Remote Sensing of Oceanic Rossby Waves: New Techniques and Results

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ABSTRACT

In recent years, satellite remote sensing has provided a global picture of westward-propagating Rossby waves. This paper reviews some techniques that are needed to extract the information about the waves from different satellite datasets. Geophysical effect corrections and signal processing techniques are described, including the use of the Radon Transform on longitude/time plots of satellite data and its extension to the 3-D domain. The main results in terms of global distribution and speed of Rossby waves are presented and discussed.

INTRODUCTION

Long baroclinic planetary waves or Rossby waves play a fundamental role in ocean dynamics and can dramatically affect weather patterns and climate. They affect currents and transport momentum and information across the main oceanic basins. They may also delay the effects of major climatic events like El Niño on the ocean circulation and they set the adjustment time of the ocean to atmospheric forcing. Accurate knowledge of their characteristics and distribution is thus needed and can significantly improve the way we model the oceans and climate change.

The existence of Rossby waves in the oceans and atmosphere had been postulated by Carl-Gustav Rossby in the 1930s. But while they are relatively easy to observe in the atmosphere (as they affect atmospheric fronts and winds in a visible manner), until the early 1990s we had only a few indirect clues of their presence in the oceans. This is primarily because of the unusual scale of these westward-propagating waves: at the surface of the sea they appear as an undulation of just a few centimeters, while the horizontal scale (wavelength) is of the order of several hundreds kilometers. The resulting wave profile is so flat as to be undetectable by any conventional *in situ* technique, and the few sparse measurements available have been made at the depth of the thermocline, where the amplitude of the wave signal is significantly larger (a few tens of meters) – see for instance [1].

This picture has changed dramatically with the advent of satellites, and of satellite altimetry in particular. The accuracy of the retrieval of Sea Surface Height (SSH) by satellite-borne radar altimeters such as TOPEX/POSEIDON (T/P) and those on board ERS-1 and ERS-2, has allowed a detailed study of these waves and proven them to be almost ubiquitous [2]. Subsequently, the signature of Rossby waves has been observed in the Sea Surface Temperature (SST) field from AVHRR and the Along-Track Scanning Radiometer (ATSR) on board the ERS satellites. See for instance [3] for a comparison of the SST versus the SSH signature of Rossby waves at 34° N in the Northeast Atlantic and [4] for a global study of their occurrence in ATSR-1 data. Recently, westward propagating signals which can be ascribed to Rossby waves have been observed in the ocean colour dataset [5].

A number of signal processing and statistical techniques need to be applied in order to extract the information about the westward-propagating signals from satellite data. This paper briefly presents the most recent developments. An example in the North Atlantic and some global results of their application are also presented and discussed.

DATA AND CORRECTIONS

In this section we briefly summarize the processing and the corrections applied to global datasets of sea surface height (from T/P and ERS-1 and -2 satellite-borne altimeters) and ATSR-derived SST to make them suitable for Rossby wave analysis.

<u>SSH data</u>

We apply to SSH measurements from T/P a standard set of corrections for orbit errors, atmospheric delays, tides and sea state effects (more details are in [3]). The accuracy of the SSH retrieval with T/P after these corrections is of the order of 2 cm. A mean height profile is calculated for the three calendar years 1993-1995, and SSH anomalies are computed relative to that. Each cycle of data is then interpolated onto a

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1° by 1° grid. The interpolation, which uses a weighted mean of all the data within 200 km of a grid point, reduces the instrument and correction errors whilst leaving the larger scale signal relatively unaffected. The ERS altimeter data are treated in a similar way to those from T/P, except that referencing is done to the mean ERS height profile. In particular, we use the DGM-E04 gravity model to correct for orbit errors [6]. This makes the accuracy of ERS-derived SSHs comparable with that of T/P and thus perfectly suitable for the observation of Rossby waves.

SST data

ATSR, in virtue of its low detector noise, stable on-board blackbody calibration, and dual-looking geometry to correct for intervening atmosphere, gives estimates of the SST with an accuracy as high as 0.3 K on the single 1-km measurement, and even greater on averages. We use the ASST (Average Sea Surface Temperature) product provided by Rutherford Appleton Laboratory, which consists of SST on a regular 0.5° by 0.5° latitude-longitude grid. Further filtering is then applied to the longitude/time plots in order to highlight the signature of Rossby waves (see below).

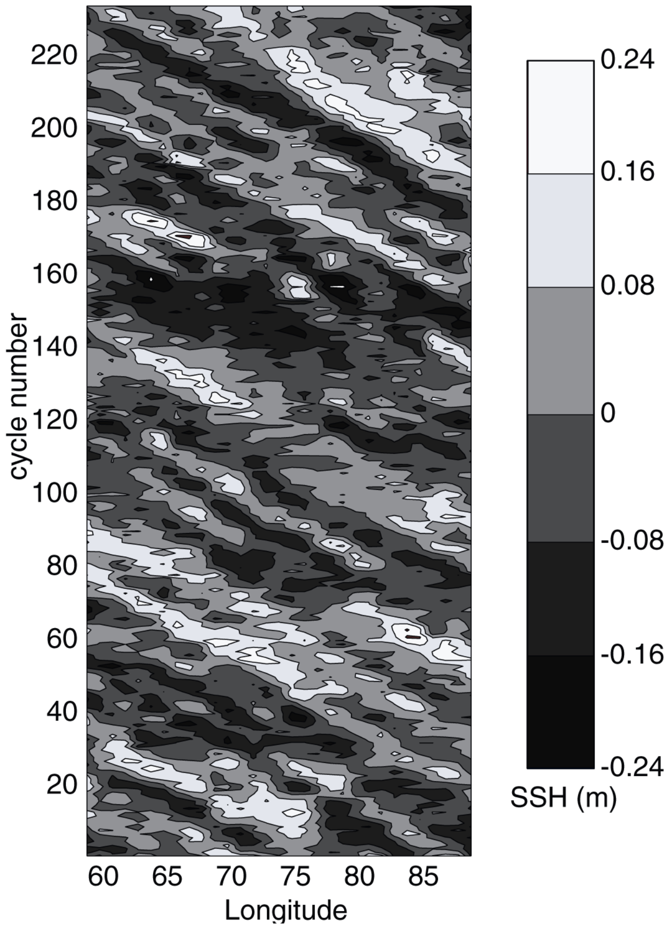

Fig. 1 – Longitude/time plot of SSH anomalies from T/P at 25° S in the Indian Ocean.

TECHNIQUES AND RESULTS

The initial approach to the observation of Rossby waves is to build a longitude/time plot of the data. Due to their mainly zonal, east-to-west propagation the wave crests and troughs appear as diagonal alignments in the plot. Fig. 1 shows clear Rossby wave propagation in a plot of SSH anomalies from T/P at 25° S in the Indian Ocean. One way of measuring the propagation speed of Rossby waves is by eye, measuring the slope of the alignments directly on the plot, but a more objective method is desirable. One such method is the Radon Transform (RT), commonly used in image processing and seismology. The 2D-RT at a given angle θ is the projected sum of the longitude/time plot along a direction normal to that angle, and can be used to give an objective estimate of the speed of the predominant propagating signal – we only need to compute the RT energy (i.e., sum the squares of the RT) for every θ, and find the value of θ for which that energy is maximum.

The 2D-RT can easily be applied to both the SSH and SST data. Fig. 2 shows the energy of the RT in the western and central portions of the Atlantic at 31° N, as inferred from different SSH and SST datasets. The position of the peaks gives an estimate of the main propagation speed of Rossby

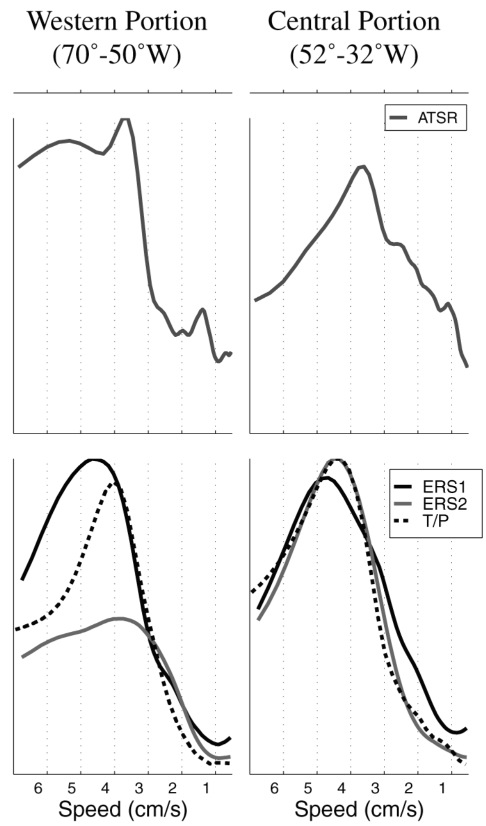

Fig 2 – Energy (arbitrary units) of the 2D-RT of various datasets at 31° N in the Atlantic.

waves. The fact that Rossby waves are seen to travel slightly slower in the SST dataset could indicate that SST is more sensitive to higher-order baroclinic modes of propagation as suggested in [3].

Before applying the 2D-RT, longitude/time plots need to be preprocessed. First, the plot window is convolved with a 2-D band pass filter designed to remove the high frequency noise and the residual large-scale variability. Then the plot is tapered using a Hanning window of the same size. This minimises the effects of the rectangular shape of the matrix to be analysed, which would otherwise generate unwanted undulations (lobes) in the Radon transform and spurious peaks in its energy. A detailed description of the methodology is in [4].

The procedure described above has been applied to global datasets of SSH from T/P and SST from ATSR. Fig. 3 summarizes the results in terms of zonal average (median) of the propagation speed of the waves detected. The most striking feature is that speeds outside the tropics appear to be significantly faster (up to a factor 2-3) than those predicted by the linear theory. This fact has been initially pointed out in [2] and has prompted a n umber of further theoretical studies.

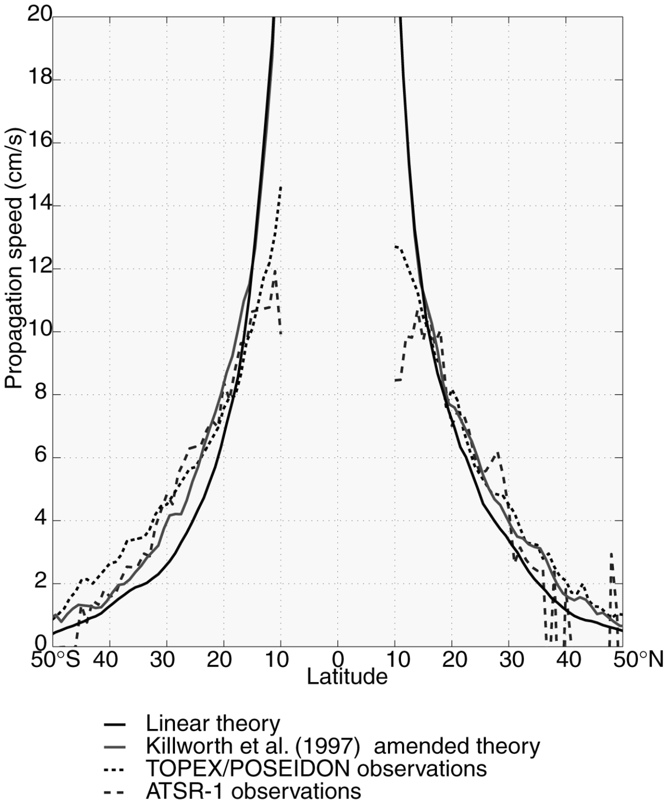

Fig. 3 – Global zonally-averaged propagation speed of Rossby waves from linear theory, Killworth et al.'s theory [7] and 2D-RT analysis of T/P SSH and ATSR-1 SST data.

In [7] a revised theory of Rossby wave propagation has been proposed, which takes the mean background flow into account. The speeds predicted by this revised theory are in a much better agreement with the observations at mid-latitude, as shown in Fig. 3, although some residual discrepancy is observed in the southern hemisphere around 30-40° S, where the SSH-derived speeds remain faster than predicted (and also than those observed in the SST dataset).

More recently, we have extended the RT to the three-dimensional (longitude/latitude/time) domain to study the directional properties of Rossby waves, that is any deviation of the direction of propagation from pure westward. The 3D-RT is a projected sum of a cuboid of data onto a plane. Thus in the 3D-RT analysis we look for alignments of crests and troughs inside cuboids (rather than longitude/time plots) of data [8]. Global results (not shown) indicate that in many areas of the world oceans the propagation is almost purely westward. Research, using the same technique, is also underway on the correlation between the variation of speed and direction with longitude and bottom topography.

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