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Characterization of westward propagating signals in the South Atlantic from altimeter and radiometer records

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ABSTRACT

Radar altimeter data from TOPEX/Poseidon and Jason-1 and microwave radiometer data from TRMM/TMI are used to investigate the large-scale variability between 10.5°S and 35.5°S in the South Atlantic Ocean. The proposed method for the analysis of the longitude–time diagrams of the cross-correlation between SSH and SST anomalies shows that the variability in mid latitudes is a blend of first-mode baroclinic Rossby waves and propagating mesoscale eddy-like structures. The estimated phase speed of the wave (c_p) and propagation speed of the eddies (c_v) are similar. In 70% of the cases, the absolute difference between c_p and c_v is less than 11%. In 40% of the cases this difference is less than 5%. Statistical results indicate that in the case of eddies, as the thermocline deepens the sea surface temperature rises and vice-versa. However, planetary waves show more complex, yet self-consistent results. In lower latitudes (10.5°S–15.5°S), the shallower thermocline and the weak thermal gradients impose a zero phase lag between temperature and height, similar to eddies. Poleward of those latitudes, sea surface temperature and height are in quadrature of phase. This indicates that geostrophic advection of the relatively stronger thermal gradient is performed by Rossby waves.

1. Introduction

Apart from the large-scale non-propagating signal, the most energetic signal in the sea surface temperature (SST) and sea surface height (SSH) data is composed of meso- to large-scale anomalies, approximately 300–1000 km, that propagate westward and oscillate with annual to intra-annual frequencies. According to Robinson (1983) there are two processes able to explain variability on these spatial and temporal scales: Rossby waves and eddies. Previous studies (Chelton & Schlax, 1996; Cipollini et al., 1997; Polito & Cornillon, 1997; Polito & Liu, 2003) showed that the largest portion of these propagating signals is associated with first-mode baroclinic Rossby waves. However, recent studies performed by Chelton et al. (2007); Chelton, Schlax, et al. (2011) conclude that most of the observed westward propagating signals previously classified as Rossby waves cannot be explained by existing wave theories and should be reinterpreted as nonlinear mesoscale eddies, i.e. the westward propagating variability is dominated by mesoscale eddies. On the other hand, they do not rule out the role of Rossby waves in this variability completely. The latest results obtained by Chelton, Schlax, et al. (2011) reinforce the discussion about the predominance of eddies on Rossby waves and it is the main motivation for the present study in attempting to separate the contributions of these two classes of phenomena.

The meso- and large-scale oceanic variability obeys the quasi-geostrophic vorticity equation whose linearized solution supports Rossby waves. The formation of eddies is associated with instability processes, thus they depend on the nonlinear terms of the equation. Despite the fact that they are dynamically two distinct phenomena, the main observational problem is how to distinguish between Rossby waves and eddy-like features, because eddies propagate with speeds similar to the phase speed of baroclinic Rossby waves. Therefore, in longitude-time diagrams, eddies and waves would generate somewhat similar patterns of propagation. There are some important differences: eddies are generally isolated features, more intermittent when compared with waves. In addition, they have a significant meridional propagation speed and impose a specific phase lag between SST and SSH. The working hypothesis is that the eddy and wave signals are distinguishable through the analysis of the 2D cross-correlation between SST and SSH. In that, both eddies and waves imprint their statistically relevant length and time scales in their auto-correlation matrices. However, the cross-correlation selects commonalities between the two spectra and retains the phase lag information.

Altimetry and thermal satellite records are, respectively, the observational data most often used to identify wave and eddy signals. The method developed here uses SSH and SST data to quantify the relative contribution of each portion of the signal, wave and eddy, to the total variance. The objective is to characterize the westward propagating signals in terms of their dominant physical processes and propagation speeds obtained from SSH and SST data. Our focus is the simultaneous analysis offirst-mode baroclinic Rossby waves and eddies in the two datasets, SSH and SST. To do that, a method based on the analysis of the zonal-temporal cross-correlation matrices was developed.

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1.1. Observations of westward propagation

Described in the 1930s by Carl-Gustav Rossby, oceanic Rossby waves were observed for the first time from *in situ* data by Emery and Magaard (1976); McWilliams and Flierl (1976), and studied in numerical models by Barnier (1986); Kirtman (1997); Subrahmanyam et al. (2009), and many others. The advent of precise satellite altimetry in the 1990s provided an observational basis that allows the identification of propagating features through measurements of the sea surface height anomaly (SSHA). Using data from TOPEX/Poseidon (T/P) satellite altimeter Polito and Cornillon (1997); Cipollini et al. (1997); Polito and Liu (2003) observed and quantified the main parameters associated with the propagation of baroclinic Rossby waves in the Atlantic Ocean. The discrepancy between the phase speeds obtained from altimeter observations (Chelton & Schlax, 1996) and the linear theory elicited an extension of the classical theory by Killworth et al. (1997); Killworth and Blundell, 2003a, 2003b. In these extensions the authors suggested that the presence of baroclinic east–west shear flow and a slowly varying of the topography induces variations in the potential vorticity gradient able to modify the phase speed of the waves.

Baroclinic Rossby waves have also been observed in SST records from microwave radiometers. The Along-Track Scanning Radiometer (ATSR) onboard the European Remote Sensing satellites (ERS-1; ERS-2) and the TRMM Microwave Imager (TMI) onboard the Tropical Rainfall Measuring Mission (TRMM) are the radiometers most used to observe westward propagating signals in the ocean (Challenor et al., 2004; Cipollini et al., 1997; Hill et al., 2000). First mode baroclinic Rossby waves generate perturbations in the thermocline/pycnocline depth on the order of three times greater than at the surface, but with the opposite phase. These vertical displacements generate thermocline-induced signals that can reach the surface by two distinct but non-exclusive reasons. One is that the vertical motion induced by the passage of the wave can advect colder waters closer to the surface. Turbulent mixing acting on a thinner upper layer could expose these colder temperatures to the surface. The other is that, because the dominant β-induced propagation of long Rossby waves is mostly zonal (Polito & Cornillon, 1997), the slopes of the surface and thermocline produce a north–south geostrophic flow. This, in the presence of a meridional gradient temperature in the background, results in periodic SST variations caused by horizontal advection. In that, the phase lag between SSH and SST in the two cases would be different and thus the dominant process can, in principle, be identified. Killworth et al. (2004) used the same idea of horizontal and vertical mechanisms to discuss the observation of planetary waves in satellite-derived chlorophyll-a concentrations.

Early satellite-based studies used radiometers to estimate eddy characteristics from local maxima in the SST gradients with a somewhat circular symmetry (e.g., Auer, 1987; Halliwell & Mooers, 1979; Hooker & Brown, 1994). Altimeters were introduced in the study of eddies after the Geodetic Satellite Exact Repeat Mission (Geosat ERM) whose cross-track resolution was sufficient to resolve the mesoscale vortices (Fu & Zlotnicki, 1989). Estimates of eddy characteristics from altimetry satellites were presented by Stammer (1997); Ducet et al. (2000); Wang et al. (2003); Fu (2006). Crawford et al. (2000) observed mesoscale eddies with propagation speeds similar to that of Rossby waves in the Alaskan Stream from altimeter records. This merged eddy-wave signal is suggested from observations that show westward propagating signals with characteristics that fit neither the classical theory for Rossby waves nor its extensions. Challenor et al. (2001) observed wave-like SSH anomalies in the North Atlantic Ocean that propagate westward with little meridional deviations. Chelton, Schlax, et al. (2011) made a comprehensive analysis of eddies in mid latitudes using a methodology based on the Okubo-Weiss parameter to identify and track vortex cores based on their high relative vorticity and low strain rate. The authors suggest that previous observations may have erroneously identified eddies as waves.

Despite the similarity in phase speed or propagation speed, there are important differences between Rossby waves and eddies. Rossby waves are forced by the wind stress at the eastern boundaries or by its curl in the open ocean, may be dispersive or non-dispersive and transport a large quantity of potential energy westward (Chelton & Schlax, 1996). In principle, they do not transport a significant amount of mass, and have an important role in the maintenance of the western boundary currents (Anderson & Gill, 1975). Pedlosky (2003) defines a wave as "a moving signal, typically moving at a rate distinct from the motion of the medium." The term "eddy" is generically used to different types of variable flow (Robinson, 1983). Here, we use the definition for eddies proposed by Cushman-Roisin (1994): "Eddy is a closed circulation roughly circular and relatively persistent, that is, the turnaround time of a parcel of fluid embedded in the structure is shorter than the time during which the structure remains identifiable."

If a relatively high correlation between SSH and SST is observed in certain oceanic regions, then it is reasonable to assume that advection (horizontal or vertical) is the mechanism that connects the variabilities in both fields. To that effect, two physical processes are foreseen: (1) westward zonal propagation of the waves generates a dominant meridional geostrophic flow. This meridional flow can result in a horizontal advection of the SST anomalies in the presence of a background meridional temperature gradient; and (2) the vertical flow generated by the wave propagation on the interface can modify the SST by vertical advection of the isotherms, to the point where they enter the mixed layer and, via turbulent mixing, imprint a low temperature signal at the surface. The simplest model that supports Rossby waves is the quasi-geostrophic model (see Gill, 1982, Section 12.2), in which we can separate the total velocities in geostrophic and ageostrophic parts. The geostrophic velocities are, in this formulation, dominant and perpendicular to the direction of wave propagation. The physical process (1) refers to the term $v_g\frac{\partial\theta}{\partial y}$ where $v_g = \frac{g'}{f}\frac{\partial\eta}{\partial x}$. The vertical advection in process (2) refers, in a $1\frac{1}{2}$ layer model, to the motion of the thermocline $w\frac{\partial\theta}{\partial z}$ where, to first order, $w = \frac{\Delta\rho}{\rho}\frac{\partial\eta}{\partial t}$. If η can be represented by a sinusoidal function and the first hypothesis is true, the SST will be correlated to the SSH with a phase lag of 90° in zonal space, because of the x-derivate. If the second hypothesis is true, a significant correlation between SSH and SST at zero zonal lag is expected. Killworth et al. (2004) showed that phase in observed westward propagating signals depends on the response time of the chlorophyll to the vertical advection as a consequence of exposure of phytoplankton to sunlight and/or upwelling of nutrients from the deep layers. Although the same conceptual model is considered in the following analysis, in the present case this response time should be zero because we are observing temperature and not a biological process.

2. Data processing

The altimeter data used here are the along-track TOPEX/Poseidon and Jason-1 (T/J) sea surface height anomalies distributed by the Physical Oceanography Distributed Active Archive Center for the period January 1998 to December 2007. TOPEX/Poseidon was launched in August 1992 and kept in operation until October 2005. Jason-1, its successor, was launched in December 2001 with the same characteristics of the TOPEX/Poseidon. TOPEX and Jason use a radar operating in the frequency of 13.6 GHz to determine the SSH between the latitudes of 66°N and 66°S with precision and accuracy of ± 2.4 and ± 1.4 cm, respectively (Benada, 1997). The along-track SSHA data were interpolated to a regular grid of $1° \times 1° \times 9.9156$ days. The interpolation uses a method similar to the one developed by Polito et al. (2000), based on the local 3D (x, y, t) auto-correlation.

Our focus in the present study are phenomena with annual and semiannual periods and 300–1000 km of characteristic length. With a sampling period of less than 10 days, the temporal resolution of