speeds at the same locations and the global zonal mean of the speeds predicted by Killworth et al.'s theory.

In some of the filtered longitude-time plots we do see features propagating westward. They are neither as sharp nor as ubiquitous as those observed in altimeter data [*Chelton and Schlax*, 1996] and infrared data [*Hill et al.*, 2000]. Nevertheless they are unambiguously detectable and appear at various latitudes in all three main oceanic basins. Their speed depends on latitude; as a general trend, the closer to the equator, the faster they propagate, just as Rossby waves do. As an example, figure 3 shows, analogously to figure 1, the two-step processing of the longitude plot of ocean colour data at 14.75°S in the Indian Ocean. In figures 3 b) and 3 c) we observe propagating features some of which are indicated by dashed lines. They propagate at a speed between 6.9 and 14.8 cm/s (much faster than those seen in figure 1) and the RT estimates a mean speed of 11.7 cm/s. The same analysis on T/P data gives a mean speed of 12.1 cm/s.

By analysing the longitude-time plots at all mid- and low latitudes we have been able to select a number (N=31) of locations where the propagating signals in the ocean colour data are unequivocal. For these locations we also checked that the RT estimates of speed were visually consistent with the longitude-time plots, as *Chelton and Schlax* [1996] did for T/P data. The speeds for these locations are plotted against latitude in figure 4. In a small number of locations where the longitude-time plot and the RT consistently showed two distinct speeds, both those speeds have been kept in the plot. The same figure also shows the speeds derived from T/P data in the same locations, alongside the zonally-averaged propagation speed predicted by the revised theory of Rossby waves by *Killworth et al.* [1997]. In some places (amongst which 5 locations in the Indian Ocean) the colour- and T/P-derived speeds agree to within 10%. Elsewhere the relation is more complex, but the overall picture shows a broad agreement. Both the T/P and the ocean colour speeds are greater than theory at mid-latitudes in the Southern Hemisphere. Closer to the equator, in both hemispheres, ocean colour seems to yield slower speeds than altimetry. One possible explanation of this could be that with different parameters we see different baroclinic modes of propagation (higher order modes in ocean colour), as already observed in SST versus altimetry by *Cipollini et al.* [1997], but this will have to be investigated further.

Discussion

The propagating features that we observe in ocean colour fields at latitudes lower than 35°-40°appear in different places across the three main ocean basins. Their speeds tend to increase equatorward and broadly match both the speeds inferred from the analysis of altimeter data and the speeds predicted by the most recent theory. It is also worth noting that we do not see anything similar propagating eastward. For these reasons we believe that the features observed are the effect of Rossby wave propagation on ocean colour. Although *Machu et al.* [1999] interpreted some features seen in a few snapshots of SeaWiFS data from the subtropical convergence zone south of Africa as due to Rossby waves, the present study marks the first geographically-distributed identification, as far as the authors are aware, of unambiguous propagation of extra-tropical Rossby waves in the ocean colour field.

The above result opens several intriguing questions. One is why we seem to see Rossby waves in ocean colour in just some areas, and not necessarily where they are stronger in SSH. Is biology affected by Rossby waves only in some places and under particular conditions, and by which modes? And how can the mechanism of interaction be explained?

Such questions will be tackled on an interdisciplinary basis. For the moment it seems appropriate to suggest a couple of possible mechanisms for the effect of Rossby waves on ocean colour. The first explanation is mainly mechanical: the modification of the isopycnals due to the passage of a Rossby wave could bring more phytoplankton cells closer to the surface (or vice versa) and thus either affect the amount of phytoplankton seen by the satellite without changing its total (vertically-integrated) amount, or increase/decrease growth, by bringing more cells into the euphotic zone or pushing them out of it. The second possible explanation would be the modification in the upwelling of nutrients due to the raising and lowering of the thermocline associated with a Rossby wave, and thus a direct effect on the growth of a nutrient-limited population of cells.

We can conclude that propagating long-wavelength baroclinic Rossby waves can be detected in global ocean colour data, and that further work, including modelling studies and a detailed comparison of the ocean colour-derived speeds and phases with those derived from altimetry and SST, is needed to shed more light on this intriguing phenomenon and the underlying mechanisms.

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