SHELF EDGE CIRCULATION OFF THE CAMPOS BASIN FROM ALTIMETRY AND CURRENT METER MOORINGS

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Abstract. Boyer-Levitus high resolution annual mean hydrographic data and five years of Topex/Poseidon and ERS2 collinear real time data were used to prepare 10-day circulation and sea surface height variability maps in a 0.25^ox0.25^o grid centered around the most important offshore oil production basin in Brazil, the Campos Basin, at 22^o S; 40^o W. The large eddy perturbations on the Brazil Current flow are shown to significantly influence the generation of unexpected mean currents near the shelf break, measured by current meter moorings. Offshore the Campos Basin a very recurrent cyclonic eddy, with about 20 days lifetime, causes a counter current of intensity varying between 20-50cm/s, trending N to NE. The presence of the cyclonic eddy on the Campos Basin during last March was detected, and analysed in support of the oil spill risk analysis related to the sinking of the P-36 Rig (US$500 million only in equipment). These eddies are suggested as being related to the retroflection of the upper Tropical Water flow of the Brazil Current, which closes a Warm Water Gyre component of the South Atlantic Subtropical Double-Gyre circulation.

1. Introduction

Much work has been published in the last ten years concerning various aspects of South Atlantic ocean water masses, circulation, and property distributions, focusing on the large scale (e.g., see Stramma and England, 1999, and references therein). In the subject of the subtropical western south Atlantic circulation, effort has also been done recently on some more local mesoscale processes (Campos et al., 1999; Campos et al., 2000; Schmid et al., 1995; Gaeta et al., 1999). In Campos et al. (2000), shelf break upwelling driven by cyclonic meanders in the Brazil Current is thought to be the process which brings South Atlantic Central Water into the shelf at 26^o S. However, descriptions of these meanders has been sparse, and no large scale study of how they are generated and how they evolve have been made to date.

During the past few years, with the increasing pressure from environmental concerns about risks of oil spills in the largest offshore oil production basin in Brazil, the Campos Basin, monitoring and predicting the offshore circulation variability has become a priority. After two years of monitoring the local upper water geostrophic circulation by altimetric methods, it became clear that the shelf edge circulation is dominated by eddy activity related to the Brazil Current, whose axis is difficult to identify near the shelf edge at 22^o S, where it has a sharp turn in direction of almost 90^o .

We found it necessary to first document the scales of variability of the Brazil Current, and next document the eddy activity. In this process, it became clear that the upper layer flow in the Subtropical Gyre should be revised, and that the eddy activity could be better predicted and understood as a non-local phenomenon, before local analysis can be applied to specific cases (e.g., topographically forced, baroclinic instability, etc.).

In terms of the large scale circulation, the review of Stramma and England (1999) depicts a surface circulation characterized by one recirculation cell of the subtropical gyre centered at the latitude of 35^oS. Among the missing details of their long wavelength scheme we may cite a quasi-meridional anticyclonic gyre, and a temperature front, both features being depicted in figures 5 and 6 of Reid (1989). Also, in the surface dynamic topography of the South Atlantic presented by Gordon and Bosley (1991), an eastern extension of the gyre is present, with an eastward jet at 24^o S, and a turning point near 25^o W. This is consistent with the first description of the double-gyre structure of the South Atlantic Subtropical Gyre by Tsuchiya (1985), which has recently been supported by the cruise data of Mémery et al. (2000) and the altimetric analysis of Vianna and Menezes (2001).

Studies of seasonal and interannual variability of the large scale circulation are quite few (Matano et al., 1993; Witter and Gordon, 1999; Lazar et al., 2001, and references therein). While Matano et al. (1993) and Witter and Gordon (1999) concentrate more on latitudes larger than 30^oS, Lazar et al. (2001) concentrate on tropical-subtropical latitudes lower than 30^o S. In the latter modeling work, a recirculation cell centered at 22^o S appears in their Bernoulli function maps, while in the former, a cell centered at 35^o S is found, which is consistent with Stramma and England (1999) and the feature depicted in the first EOF mode of the interannual study of Witter and Gordon (1999). In order to distinguish between the tropical-subtropical recirculation gyre from the mid latitude one, we called the former the East Brazilian Gyre (Vianna and Menezes, 2001).

2. Data and Methods

Two data sets were used in this study:

(i) The annual mean data from the high resolution $1/4^o$ x $1/4^o$ Boyer and Levitus (1997) data set, for the region west of 20W between 12^o S and 28^o S. Dynamic heights and

geostrophic velocities were calculated from temperature and salinity data as usual, relative to the 500m depth surface;

(ii) The altimeter (Topex/Poseidon and ERS2) collinear data from the NASA Altimeter Pathfinder project (Koblinsky et al., 1999) between July 1995 and July 2000, from which we generated Sea Surface Height Anomaly (SSA) gridded fields of 1/4^o x 1/4^o for the sub-region west of 34^{o}W, 16^{o}S-28^{o}S. The method used to generate gridded SSA fields may be summarized by stating that it consists in interpolating the collinear SSA data from T/P and ERS2, obtained from the Pathfinder data base (with the recommended bias correction), into a common daily time grid, before mapping the data into a eddy-resolving 1/4^o x 1/4^o grid. The resulting time series with 1828 images are then expanded in EOF's, keeping 90% of the total variance. The Principal Component (PC) time series of the first ten PC's were inspected, and it was seen that the first EOF was dominated by the annual signal, modulated by interannual variations. However, the PC's did not separate well the various period bands, and the EOF expansion did not converge very fast.

In the next step in the analysis, the PC's were filtered to keep only variability with periods greater than 90 days, and re-sampled in 10 day time steps. They were then analyzed by MCSSA (Plaut and Vautard, 1994), with each PC expanded in components in the intraseasonal period band (<150 days), semi-annual (150-200 days), annual (200-400 days), and interannual (>400 days) bands. The variances corresponding to each band were calculated by summing the contributions from each individual PC. The image time series corresponding to each of these bands were reconstructed from these PC's and the EOF grids. Each of these data sets were then re-expanded into new band-limited EOF's and PC's, to get a condensed statistical picture of the evolution of the sea surface topography corresponding to each band, with the associated geostrophic velocity fields.

3. Separation of the Brazil Current and the East Brazilian Gyre

In figure 1 we display the surface and 100m annual mean dynamic height fields and corresponding geostrophic velocities. It can be seen that a topology corresponding to a anticyclonic gyre between 12^o S and 26^o S is clearly discernible for the surface and the 100m maps, but not in the 200m map (not shown). This confirms the view of Tsuchiya (1985) that the Sobtropical Gyre has a double-gyre structure.

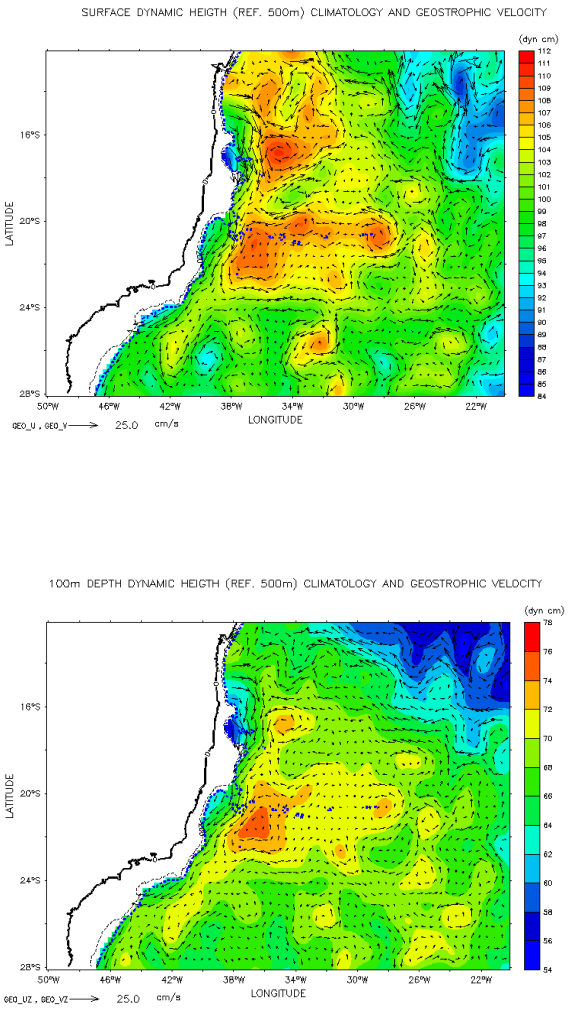

Figure 1 - Surface (upper panel), and 100m (lower panel) annual mean dynamic heights and geostrophic velocities relative to 500m. While the recirculation gyre is most notable from the surface and 100m, the South Equatorial Current westward flow and bifurcation near the coast is best seen in the subsurface map, between 12^{o}S-16^o S.

Figure 2 shows vertical sections of annual mean eastward (u) zonal velocities made in the 36^o W and 30^o W planes, and of annual mean northward (v) meridional velocities. It is seen that the annual mean (6-8cm/s) flows are mostly confined to the upper 150m layer, with the eastward jet centered at 24^o S, and the westward flows confined to the north of the seamount ridge, consisting of three jets, the one corresponding to the southern branch of the South Equatorial Current having its core at 150m. At 30^o W the zonal transport is still to the east, from 24^o S to 21^o S, and north of 20^o S the zonal transport is to the west. The zonal section shows that most of the transport to the south is confined to the Brazil Current, but between 28^o W and 40^o W the flow is to the north.

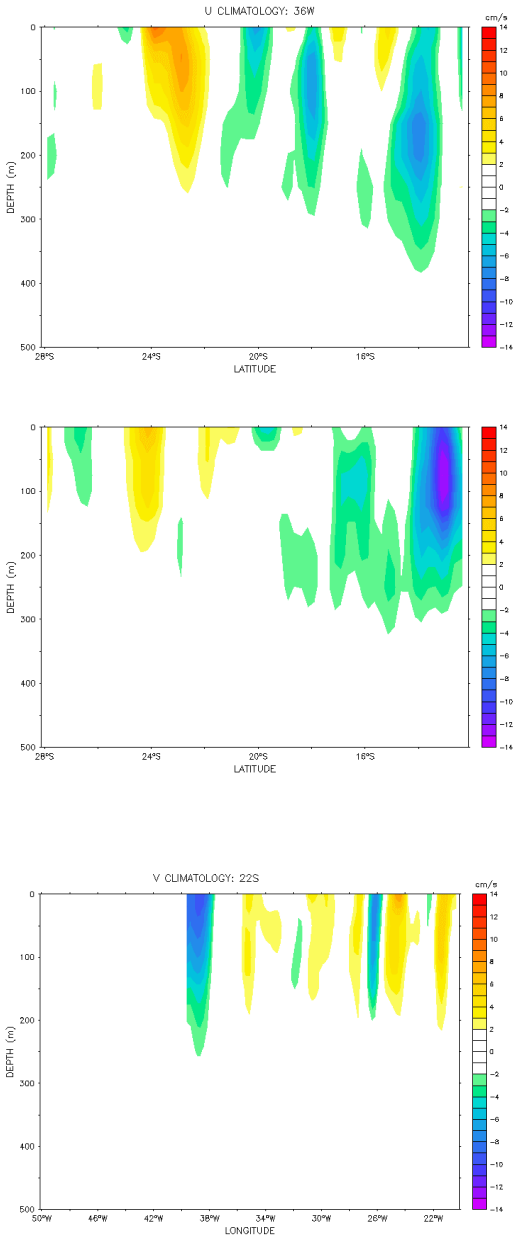

Figure 2 - Zonal velocity profiles at 36^o W (upper) and 30^o W (middle), which demonstrates that the annual mean eastward jet at 24^o S is confined to the upper 150m, the westward flow being made of three distinct cores, the one at 13^o S-14^o S possibly representing the South Equatorial Current Southern Branch (SSEC) with a core at 150m-200m. The zonal section at 22^o S (lower) shows a Brazil Current at 38^o W, and a northward transport between 28^o W and 36^o W.

The results of the analysis of the annual and interannual variability in a sub-region 16^o S-28^o S, west of 34^o W, which we have been monitoring during the last two years, showed that 36% of the variance is related to the annual band, 28% to the interannual, 23% to the intraseasonal and 12% to the semi-annual.

We are interested here in establishing preliminary details on the variability of the separation of the Brazil Current around 24^o S, and the stability of the East Brazilian Gyre. The quasi-synoptic SSA data in a 1/4^o x 1/4^o grid is dominated by eddies, which makes the identification of a mean flow field by inspection quite difficult. The best way to get the picture is to expand the band-limited data in EOF modes. Figure 3 shows the first EOF and corresponding Principal Component (PC) of the annual band, which explains 64% of the variance in this band.

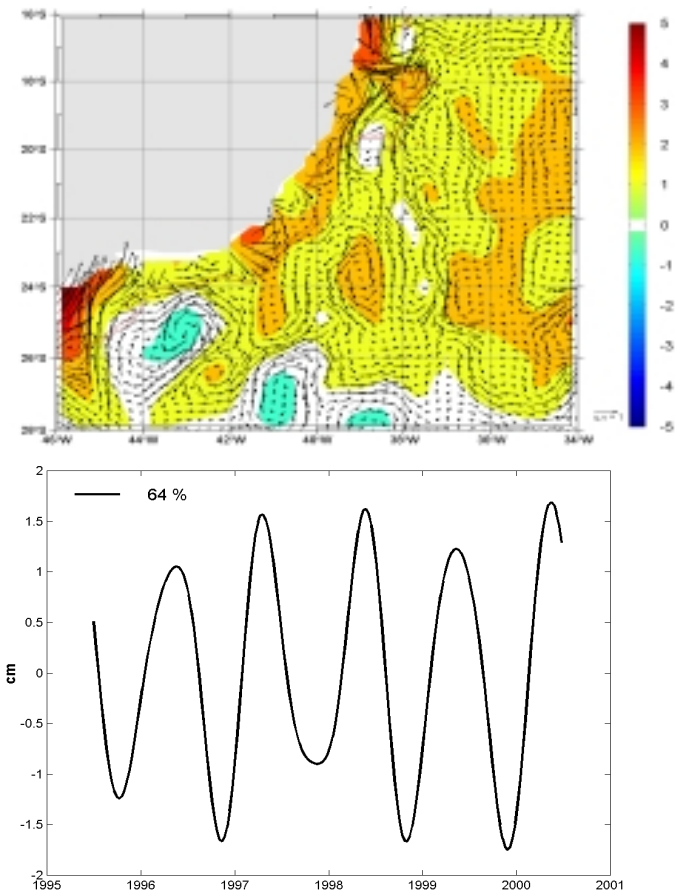

Figure 3 - EOF1 for the annual band, showing clearly the retroflection region at 24-26^o S (upper), and the PC1 time series (lower), with peaks in May and November.

We get here a preliminary picture of the dynamics of this retroflection and separation of the Brazil Current at 24^o S, and its retroflection eddies. PC1 indicates that a strengthening of

the retroflection and separation happens in the southern fall. A sequence of eddy pairs is observed in an almost zonal alignment.

Our separate study of the full time series of geostrophic currents on the shelf slope at 22° S (not shown), obtained from the original daily gridded data used here, showed a tendency for occurrence of northward slope currents in May-June, and in December. Interannual variability is strong in the region, being dominated by Quasi-Biennial Oscillations (QBO-28% of the variance), in such a way that from December 2000 to March 2001 both altimetric and current meter data showed persistency of northward slope currents, locally caused by recurring cyclonic eddies, according to our altimetric maps. This perturbation of the annual cycle recurs in alternate years.

In Figure 4 we show the leading EOF for the interannual band, explaining only 31% of the variance at this band. It can be seen that the pattern is very similar to the one shown in Figure 3 in the separation region. The leading variability is in the 2-3 year band, which is consistent to what is observed more to the south according to Witter and Gordon (1999).

We call attention to the fact that these velocity fields were calculated from the SSA EOF grids, to give a good idea of the expected circulation variations. However, the variances associated to the SSA EOF's are not exactly the same as the variances that would be obtained for the EOF expansions of the velocity field data set calculated directly from the spatial grids at each time step.

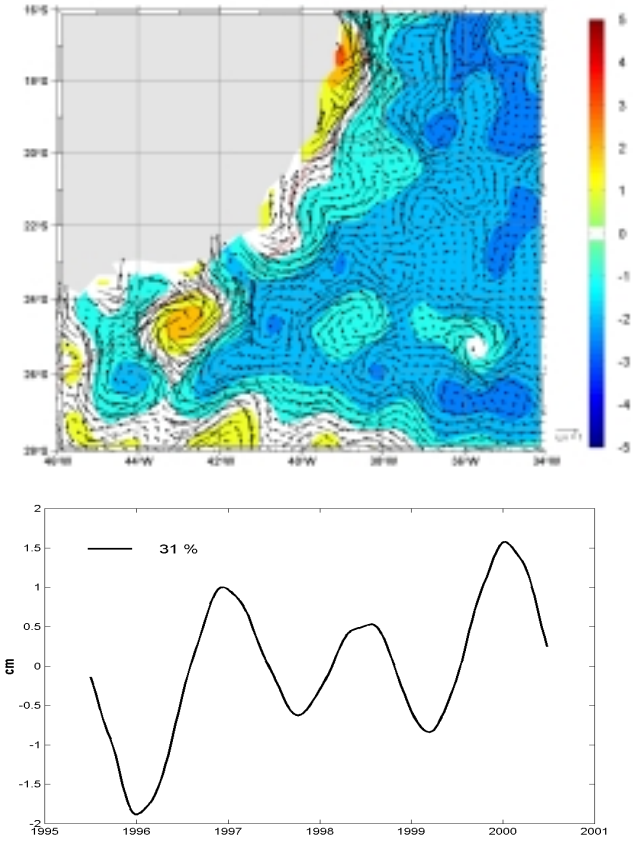

Figure 4 - EOF1 for the interannual band, also showing clearly the retroflection region at 24-26° S (upper) and PC1 (lower), showing Quasi-Biennial Oscillations, corresponding to average eastward currents at 26° S, when summed to the annual mean.

4. Seasonal Circulation

A data set consisting of the daily SSA summed to the Boyer-Levitus annual mean, giving a estimate of the SSH, and corresponding geostrophic circulation, permits the computation of the average May and average November circulation, which is shown in Figure 5. In May the broader SSH plateau at 22° S is related to a more slender Brazil Current, more confined to the west, to a Vitória Eddy, to a cyclonic eddy of the kind studied by Campos et al. (2000), and a more vigorous retroflection eddy at 26° S. In November, the plateau is weaker, the Brazil Current is broader, and most of the upper water retroflects at 24° S. There is no Vitoria Eddy at this time, nor the cyclonic meander, in the mean. During all times a never recorded coastal upwelling region is present in the Abrolhos Bight, north of the Abrolhos Bank.

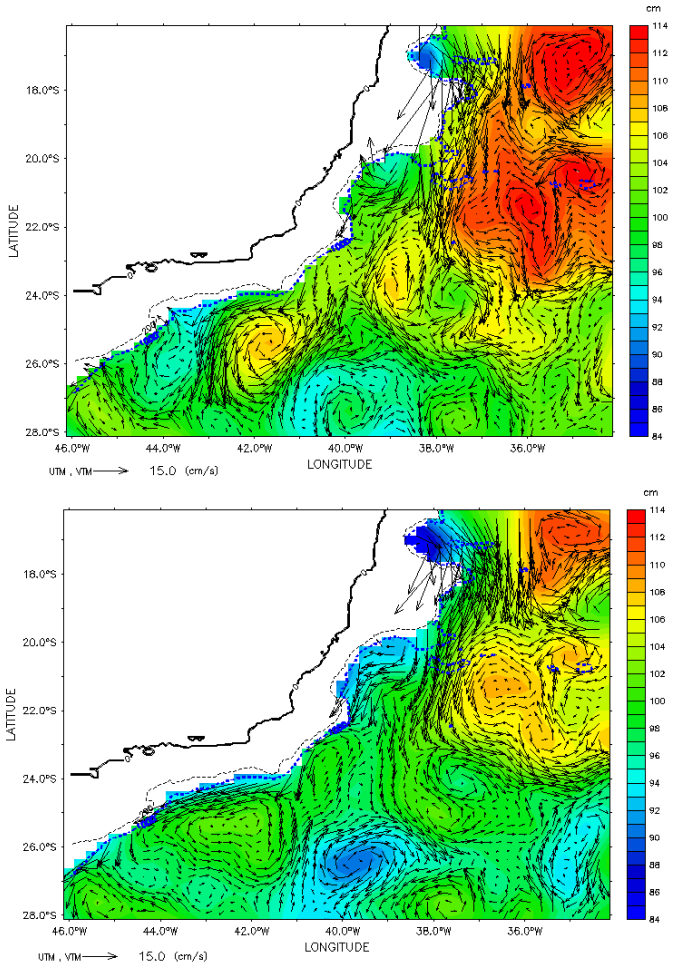

Figure 5 – Sea Surface Height (altimetric SSA+annual mean Boyer-Levitus) for mean May (upper panel) and mean November (lower panel).

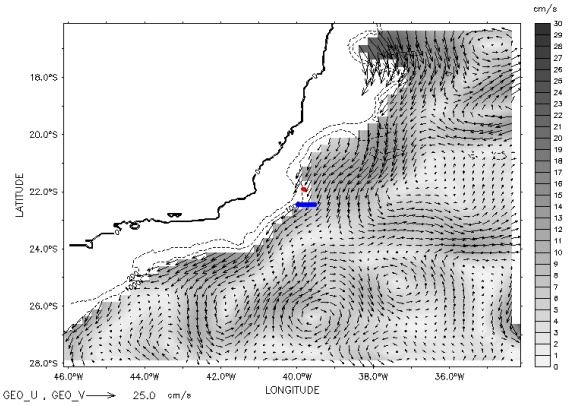

Figure 6: Position of the P-36 Rig (red dot) and the zonal cut (blue) used to calculate the space averaged meridional velocity.

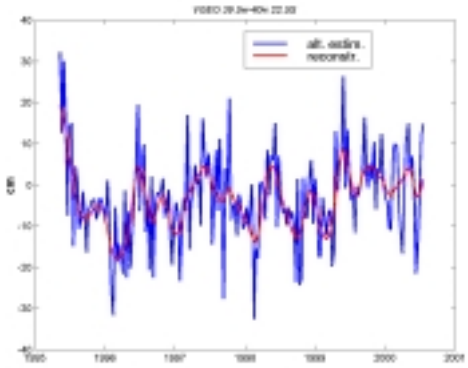

Figure 7: altimeter plus Boyer Levitus-derived geostrophic meridional current velocity near the shelf break at 22^{o} S, exhibiting frequently occurring N flow.

5. Geostrophic Circulation on the Shelf Edge

We now describe variability near the shelf break by use of altimeter and the annual mean Boyer-Levitus data, averaged over a zonal strip near 22^{o} S at the shelf break, and exhibit the situation during the southern summer of 2001 with the inclusion of current meter data from the same area.

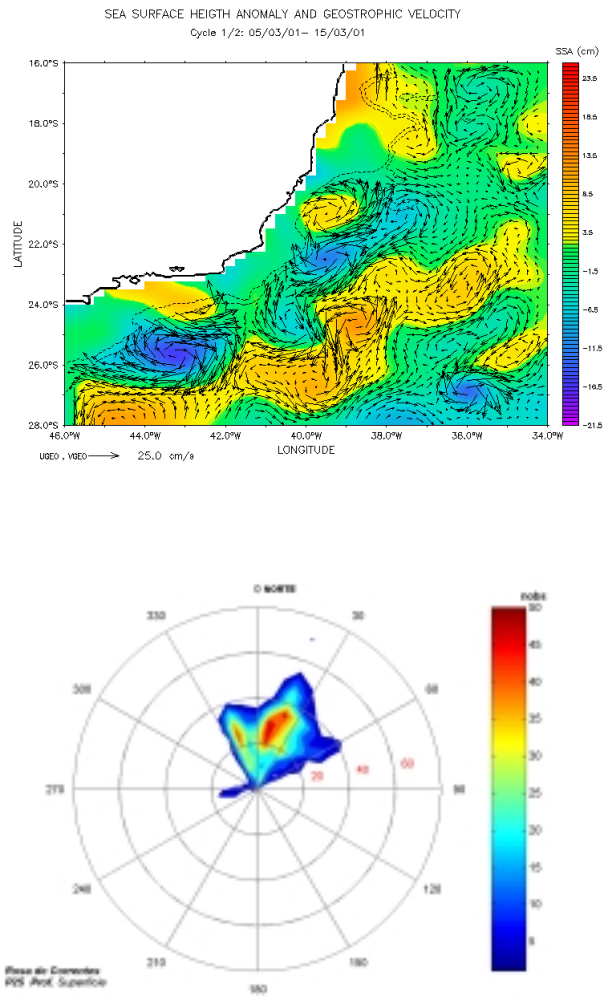

Figure 8: Flow pattern during the P-36 accident (upper), and current meter data rose from hourly data between December 1, 2000 and March 20, 2001 (lower).

Figure 6 illustrates the position of the P-36 Rig, and the zonal section used to estimate the N component of the geostrophic surface flow between 1995 and 2000. The series is shown in Figure 7. It is seen that episodes of northward flow are very frequent (35% of the time period), having been more frequent in 1995, 1997 and 1999. During the summer of 2001 the currents were more northward (Figure 8), as measured by a current meter time series near Rig P-19 (close to P-36). The flow pattern is also shown to be dominated by a cyclonic eddy during the accident period (the week of March 15, 2001).

5. Summary and Conclusions

This work suggests that the shelf edge circulation at the Campos Basin is probably dominated by retroflection eddies of the Brazil Current, and the associated Subtropical Front. Predictability of these currents could be thus related to a better knowledge of the large scale dynamics of the East Brazilian Gyre (Vianna and Menezes, 2001). According to Cushman-Roisin (1984), both the wind stresses and heat fluxes must be included in equal footing in modeling studies aimed at understanding this dynamics. The importance of this dynamics for the security of the operations in the Campos Basin can be suggested by the accident with the P-36 large oil producing rig last March, and satellite altimetry has been proved to be of importance for a correct diagnosis of the prevailing circulation in a quasi-real time mode.

This study made possible to estimate for the first time the seasonal and interannual variability of the circulation around the Campos Basin. In Figure 5 we may notice that in May the plateau is larger and higher than in November, and interannual variability is dominated by a QBO. We anticipate that the double cells with high SSH, seen in Figure 5, are of great climatic importance as potential source regions for the Subtropical-Tropical Cell (STC), and should be monitored in support of basin-wide climate change programs.

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