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Satellite observations of eddies in the Southwestern Atlantic Ocean during 1993 and 1994

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Abstract. This paper investigates the eddies (rings) found in the Southwestern Atlantic Ocean in 1993 and 1994 as observed by high-resolution AVHRR sea surface temperature images of the region. The investigation of the eddies is made according to their characteristic sizes and relation to the local internal Rossby radius of deformation. In the Southwestern Atlantic Ocean, most of the reported eddy activity is related to the Brazil-Malvinas Confluence region. This paper, however, also describes eddies located at the South Brazilian Continental Shelf where very few references are currently available. Some of the eddies present in the South Brazilian Continental Shelf are similar to shelfbreak eddies described for other parts of the World Ocean. In the Brazil-Malvinas Confluence region, cold core eddies are formed by breaking off from the crests of high amplitude meanders of the South Atlantic Current. Warm core eddies are present at the Brazil Current reversal flow region and at the troughs of the South Atlantic Current in the confluence. The characterization of the eddies in the Southwestern Atlantic Ocean is important task for better understanding the processes of across-front transport of properties between the Tropical and Subantarctic environments which can control much of the environmental and climatic processes occurring in the region.

Key words: ocean remote sensing, Southwestern Atlantic Ocean, mesoscale activity, eddies.

1. Introduction

The Southwestern region of the Atlantic Ocean (Figure 1) comprises one of the most dynamically active regions of the World Ocean, the Brazil-Malvinas Confluence (BMC) region. The BMC comprises territorial waters of Brazil, Uruguay and Argentina, and is an oceanographic front between the Brazil Current (BC) and the Malvinas Current (MC), where cold waters of Subantarctic origin carried by the MC meet warm waters of Tropical origin carried by the BC. The BMC is the western part of the Subtropical Front, the region where the subsurface South Atlantic Central Water is formed and where the South Atlantic Current (SAC) flows as part of the South Atlantic subtropical gyre. The physical processes of water mass mixture occurring in the BMC region become more complex with the addition of fresh waters originated from the La Plata River and Patos Lagoon outflows.

Much of the reported eddy activity in the Southwestern Atlantic Ocean is related to the BMC region (e.g. Legeckis and Gordon, 1982; Olson et al., 1988). With respect to the South Brazilian Continental Shelf (SBCS[1]), the situation is a more complicated because the presence and dynamics of the wintertime currents occurring there is not fully understood. Souza and Robinson (2004) described that during wintertime a strong lateral front occurs between BC and a northward coastal current named Brazilian Coastal Current (BCC). Although the BCC had not yet been named, some previous descriptions of the eddies in the BC along the BC/BCC front can be found in the works of Garfield (1990) and Schmid et al. (1995), for example. Unfortunately, these individual efforts fail to provide a general description of the eddies across the SBCS or at the BC/BCC front and over long periods of time. Some eddy

[1] SBCS in this text denotes the regions named by Castro and Miranda (1998) as Southern Brazilian Shelf (from Arroio Chuí - 33°48'S to Santa Marta Cape - 28°40'S) and South Brazil Bight (from Santa Marta Cape to Cabo Frio - 23°S).

activity in the SBCS was also described in the first results of project *Oceanic Circulation in the Western Region of the South Atlantic* (COROAS) (e.g. Campos et al., 1996; Stech et al., 1996).

This paper investigates the characteristics of the eddies found in the Southwestern Atlantic Ocean in 1993 and 1994 as they were observed by satellite images obtained during project COROAS. The characterization of the eddies is made according to their sizes and relation to the local internal Rossby radius of deformation. At the present, eddy properties are being investigated by many authors in order to assess the importance of such structures in the world ocean's climate and heat and mass balance.

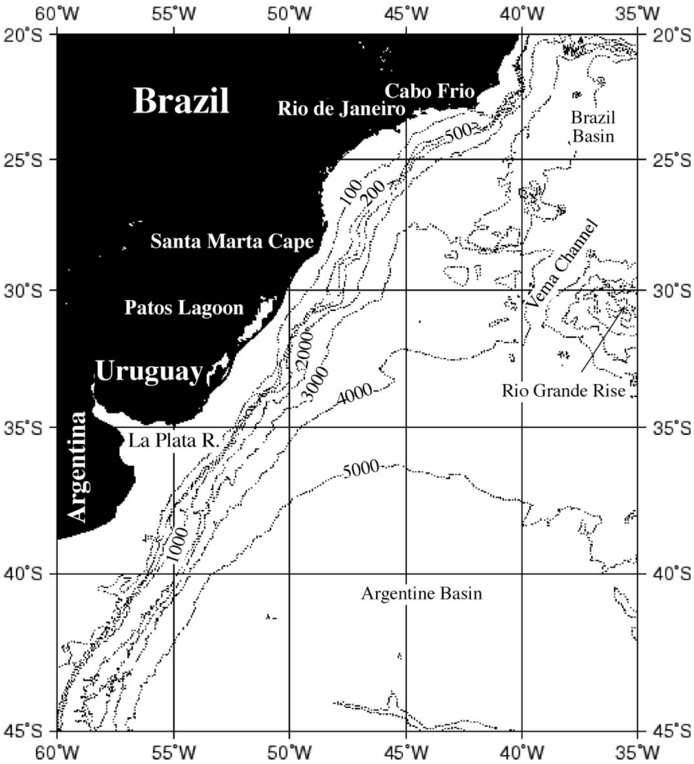

Figure 1. The Southwestern Atlantic Ocean: bathymetry (meters) and main features.

2. Data and methods

The images used in this work were high-resolution (1 km × 1 km) Advanced Very High Resolution Radiometer (AVHRR) provided by INPE, which operates an antenna in Cachoeira Paulista, Brazil. Sea surface temperature (SST) images were generated according to the NOAA (National Oceanic and Atmospheric Administration) algorithms described by Kidwell (1995).

A total number of 81 SST images were used in this work. They covered the period between 10 March 1993 and 11 July 1994. All the images were resampled to 4 km × 4 km pixel size and geolocated to the Mercator projection over a coherent area in the Southwestern Atlantic Ocean (26.4°S to 42.7°S; 38.8°W to 58.8°W).

Individual eddies were visually located in the AVHRR images. Typically, the eddies present in the satellite SST images are identified by their surface signature as closed elements with the borders delimited by strong horizontal thermal gradients in relation to adjacent waters. The gradients, however, change in intensity according to the stage of formation or coalescence of a particular eddy. Besides that, the absolute temperatures inside and outside the eddies are also often not constant, which make very difficult the establishment of a single palette of colors to reveal eddies in a temporal sequence of SST images. Cloud coverage is another crucial problem whenever a particular feature needs to be tracked in satellite images.

Each AVHRR image used here was independently processed to enhance the presence of eddies. Each time one of these features was located, it was treated as an ellipse, and its minor and major axis were measured. From the ellipse's equation, the eddy perimeter (P) was estimated. Moreover, the mean latitudinal and longitudinal position of the eddy was assessed, and the temperature profiles for the eddy's minor and major axes were generated. From these profiles (and discarding the cloud covered pixels when detected), an average temperature was computed for each particular eddy.

Using this procedure, 78 eddies were located in the overall set of images. From this total, a few were double counted when they persisted from one image to the subsequent one. Mainly because of cloud coverage but also advection, unfortunately, the location and tracking of a particular eddy in a sequence of images was rare. This made the estimation of the eddies' lifetime extremely difficult. Both the warm core and cold core eddies present in the images were subject to simple statistical analysis in order to assess their typical length scales. The ratio between the eddies' average diameter (D) and the local internal Rossby radius of deformation (Rd) was also computed.

Considering an idealized two layer density ocean in the front between the BC and MC (the western subtropical front in the BMC region) and in the BC/BCC front, Rd was computed for the range of latitudes where the eddies were present. Rd gives a length scale at which the rotational (f) forces become comparable to the buoyancy forces (pressure gradient) in the equation of motion (Richards and Gould, 1996). Rd is defined as (Pond and Pickard, 1983):

$$Rd = (g' H_o)^{1/2} / f \qquad \textbf{\textit{Eq. 1}}$$

where $f = 2\Omega\sin\Phi$ is the Coriolis parameter related to Earth's rotation; the reduced gravity (g') is the gravity (g) times the density difference between layers ($g' = g\ (\Delta\rho/\rho)$) and H_o is the upper layer depth.

In the study region, BC was considered to carry Tropical waters with density (ρ) of 1025 kg/m^3 in a 200 m water column above the South Atlantic Central Water, whose typical density was assumed to be 1027 kg/m^3. In the BC/BCC front, the BCC density was assumed to be 1023 kg/m^3 (coastal waters) extending in a water column of 100 m above the BC waters with density of 1026 kg/m^3. These numbers were based on the vertical profiles of temperature (T) and salinity (S) presented by Castro and Miranda (1998) and Ciotti et al. (1995).

3. Results and discussion

Figure 2 presents the distribution of the cold core and the warm core eddies found in AVHRR images for the study area between March 1993 and July 1994. The sizes of the eddies are represented by the proportional crosses. No relation was obtained between the eddies' core temperature and the position where the eddies were found. Although for the small eddies the temperature of the core does not imply a specific direction of rotation, it is generally true that the mesoscale warm core eddies are anticyclonic features, and cold core eddies are cyclonic ones. Figure 2 indicates that smaller eddies are found in the BC/BCC front distributed along the continental shelf break.

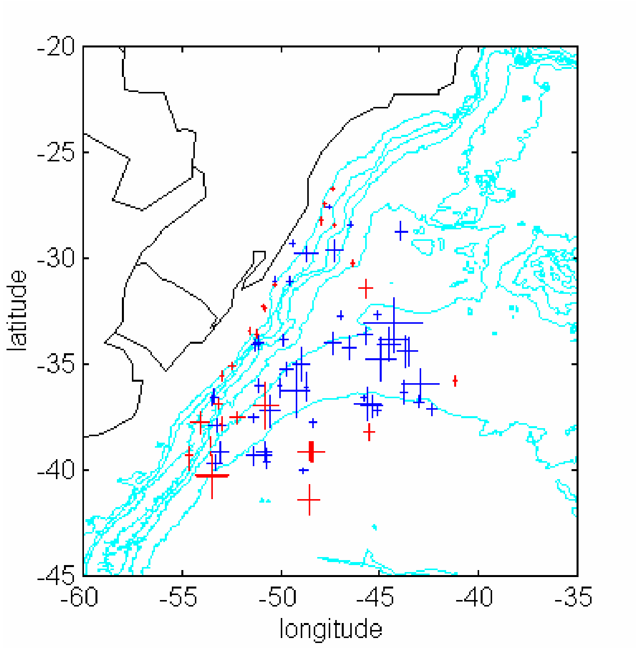

Figure 2. Eddies present in the images of 1993 and 1994. Cold (warm) core eddies are represented in blue (red). The crosses represent the major and minor axes of the individual eddies. Bathymetric contours are seen in light blue.

The distribution of the eddies' core temperatures (mean and standard deviation derived from temperature transects along the major and minor axes – not shown) revealed that they do not have relation with the eddies' sizes. The temperature dynamical range for all the eddies ranged about 10°C to 30°C.

Table 1 shows the size statistics for the eddies. All the parameters analyzed in Table 1 (apart from the diameter std.) indicated that, for the area and period studied, cold core eddies were larger than warm core ones. The mean diameters of the cold and warm core eddies were 82 km and 65 km, respectively. Maximum values for the eddies' diameters reached values of 262 km and 182 km (cold and warm core eddies, respectively).

Table 1. Size statistics for the eddies

	cold core eddies				*warm core eddies*			
size (km)	***min.***	***max.***	***mean***	***std.dev.***	***min.***	***max.***	***mean***	***std.dev.***
major axis	20	284	101	61	16	244	83	64
minor axis	12	252	63	46	8	144	48	43
diameter	18	262	82	51	16	182	65	51
perimeter	57	824	269	163	50	604	217	165

Size measurements obtained here are distinct from the ones presented by Legeckis and Gordon (1982) and Garzoli (1993) for the BMC region. When analyzing Table 1 one must remember, however, that the observations described here for the 1993 and 1994 SST images included the anticyclonic eddy generally present at the location of the BC return flow at about 37°S, 50°W, but missed the eddies which were possibly ejected by the BC southwards of this extreme location. That is because the images used here were restricted to the latitudes lower than 42°S. Authors like Legeckis and Gordon (1982) and Olson et al. (1988) indicate the presence of anticyclonic eddies formed by detachment from the BC extremes in the region south of 42^{o}S. These eddies formed at the BC extremes generally have dimensions larger than the mean found here.

Values of the ratio D/Rd (Figure 2) ranged from about 0.1 to about 5, the first representing small-scale eddies mainly formed in the BC/BCC front and the last being characteristic of a fully developed eddy field at the BMC region. According to Richards and Gould (1996), wavelengths of about 4 to 6 times Rd dominate a fully developed eddy flow. Eddies with D larger than Rd tend to be generated by detachment from meanders in the main flow, generally caused by baroclinic instabilities, and tend to be in geostrophic balance. Small-scale eddies, on the other hand, tend to follow a very unpredictable behavior typical of turbulent flows. In the last case, eddy diameters are several times smaller than Rd.

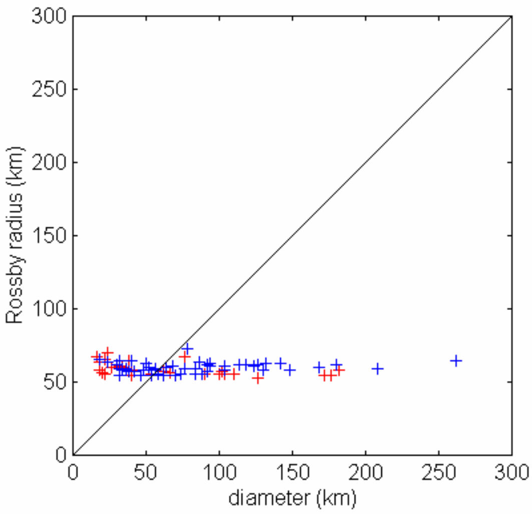

Figure 2. Relationship between the diameter and the internal Rossby radius of deformation for the eddies. Cold (warm) core eddies are represented in blue (red).

Figures 3 and 4 present SST images with some examples of the eddies found in the overall set of images studied here. They show eddies generated at the BMC region and at the BC/BCC front in the SBCS region. Figure 3a is a very good example of the cold core eddy formation in the BMC by the detachment from meanders of the SAC. The figure shows three eddies being expelled from the main current by the breaking off from high amplitude meanders. These structures travel towards the warm part of the BMC region. They are a source of eutrophic water from Subantarctic origin to the tropical domain of the BMC region, and possibly have direct association with high primary production and fish. Their fate is still unknown in the BMC region, and the data set available for this work, although suggesting time scales of few months for their lifetime, was unfortunately not enough to verify their complete evolution or coalescence. That limitation was mainly caused by cloud coverage.

Legeckis and Gordon (1982) have reported that the formation of cold core eddies in the BMC region is less frequent than that of the warm core eddies. The latter were reported to be formed as a detachment from the BC extremes. Garzoli and Garraffo (1989) studied 17 months worth of echo sounders records in the BMC region from November 1984 to March 1986. They have reported that during this period of time cold intrusions were present in the records with no apparent periodicity. Three of these intrusions were associated with cold core eddies which were present in the records for periods of time between 20 days and 60 days.

Garzoli and Garraffo (1989) also computed the potential energy associated with the cold core eddies (6.5×10^{15} J), adding that it is of the same order of magnitude as the Gulf Stream eddies. The AVHRR data set analyzed here, although suggesting that the periods of about a month or two can reflect the time scales for the cold core eddies lifetime in the BMC region in agreement with Garzoli and Garraffo (1989), disagrees with the suggestion made by Legeckis and Gordon (1982) that the cold core eddies are less frequent than their warm counterparts in the BMC region.

Figure 3b exemplifies the presence of warm core eddies which tend to be formed in the warm part of the BMC between two consecutive cold meanders in the SAC. The eddies are circular, have diameters close to 100 km, and are very typical. However, previous descriptions of the warm core eddies in the BMC generally reported the eddies formed to the west of the first SAC meander (seen in Figure 3a at 39^{o}S, 52^{o}W) or at the south of the BC extreme location, below 42^{o}S. There are indications in the images analyzed here that this sort of eddy is formed regularly at the meander's trough in the warm part of the BMC. It is unlikely that they can break through the front and travel southwards, although this paper does not present enough material to confirm that. If traveling towards the cold part of the front, these eddies could add a huge amount of heat, salt and momentum from the Tropical to the Subantarctic domain of the BMC region.

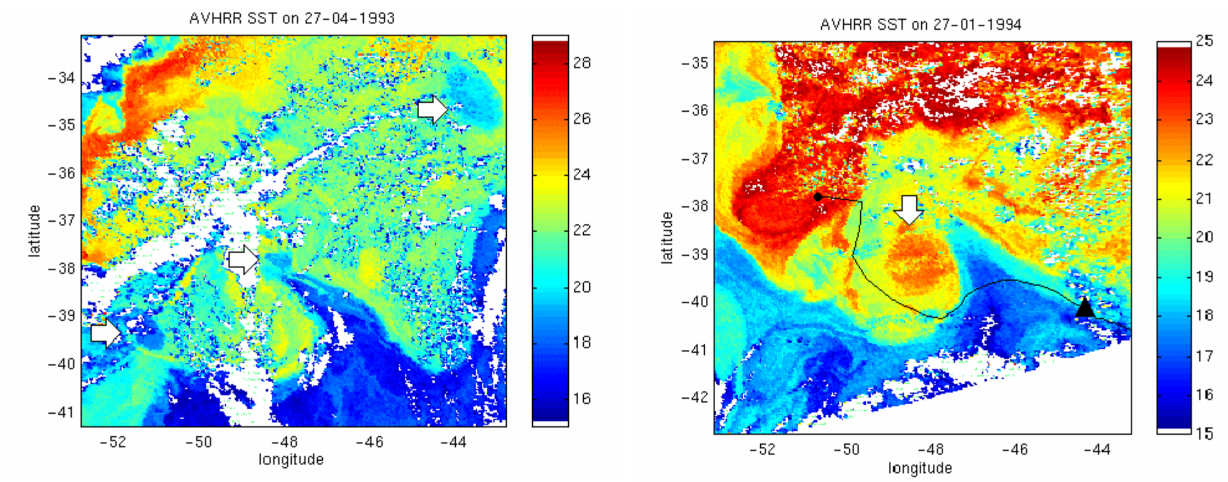

Figure 3.a (left). Image of 27 April 1993 showing the 'pinching off' of three cold core (cyclonic) eddies from the cold part of the BMC. The eddies are indicated by the arrows. **b (right).** Image of 27 January 1994 showing a warm core (anticyclonic) eddy originated from the warm (BC) part of the BMC. The trajectory of a surface drifter is also seen, where the circle indicates its position 20 days before the image's acquisition time and the triangle indicates its position within ± 12 from the image's acquisition time. The color bars indicate temperature in degrees Celsius.

Figure 4 presents examples of eddies or frontal instabilities found at the BC/BCC front and SBCS region. Very often these structures are noticed as mushroom-like features or wave-like features related to shear instabilities of the front. Length scales can reach 50-60 km. Garvine et al. (1988) reported typical diameters of 40 km for the shelfbreak eddies of the Middle Atlantic Bight in the United States coast. The structures were described to be about 4 times smaller than the eddies of the Gulf Stream. The authors also described that the front in which the eddies were formed separates cooler, fresher waters in the shelf from warmer, saltier water from the slope. Prominent features of the eddy groups, following Garvine et al. (1988), were described to be the (1) plumes of lighter shelf water that protruded into slope water curling backwards in opposite direction of the shelf flow and (2) neighboring cyclones with slope water partially or wholly surrounded by the plumes.

The characteristics of the BC/BCC front are very similar to those from the shelf/slope front off the American Middle Atlantic Bight. By analogy, some of the eddies formed in the BC/BCC front are considered here to be shelfbreak eddies. Together with frontal instabilities of the BC and BCC in the form of waves with crests protruding in direction opposite to that of the current, mushroom-like features are quite common at the BC/BCC front. These features would liberate warm core eddies from BC into BCC or cold core eddies from BCC into BC. Several structures like that are likely to be formed all along the BC/BCC front. The exchange of heat, salt and momentum between the BC and the BCC through the detachment of small scale eddies is a very important process which demands further investigation.

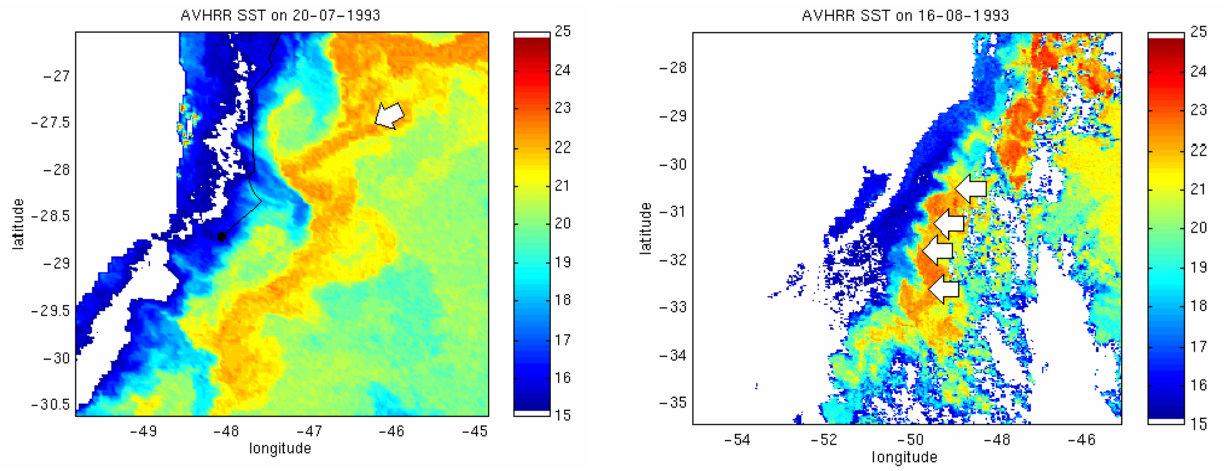

Figure 4.a (left). Image of 20 July 1993 showing the development of a mushroom-like structure of the BC at 28°S (indicated by the arrow). The trajectory of a drifting buoy moving northwards in the BCC is also seen. The image is an example of the complex interaction between BC and BCC waters at the shelf break in the southern coast off Brazil. **b (right).** Image of 16 August 1993 showing the effect of lateral mixing by shear instabilities between the BC and BCC currents flowing in opposite directions. The arrows indicate the instability waves at the front. BC/BCC front. The color bars indicate temperature in degrees Celsius.

Conclusions

AVHRR images were utilized here to characterize the eddies present in the Southwestern Atlantic Ocean during the period of March 1993 to July 1994. The eddy sizes were smaller in the SBCS region than in the BMC region. Distinct properties and generation mechanisms characterize the eddy field in those two regions. Shelfbreak eddies occur at the SBCS owing to shear instabilities between the BC and BCC flowing in opposite directions during wintertime. To our knowledge, they have not been previously described before. That can be explained mainly because (1) the BC/BCC front, where some of the eddies occur, is still not fully studied and (2) because they are difficult to be spotted in satellite images. However, their presence can be revealed in satellite imagery if correct enhancing techniques are applied. As mentioned before, depending on the rate and number of structures formed, the shelfbreak eddies of the BC/BCC front can be responsible for a considerable part of the mass and heat exchange between tropical and coastal waters.

In the BMC region, cold core eddies were observed to be formed by breaking off from the crests of high amplitude meanders of the SAC. Warm core eddies were present at the BC reversal zone and in the troughs of the SAC in the BMC region. The mean diameter found here for these eddies were smaller than previous descriptions (e.g. Legeckis and Gordon, 1982; Garzoli, 1993). Reasons for that can lie in the fact that the generally larger warm core eddy, formed by a detachment of the BC at its southernmost position south of 42^{o}S, is not detected in our images that do not cover this area.

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References

Campos, E.J.D.; Ikeda, Y.; Castro, B.M.; Gaeta, S.A.; Lorenzzetti, J.A.; Stevenson, M. R. Experiment studies circulation in the Western South Atlantic. **EOS Transactions Am. Geophys. Union**, 77(27):253-259, 1996.

Castro, B.M., Miranda, L.B. Physical oceanography of the Western Atlantic continental shelf located between 4^{o}N and 34^{o}S, coastal segment (4,W). In: Robinson, A.R., Brink, K.H. (Eds.), The Sea, vol. 11. John Wiley and Sons, 1998.

Ciotti, A.M.; Odebrecht, C.; Fillmann, G.; Moller Jr., O.O Freshwater outflow and Subtropical Convergence influence on phytoplankton biomass on the southern Brazilian continental shelf. **Continental Shelf Research**, 15(14):1737-1756, 1995.

Garfield, N. III. The Brazil Current at subtropical latitudes. Ph.D. thesis, University of Rhode Island, USA, 1990, 122pp.

Garvine, R.W.; Wong, K-C.; Gawarkiewicz, G.G.; McCarthy, R.K.; Houghton, R.W.; Aikman III, F. The morphology of shelf break eddies. **Journal of Geophysical Research**, 93(C12): 15593-15607, 1988.

Garzoli, S. Geostrophic velocity and transport variability in the Brazil-Malvinas Confluence. **Deep-Sea Research**, 40(7):1379-1403, 1993.

Garzoli, S. and Garraffo, Z. Transports, frontal motions and eddies at the Brazil-Malvinas Currents Confluence. **Deep-Sea Research**, 36(5):681-703, 1989.

Kidwell, K.B. NOAA Polar Orbiter Data users guide (TIROS-N, NOAA-6, NOAA-7, NOAA-8, NOAA-9, NOAA-10, NOAA-11, NOAA-12, NOAA-13 and NOAA-14. NOAA/NESDIS National Climatic Data Center, Satellite Data Services Division, Washington, D.C., 1995.

Legeckis, R. and Gordon, A.L. Satellite observations of the Brazil and Falkland currents - 1975 to 1976 and 1978. **Deep-Sea Research**, 29:375-401, 1982.

Olson, D.B., Podestá, G.P., Evans, R.H., Brown, O. B. Temporal variations in the separation of Brazil and Malvinas currents. **Deep-Sea Research**, 35(12):19711-1990, 1988.

Pond, S. and Pickard, G.L. Introductory dynamical oceanography. 2nd. Ed. Butterworth-Heinemann Ltd., Oxford, 1983, 329 p.

Richards, K.J. and Gould, W.J. Ocean weather - eddies in the sea. In: Chapter 4, Summerhayes, C.P. and Thorpe, S.A. (Eds.) Oceanography: an illustrated guide. Manson Publishing Ltd., London, 1996, 352 p.

Schmid, C.; Schafer, H.; Podestá, G.; Zenk, W. The Vitória eddy and its relation to the Brazil Current. **Journal of Physical Oceanography**, 25(11): 2532-2546, 1995.

Souza, R.B.; Robinson, I.S. Lagrangian and satellite observations of the Brazilian Coastal Current. **Continental Shelf Research**, 24: 241-262, 2004.

Stech, J.L.; Lorenzzetti, J.A.; de Souza, J.M.C.; Araujo, C.E.S. A mesoscale Brazil Current frontal eddy observed through AVHRR images and current meter moorings. In: Proceedings from the International Archives of Photogrammetry and Remore Sensing. Vienna, Austria, 1996, Vol. 31, Part B7, 1996, p. 650-653.