Global characteristics of Rossby wave propagation from multiple satellite datasets

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ABSTRACT

This paper presents a study of the global characteristics of extra-tropical oceanic Rossby waves from datasets of Sea Surface Height (SSH), Sea Surface Temperature (SST) and ocean colour. We deal in particular with the propagation speed of the waves and compare the observational results with the speeds predicted by the classical theory and by an extended theory of Rossby waves. We also discuss, with an example, the additional information that can be derived by a comparison of the wave signatures in the different datasets.

1. INTRODUCTION

One of the most intriguing phenomena in the oceanic and atmospheric circulation is a particular class of internal, long-wavelength waves known as Rossby (or planetary) waves, whose existence is due to the shape and rotation of the Earth. In the oceans these waves have surface manifestations of just a few cm, and wavelengths at mid-latitudes of hundreds of km. They travel zonally from east to west at speeds of few cm/s (increasing equatorwards), and consequently can take months or even years to cross the main ocean basins, delaying the transmittal of information about climatic events that happened in the eastern part of the oceans (such as El Niño in the Pacific). Rossby waves affect the western boundary currents and thus can have major effects on ocean circulation and climate.

Until the late 1980s there had been only a few very sparse and incomplete *in situ* observations of oceanic Rossby waves, as undulations of tens of meters in the thermocline. With the 1990s advent of satellite altimetry these waves have finally been observed and studied in detail. Using data from the TOPEX/POSEIDON (T/P) satellite altimeter Chelton and Schlax (1996) have shown that Rossby waves are almost ubiquitous in the world's oceans.

2. OBSERVATIONS OF ROSSBY WAVES

2.1 Global observations

Because of their mainly zonal propagation, Rossby waves can be easily observed in longitude/time plots of Sea Surface Height (SSH) data. Figure 1 shows a longitude/time plot of T/P SSH anomalies (about a 3-year mean) across the whole globe at 28°S. Rossby waves are apparent as diagonal alignments of crests and troughs propagating westward with time. Their speed (the slope of the alignments) is different from ocean to ocean and varies also within the same basin – as a general trend, the waves tend to speed up as they move westward (this is evident for some of the crests and troughs in fig. 1), but there can be local variations of both signs due, for instance, to the interaction of the waves with the bottom topography (Killworth and Blundell, 1999). An average or 'main' propagation speed can however be measured on each basin (or on smaller regions where it is more constant) with image processing techniques such as the Fourier Transform or the Radon Transform.

Altimeter-based observations of Rossby waves, and in particular the global study by Chelton and Schlax (1996), have pointed out that on average the waves propagate faster than would be expected from the classical (linear) theory of Rossby wave propagation. In some locations especially at mid-latitudes, the propagation speed is 2 to 3 times greater than that predicted by theory. This has stimulated critical reconsideration of the assumptions in the linear theory, and one of the most promising amendments to date is the extended theory by Killworth et al. (1997). Figure 2 shows a global map of the ratio between the speeds observed in a Radon Transform analysis of about 6 years of T/P data and the speeds predicted by Killworth et al.'s theory. Although there are differences from one basin to another, in both hemispheres there is a region, roughly between 15° and 35° of latitude, in which the observations and the extended theory agree. Equatorwards of 15° the observed speeds are significantly slower than those predicted, while polewards of 35°-40° the amplitude of Rossby waves decreases (as expected from the theory, which also predicts a *cut-off latitude* beyond which the waves should disappear) and the signal becomes noisy. However in some regions of the Southern Ocean we observe eastward-propagating features which can be interpreted as Rossby waves being advected by the Antarctic Circumpolar Current, due to the strong barotropicity of this current. At mid-latitudes speeds are only slightly faster than Killworth's theory; note the zonal bands at 25°-35°S in the S Atlantic, 30°-40°S in the Indian and 30°-35°N in the N Atlantic.

2.2 Multisatellite observations of Rossby waves

Baroclinic Rossby waves have also been observed in SST and ocean colour. Cipollini et al. (1997) found evidence of the first three baroclinic modes of propagation in Along-Track Scanning Radiometer (ATSR) data at 34°N in the Atlantic. More recently, the global study of Hill et al. (2000) has demonstrated the waves to be almost ubiquitous in the SST dataset too. A longitude/time plot of ATSR data at 28°S (not shown here) reveals clear alignments of crests and troughs similar to those seen in figure 1, and propagating at comparable speed. Hill et al. have compared the speeds retrieved from the SST analysis to the predictions of the extended theory by Killworth et al. (1997), and found a broad agreement. They too observe the waves going slower than expected in the tropics. In a number of locations spread across the ocean basins, using chl-*a* data from OCTS and SeaWiFS, Cipollini et al. (2001) have observed westward-propagating features, whose characteristics are similar to those of baroclinic Rossby waves. While this implies some effects of the waves on biology, the detailed mechanisms are still under investigation.

In some locations, the simplest explanation for the SST and ocean colour observations of Rossby waves is advection of meridional gradients. We illustrate this with an example at 32°S in the Indian Ocean. Figure 3 shows a comparison of longitude/time plots of four different datasets: SSH from T/P, chl-*a* anomalies from SeaWiFS, SST from both the ATSR and the passive microwave radiometer TMI on board TRMM. The plots have been zonally band-passed to remove the large-scale seasonal variations, as described in Quartly et al. (2000). Note in particular the very good agreement between the two SST datasets, which excludes that the propagating signals observed might be an artefact of a particular instrument. The solid lines mark four propagating minima in the chl-*a* dataset, and also correspond to local maxima in the SST dataset. Moreover the SSH signal for the two first mode baroclinic Rossby waves in the western part of the basin lags the SST by about 90°, whilst there is no SSH signal apparent for the two slower features in the east. Given that in this region the meridional gradients of SST and chl-*a* have opposite signs, advection of those gradients by the geostrophic currents associated with the passage of a Rossby wave can explain the phase opposition between the features seen in SST and those seen in ocean colour. Other mechanisms are possible in principle (including shoaling of the deep chlorophyll maximum and increased productivity due to nutrient upwelling), and a detailed analysis of the phase relationship between the different datasets is now needed to shed some light on these multisatellite observations.

Figure 4 shows a summary of the propagation speeds obtained from the different observations. The figure shows the zonally-averaged (median) speed from T/P and ATSR, compared with the prediction of the old linear theory and the extended theory by Killworth et al. (1997), and also includes the ocean colour results of Cipollini et al.'s (2001). The extended theory matches well the ATSR-derived speeds, and greatly reduces the discrepancies with respect to the T/P-derived speeds. A residual discrepancy remains between SST observations, extended theory and T/P observations in the S hemisphere, polewards of 30-35° (as shown in figure 2, this residual divergence is concentrated in the S Atlantic and S Indian oceans). One possible explanation for the differences between the SSH and SST observations is that the SST might be more sensitive to higher-order, slower modes as observed by Cipollini et al. (1997) in the northeast Atlantic.

3 CONCLUSIONS

Rossby waves in the oceans are an important phenomenon, which can now be studied in detail thanks to satellite observations. The advent of altimetry has revealed the shortcomings of the classic linear theory and prompted theoreticians to extend it, in order to reduce the discrepancies between observed and predicted speeds. We have presented the global results derived from datasets of SSH, SST and ocean colour and illustrated, with an example, how a study of the signature of the single wave events in different datasets can help understand the underlying interaction mechanisms. Such a global study, and a detailed analysis of the multiple baroclinic modes apparent in SST and SSH, is now needed to obtain valuable information about the ocean interior from space.

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FIGURES

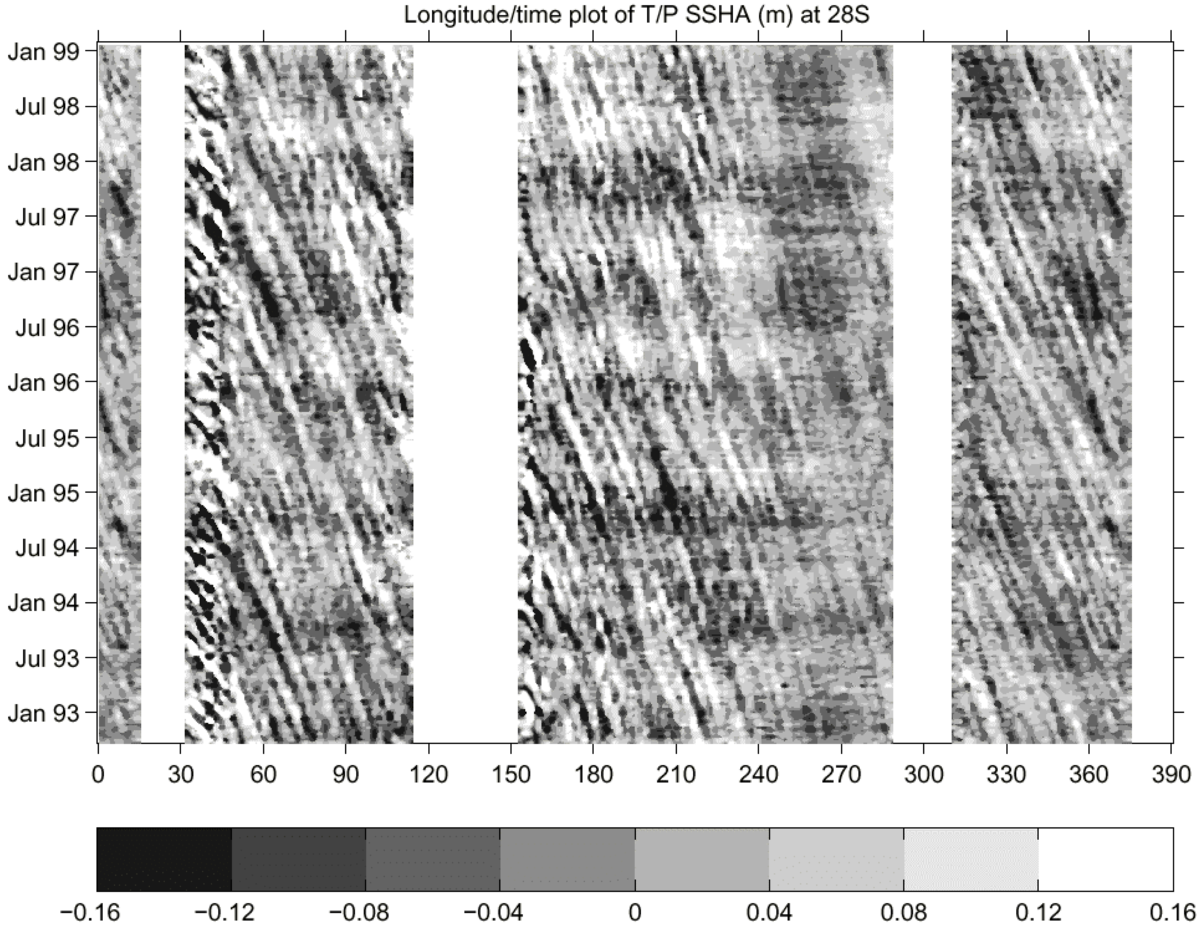

Figure 1 – Global longitude/time plot of Sea Surface Height residuals at 28°S from the T/P altimeter

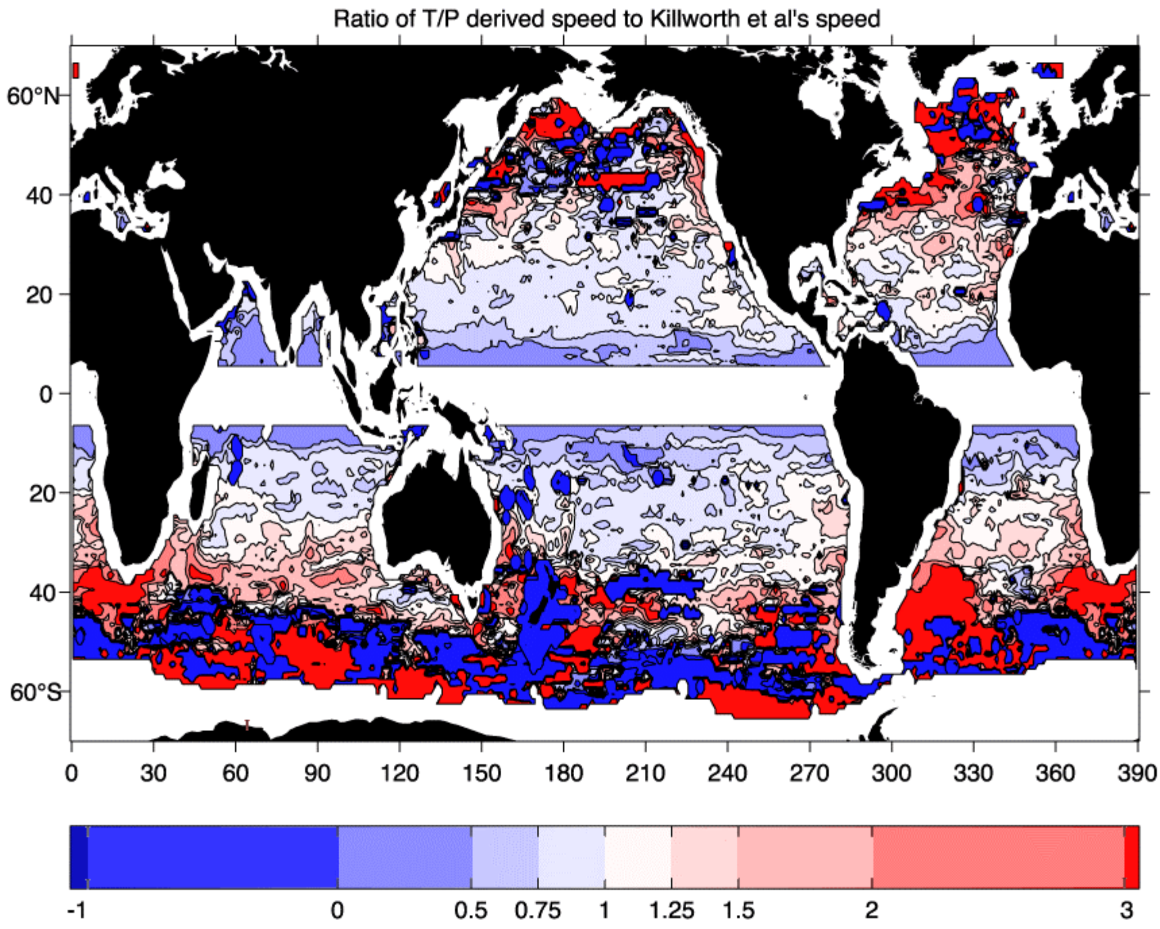

Figure 2 - Ratio between the T/P derived Rossby wave propagation speeds and the speeds predicted by the extended theory by Killworth et al. (1997)

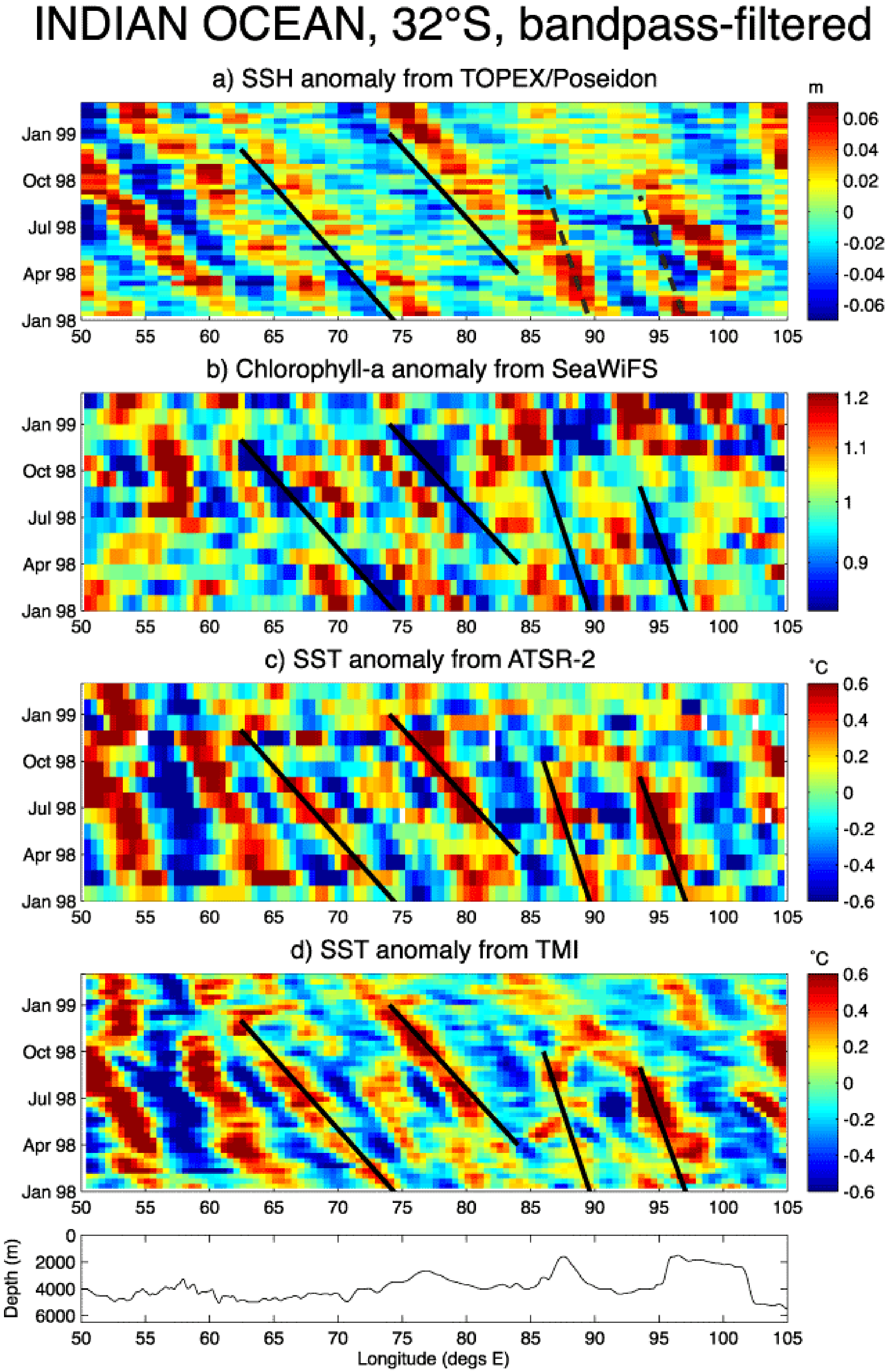

Figure 3 - Comparison of signatures of Rossby waves in four different datasets at 32°S in the Indian Ocean

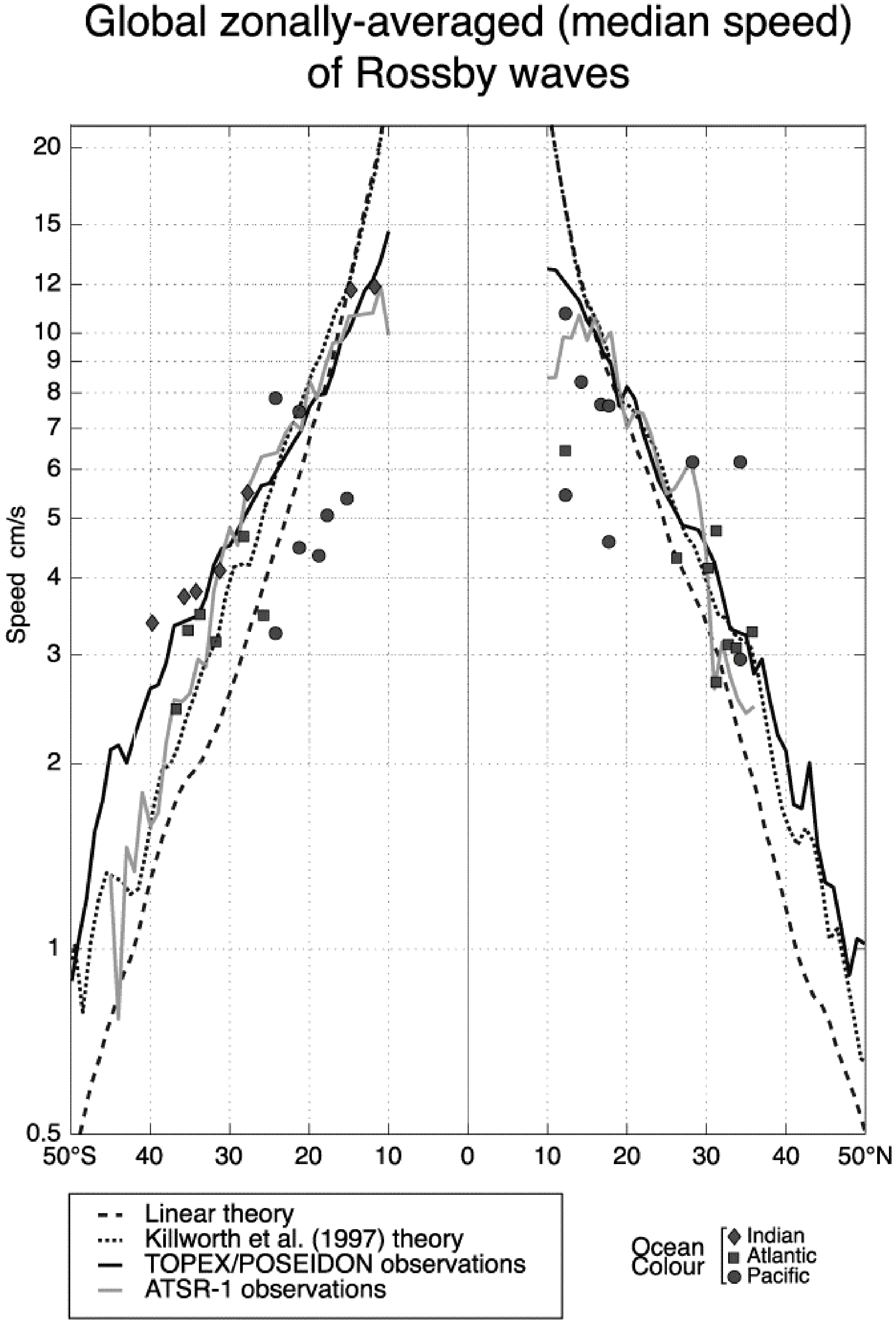

Figure 4 – Summary of zonally averaged speeds from linear theory, extended theory, T/P and ATSR observations, plus single (non zonally-averaged) ocean colour observations.