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Seasonal Variability in the Southwestern Atlantic

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The circulation of the southwestern Atlantic Ocean is dominated by the Subtropical Gyre and the confluence of the Brazil and Malvinas currents. Observations indicate that the latitude of this confluence changes seasonally, lying farther north during the austral winter than during the summer. This phenomenon has important consequences for the local climate and marine population, as the latitude of the confluence also marks the boundary between the warm waters of the subtropical gyre and the cold waters of the Antarctic Circumpolar Current. We present evidence that these seasonal migrations may be related to changes in the transport of both the Brazil and Malvinas currents. A numerical model forced by climatological wind stress indicates that the transport of the Brazil Current decreases during winter months and increases during summer months. Geosat altimeter data corroborate the model results and also indicate that the transport of the Malvinas Current undergoes a seasonal cycle with phase opposite to that of the Brazil Current. Our hypothesis is that during the austral summer, a southward displacement of the latitude of the confluence is coincident with an acceleration of the flow in the subtropical gyre and a weakening of the transport of the Malvinas Current. This situation reverses during the winter when the Malvinas Current grows stronger, the Brazil Current transport decreases, and the latitude of the confluence of these two currents moves northward.

1. INTRODUCTION

The Brazil Current is the subtropical western boundary current of the South Atlantic Ocean. It flows south along the continental slopes of Brazil, Uruguay, and Argentina to a point between 33°S and 40°S where it encounters the northward flow of the Malvinas Current, the subpolar western boundary current of the South Atlantic that originates as a branch of the Antarctic Circumpolar Current (ACC). The juncture of the currents, known as the Brazil/Malvinas confluence (hereinafter referred to as the confluence) is one of the most energetic regions in the world ocean [*Chelton et al.*, 1990] and has been previously described by numerous authors [*Legeckis and Gordon*, 1982; *Roden*, 1986; *Reid*, 1989; *Gordon*, 1989; *Garzoli and Garrafo*, 1989]. After joining at the confluence, both currents turn eastward and flow offshore in a series of large-scale meanders. Observations indicate that the exact latitude at which the confluence occurs varies seasonally, lying farther north during the austral winter (July–September) than during the austral summer (January–March) [*Balech*, 1949; *Olson et al.*, 1988; *Garzoli and Garrafo*, 1989]. This phenomenon has important consequences for the local climate and marine population, as the latitude of the confluence marks the boundary between the warm waters of the Subtropical Gyre and the cold waters of the ACC. The cause of these oscillations has not been established. *Garzoli and Bianchi* [1987] analyzed an 8-month record of inverted echo sounder data and reported a peak in the mass transport of the Brazil Current during the month of January and a consequent displacement of the confluence to the south. *Garzoli and Garraffo* [1989] noted that the latitude of the strong thermohaline front associated with the confluence underwent a 12-month oscillation and suggested that these motions may be related to sporadic intrusions of the Malvinas Current. *Peterson and Stramma* [1991], in a review of the upper circulation in the South Atlantic Ocean, hypothesized that the meridional displacements of the confluence were related to excursions of the wind stress forcing.

The purpose of this study is to investigate the causes of the north-south oscillations of the latitude of the Brazil/Malvinas confluence. Numerical experiments indicate that the position of the confluence depends on the mass transport of both the Brazil and Malvinas currents [*Matano*, 1993]. Our hypothesis is that the meridional motions of the confluence are related to changes in those transports. During the austral summer, an increase in the transport of the Brazil Current simultaneous and a weakening of the transport of the Malvinas Current may produce a poleward shift of the confluence, while the opposite situation during the winter may produce an equatorward shift of the confluence. This hypothesis is examined here using a numerical model and Geosat altimeter data. In section 2, we present the results of a numerical experiment aimed at investigating the effect of changes in the wind stress forcing on the mass transport of the Brazil Current. In section 3 the model results are complemented by an observational study of the surface variability in the southwestern Atlantic using Geosat altimeter data. The combined results are summarized and discussed in section 4.

2. NUMERICAL EXPERIMENTS

In a pioneering study of the seasonal variability of a flat-bottomed ocean at midlatitudes, *Veronis and Stommel* [1957] pointed out that the response of the ocean to seasonal changes in the wind stress should consist of both barotropic and baroclinic forced oscillations. In a later study, *Gill and Niiler* [1973] suggested that, for regions poleward of 30° latitude, the response of the ocean to seasonal winds is primarily barotropic. For large horizontal scales in particular, no significant role was expected for baroclinic Rossby waves. The influence of bottom topography was studied by *Anderson and Killworth* [1977] with

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a two-layer model. They showed that the adjustment of the oceans occurs in two phases. Initially, the barotropic mode is excited and rapidly carries energy away from the eastern boundary. After a few days, the response in the interior of the ocean is described by the topographic Sverdrup relation. This barotropic adjustment is then followed by a baroclinic response in the form of a westward propagating Rossby wave. In the wake of this wave, the flow in the lower layer vanishes and the circulation becomes independent of bottom topography. At midlatitudes, however, the baroclinic adjustment is so slow that even at seasonal time scales the response in the interior of the ocean is still described primarily by the topographic Sverdrup relation. *Willebrand et al.* [1980] arrived at a similar conclusion based upon numerical and theoretical analyses of the oceanic response to a large-scale atmospheric disturbance. *Anderson and Corry* [1985*a*, *b*] investigated the dynamics of seasonal variations in the transport of the Gulf Stream using barotropic and baroclinic models and showed that the phase of the changes in the transport of this western boundary current is well described by the the topographic Sverdrup relation. They also showed that the flat-bottomed Sverdrup balance is unlikely to hold at the annual period for the North Atlantic. Based on similar arguments, several studies on the seasonal variation of the wind-driven circulation in the North Atlantic and the North Pacific oceans have been carried out using barotropic models including bottom topography [*Anderson and Corry*, 1985*a*, *b*; *Greatbatch and Goulding*, 1989].

Following a similar approach, we have investigated the effect of wind stress changes on the mass transport of the Brazil Current using a barotropic model. The model utilized is the multilevel numerical model described by *Bryan* [1969] and implemented by *Cox* [1984]. Its domain extends from 25°S to 55°S and from 70°W to 15°E. Bottom topography and coastlines are realistic with the exception of the inclusion of east-west walls at the northern and southern boundaries. The model has a horizontal resolution of 1° and 15 vertical levels. It is initialized with homogeneous fields of temperature and salinity and is forced at the surface with climatological wind stress fields [*Hellerman and Rosenstein*, 1983]. The model was started from rest and integrated for 5 years. There was very little difference between the results for the second and third years of integration and almost none between the results for the third, fourth, and fifth years.

Figure 1 shows synoptic views of the mass stream function of the model simulation during the fifth year of integration. Although the detailed structure of the wind-driven circulation is strongly affected by the bottom topography, the anticyclonic gyre that dominates the circulation in the South Atlantic Ocean is clearly evident. The concentration of streamlines near the western boundary marks the poleward flow of the Brazil Current. The "Subtropical Gyre" depicted in Figure 1 extends southward of what observations indicate. This discrepancy is due to the absence of an ACC in the model that may shift the Subtropical Convergence farther north [*Matano*, 1993] and the deformation of planetary vorticity contours by the bottom topography. In this regard it must be remembered that Figure 1 is not a representation of the total dynamical field in the Subtropical Gyre but represents only that part due to the propagation of barotropic disturbances. To the extent that the problem can be considered linear and that the most important component of the variability is wind-driven, the total circulation may be obtained by a simple superposition of some (unknown) baroclinic mean field and the barotropic component depicted in Figure 1.

Figure 2 shows the seasonal variation of the zonally averaged wind stress curl in the South Atlantic Ocean from the climatological data of *Hellerman and Rosenstein* [1983]. South of approximately 35°S there is a distinct seasonal cycle in the wind stress curl with a maximum during the austral summer and a minimum during the austral winter. North of 35°S there is an opposite cycle with an absolute maximum during the winter months.

From Figures 1 and 2 it is apparent that the circulation in the southwestern Atlantic is highly correlated with the wind stress curl in the latitude band of 35° to 45°S. Starting from January (summer) there is a gradual decrease in the strength of the circulation, followed by a slow increase toward the winter. Figure 3 shows the time evolution of the mass transport of the Brazil Current at 40°S (solid line) as derived from the model. There is a distinct seasonal cycle with high values during the austral summer (a maximum of 17 Sv in December) and low values during the austral fall and winter (a minimum of 8 Sv during May). These transport changes are strongly correlated with changes in the wind stress curl at 40°S (dotted line). It should be noted that the phase of the changes in the transport of the Brazil Current shown in Figure 3 is a robust feature of our calculation and does not depend on the exact location at which they are made, i.e., transport changes calculated at lower latitudes have the same phase (although different amplitudes).

The effect of the wind stress curl north of 35°S is mostly confined to the northeastern portion of the South Atlantic, where there is a subcell of intensified circulation during the winter months that weakens toward the spring and fall.

The partition of the circulation into two distinct gyres is the result of the bottom topography in the South Atlantic Ocean. Figure 4 shows the bottom topography and the planetary vorticity contours (f/H) in this region. Isolines of f/H near the western boundary are connected to those of the southern portion of the basin and are separated from those in the eastern South Atlantic by the sharp inflections associated with the presence of the Mid-Atlantic Ridge. Wind anomalies produced in the southern part of the Atlantic, where the bottom topography is relatively homogeneous, can propagate along the f/H contours to the western boundary. Similar wind anomalies in the northern portion of the basin (primarily associated with maxima in the wind stress curl occurring near the coast of Africa [*Hellerman and Rosenstein*, 1983]) are mostly confined to the region east of the Mid-Atlantic Ridge and have almost no effect on the seasonal changes of the transport of the Brazil Current.

The Brazil Current mean transport of 12 Sv calculated from the model at 40°S can be compared with the values estimated from direct observations. As reviewed by *Peterson and Stramma* [1991], the Brazil Current is weak and shallow north of 25°S, with an estimated transport of less than 11 Sv. To the south, transport estimates from hydrographic data indicate an intensification rate of about 5% per 100 km [*Gordon and Greengrove*, 1986] caused by the presence of a recirculation cell [*Reid et al.*,

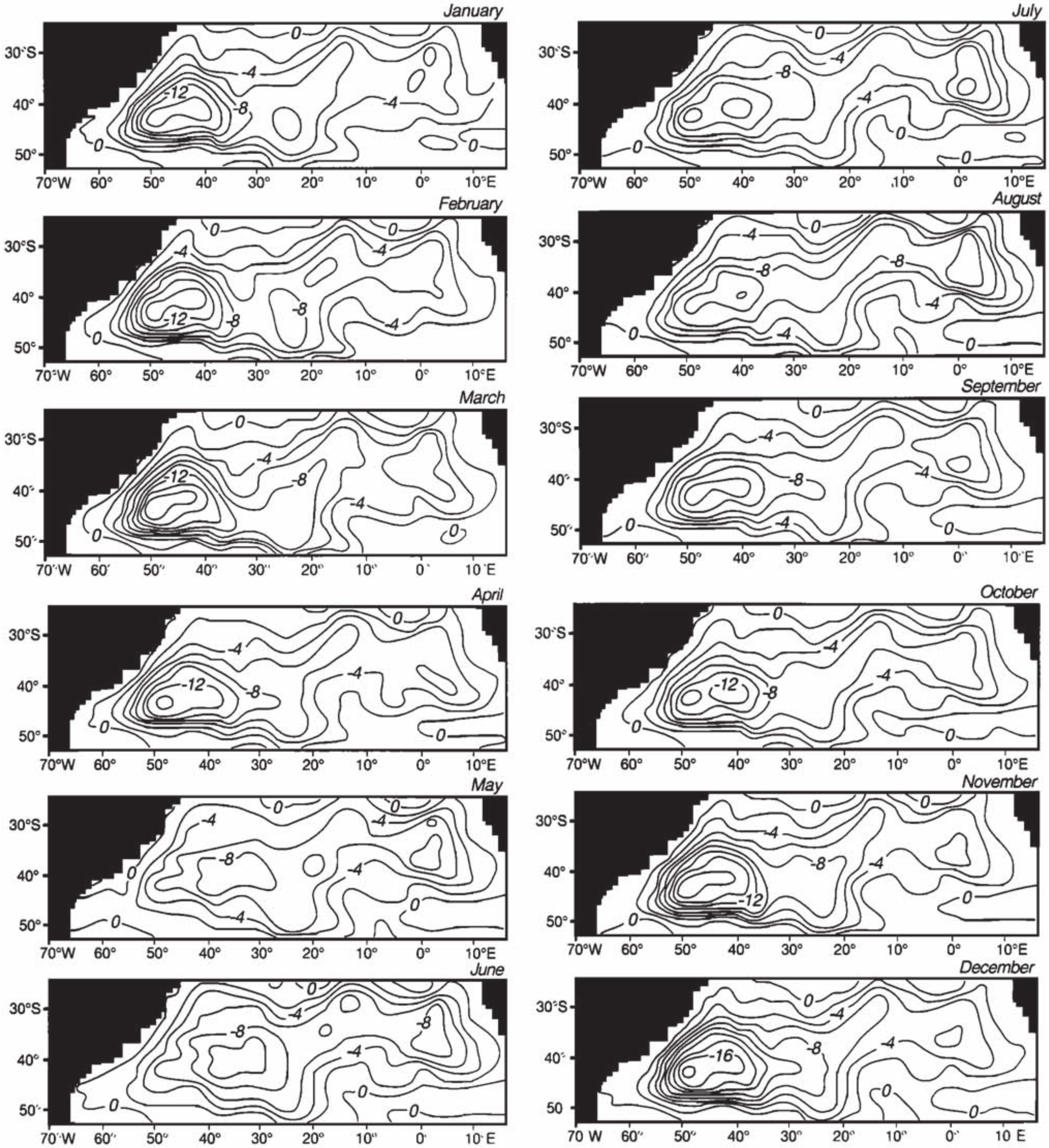

Fig. 1. Mass stream function of the barotropic model after 5 years of integration. The contour interval is 2 Sv.

1977; *Olson et al.*, 1988]. At approximately 38°S, the mass transport of the Brazil Current has been estimated from hydrographic and inverted echo sounder data to lie between 19 and 22 Sv relative to 1400–1500 m [*Gordon and Greengrove*, 1986; *Gordon*, 1989; *Garzoli and Garraffo*, 1989]. The disagreement between the amplitudes of the transports calculated by the model and those estimated from observations is not surprising. As was pointed out by *Anderson and Killworth* [1986], barotropic models can accurately reproduce the phase of changes of the transport of western boundary currents, but estimates of the transport magnitude require consideration of the effects of density stratification, such as the propagation of baroclinic coastal Kelvin waves. The aim of this study is not to obtain precise estimates of the magnitude of changes in the transport of the Brazil Current, but to examine the hypothesis that the phase of transport changes is consistent with the observed displacements of the confluence. The

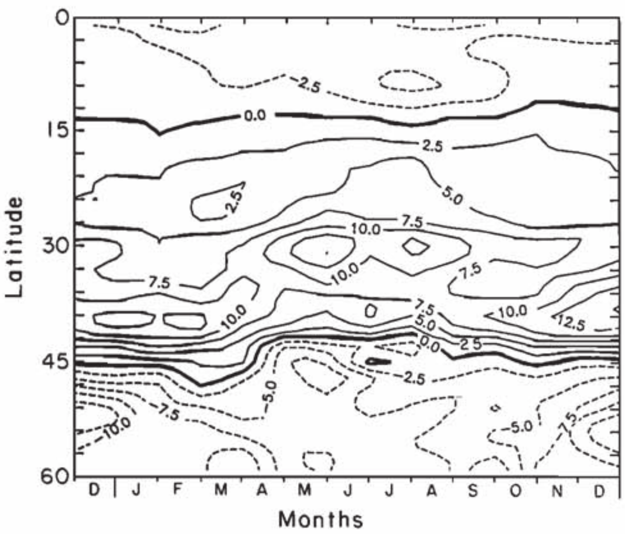

Fig. 2. Zonally averaged wind stress curl in the South Atlantic Ocean calculated from the climatological data set of *Hellerman and Rosenstein* [1983].

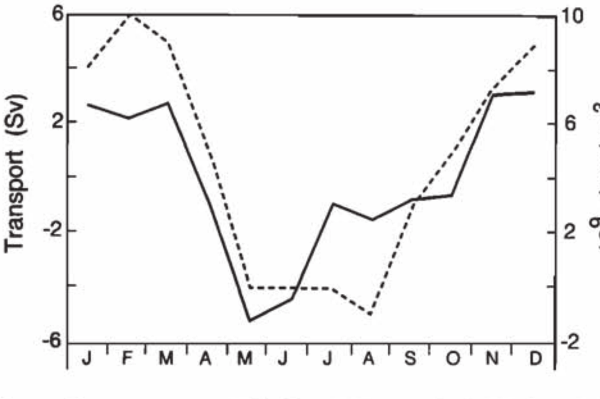

Fig. 3. Mass transport of the Brazil Current (solid line) and the zonally averaged wind stress curl (dotted line) at 40°S.

results of the present numerical experiment are consistent with this hypothesis. The strongest (weakest) seasonal wind-driven transport of the Brazil Current coincides with the observed extreme poleward (equatorward) location of the confluence.

The numerical experiment described above may seem a crude representation of the complex dynamics of an ocean with a realistic density stratification. It is noteworthy, however, that the results are in good agreement with the far more sophisticated numerical simulation of the global ocean circulation of *Semtner and Chervin* [1992], who used an eddy-resolving version of *Bryan*'s [1969] model. Their model was initialized with climatological values of temperature and salinity [*Levitus*, 1982] and forced by the same *Hellerman and Rosenstein* [1983] wind stress data used for the present experiment. A computation of the mass transport of the Brazil Current at 40°S (Figure 20 of Semtner and Chervin) shows a seasonal cycle very similar to that shown in Figure 3, with a high transport of the Brazil Current during the austral summer and a low transport during the austral winter. Semtner and Chervin's results differ from those presented in this study in the range of the seasonal transport variations, which in their case was near 50 Sv; but as was previously noted, the lower transport of our barotropic simulation is not unexpected.

3. GEOSAT ALTIMETER DATA ANALYSIS

Since in situ observations in the southern Atlantic are too sparse in space and time to verify the existence of the seasonal cycle in the Brazil Current transport, we investigate the temporal variability of the upper circulation from 24 months of sea surface height (SSH) data obtained by the Geosat satellite altimeter. The Geosat data were obtained from the NASA Ocean Data System and covered the first 24 months of the Exact Repeat Mission (November 1986 to October 1988). These data have been corrected for tidal and various atmospheric effects, edited, and interpolated to a fixed geographical grid at approximately 7-km intervals along the ground track [*Zlotnicki et al.*, 1989]. Additional steps were removal of the GEM-T2 estimates of orbit height (B. J. Haines et al., Application of GEM-T2 gravity model to altimetric satellite orbit computation, submitted to Journal of Geophysical Research, 1993), removal of the semiannual component of the oceanic tidal correction [*Chelton et al.*, 1990], application of a wave height dependent electromagnetic bias correction [*Witter and Chelton*, 1991], and geoid and orbit error removal [*Chelton and Schlax*, 1993]. In order to reduce both the volume of data and the energy of short-scale features, the residual SSH data were smoothed along the ground tracks

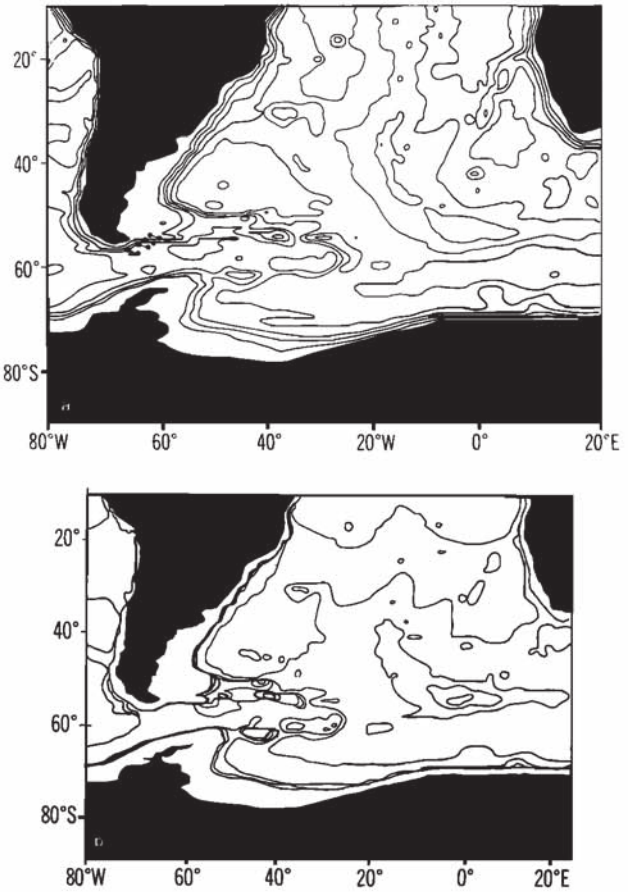

Fig. 4. (*a*) Bottom topography and (*b*) planetary vorticity contours in the South Atlantic Ocean. The dots in Figure 4*a* indicate the position of the points used to calculate the transport of the Malvinas Current from the Geosat altimeter data.

and subsampled to retain scales longer than 100 km. Data from shallow water areas (less than 1000-m depth) were eliminated in an effort to mitigate the effects of known inaccuracies in the tidal model used to correct the raw Geosat data in the western South Atlantic [*Parke*, 1980; *Cartwright and Ray*, 1989].

We first investigated whether the north-south oscillations of the latitude at which the confluence is located could be detected using the altimeter data. To this end, a series of maps of time-dependent smoothed sea level variability about an unknown reference mean sea level were constructed at 30-day intervals using a three-dimensional loess smoother [*Cleveland and Devlin*, 1988; *Chelton et al.*, 1990] with spans that effectively resolved scales longer than 10° of longitude, 5° of latitude and 30 days. The mean dynamic height relative to 2000 dbar determined from hydrographic data [*Gordon and Molinelli*, 1982] was added to each synoptic map of time-dependent sea level to obtain estimates of absolute sea level for each 30-day period.

For the purposes of this study, the latitude of the Brazil/Malvinas confluence was defined as the midpoint between the 1.8- and 2.0-m sea level contours at the western edge of the maps. For all but 4 of the 22 sea level maps constructed, this range spanned the sharpest meridional gradients of sea level at the western boundary and coincided with the latitude where the most intense eastward-flowing current intersected the 1000-m isobath farther offshore. Plate 1 shows two examples of maps of sea level height for the region between 70°E to 20°E and 30°S to 50°S. These maps were not extended farther south owing to gaps in the mean fields of the Gordon and Molinelli data in the high latitudes of the southwestern Atlantic. In Plate 1, the position of the confluence is marked by an arrow. Plate 1*a* shows the confluence at its northernmost position (June 1987), while Plate 1*b* shows the confluence at a more southerly summertime latitude (January 1988). Figure 5 shows the time series of the position of the confluence as computed using the previous definition in the 22 maps of sea level height. Consistent with previous conclusions from sparse in situ data [*Olson et al.*, 1988; *Garzoli and Garraffo*, 1989], the latitude at which the confluence is located is farther north during the austral winter than during the austral summer. The seasonal cycle is better defined during the year 1987 than during 1988. The extrema occur during the months of February and June. It is also apparent that at least during the time span covered by the Geosat data, there is a tendency for the confluence to linger near its northern extreme, indicating a significant component of semiannual variability. The southward excursions of the confluence occur only from December to March during the period covered by the Geosat data.

The connection between the position of the confluence and the large-scale variability in the South Atlantic Ocean was analyzed using empirical orthogonal function (EOF) analysis. This technique has proven useful in many geophysical applications and has previously been applied to altimeter sea level data in the southern ocean by *Fu and Chelton* [1984] and *Chelton et al.* [1990]. Since physical interpretation of the spatial structure of the second and higher order modes of the SSH variability is difficult, only the most energetic mode is considered here. A more extended discussion on the general variability of the surface circulation of the southern ocean based on EOF analysis of the Geosat altimeter data is given by *Chelton et al.* [1990].

Figure 6 and Plate 2 show the time and space structure of the first EOF, which accounts for 29.7% of the total variance of the gridded SSH and provides a useful summary of the large-scale coherent sea level variability in the South Atlantic. The vectors in Plate 2 indicate the geostrophic velocities associated with the surface elevation when the amplitude time series of the EOF has unit value. A coherent anticyclonic gyre with western intensification is clearly evident. The amplitude time series of this EOF exhibits a distinct seasonal cycle, indicating a deceleration of the flow from May to November and an acceleration during the austral summer months, although interannual variability is also clearly evident. A comparison between the time series of the amplitude of the first EOF and that of the latitude at which the confluence is located (Figure 5) indicates that the acceleration of the South Atlantic gyre during the months of December to March is accompanied by a poleward motion of the confluence. Conversely, the deceleration from April to November coincides with a retraction of the warm waters of the Brazil Current to lower latitudes. The time lag between these two processes is less than a month.

It is more difficult to estimate transport changes in the Malvinas Current than in the Brazil Current. The reason is that the Malvinas Current is not an integral part of a large-scale feature, like the Brazil Current is part of the subtropical gyre, but is a localized branching of the ACC by topographic effects [*Matano*, 1993]. This implies that the EOF's techniques previously applied to the subtropical gyre to deduce the time dependence of the Brazil Current's transport cannot be extended to the southern portion of the basin. With this limitation in mind, the mass transport of the Malvinas Current was calculated directly from the smoothed SSH data. Geostrophic velocities and transports, assuming a constant current velocity to a depth of 2000 m, were computed using the height differences between four pairs of points located as shown in Figure 4*a*.

Figure 7 shows the time series of the resulting estimated transport of the Malvinas Current. A robust seasonal cycle is easily identifiable in this time series, with decreased transport occurring during the summer months and increased transport during the winter. The peak to peak changes are of the order of 40 Sv, although this value depends on the arbitrarily chosen depth of no motion. We also estimated the Malvinas Current transport in locations to the north of those shown in Figure 4*a* but were unable to observe any clear seasonal cycle. This may be a result of higher-frequency variability associated with instabilities generated at the Brazil/Malvinas confluence or the local wind stress forcing. In any case, the results shown in Figure 7 should be taken as evidence for the existence of a seasonal cycle in the Malvinas Current, but not as proof of it.

There are few hydrographic observations to compare with our estimates of the Malvinas Current transport. *Gordon and Greengrove* [1986] calculated values of 9.8 Sv at 42°S and 11.4 Sv at 46°S using a reference level of 1400 m. *Peterson* [1990] estimated a mass transport of 70 Sv at 42°S using the bottom as reference level. The only other attempt to estimate seasonal changes in the transport of the Malvinas Current that we are aware of was made by

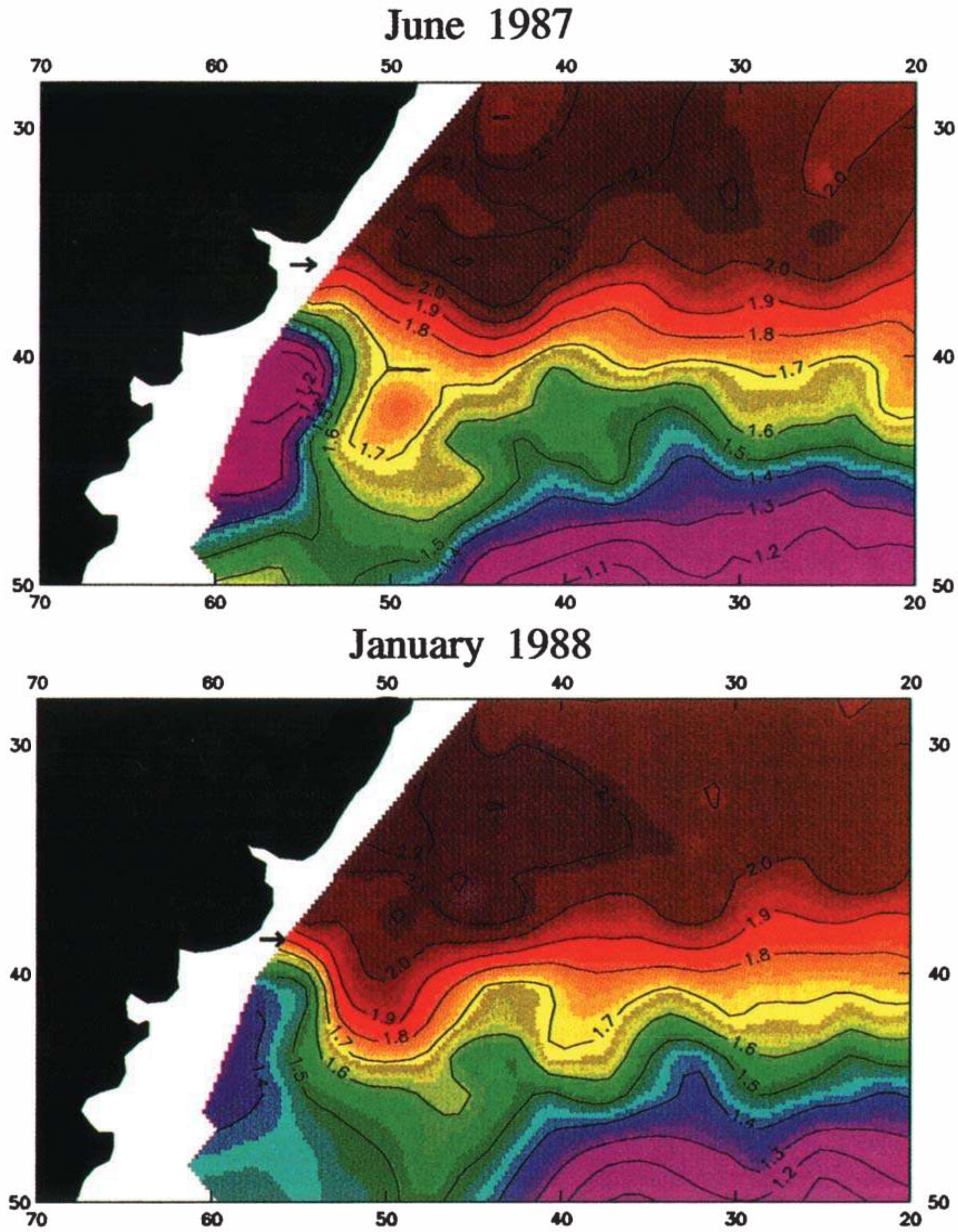

Plate 1. Sea level height of the South Atlantic Ocean relative to 2000-m depth for the months of (*a*) June 1987 and (*b*) January 1988. The sea level variability about an unknown reference mean sea level was calculated from the Geosat altimeter data at 1-month intervals. The mean dynamic height relative to 2000 m determined from hydrographic data [*Gordon and Molinelli*, 1982] was added to each synoptic map to obtain estimates of absolute sea level for each 30-day period.

Zyranov and Severov [1979] who, using a diagnostic model and historical density fields, calculated a depth-integrated transport of 32 Sv at 45°S during the austral summer and 40 Sv during the winter. They speculated that the seasonal changes in the transport were related to an increase of the cyclonic activity in the atmosphere during the winter months. *Forbes and Garraffo* [1988] used a one-dimensional model to estimate the transport over the Argentinian shelf. Consistent with the results of *Zyranov and Severov* [1979] and those reported here, they found an intensification of the northward transport over the shelf during the winter and a weakening toward the summer. This seasonal cycle was related to the local wind stress.

Since the Malvinas transport depends not only on the wind stress in the South Atlantic Ocean but also on the mass transport of the Antarctic Circumpolar Current at

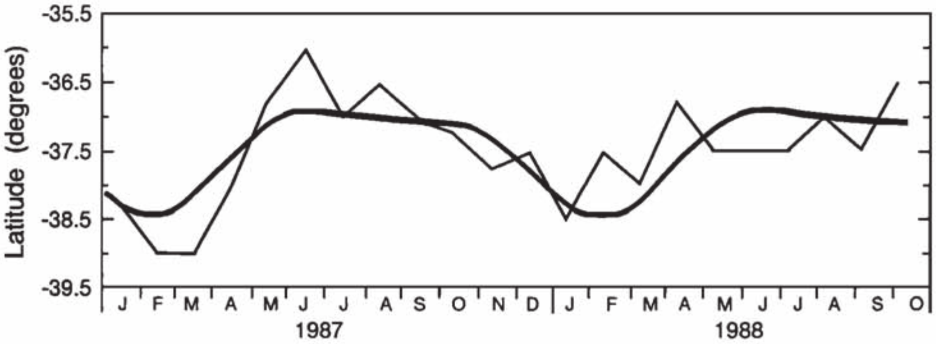

Fig. 5. Time history of the latitude of the confluence between the Brazil and the Malvinas currents near the continental slope of South America as calculated from the Geosat altimeter data. The heavy solid line superimposed on the time series is the least squares fit of an annual and semiannual harmonic to the time series.

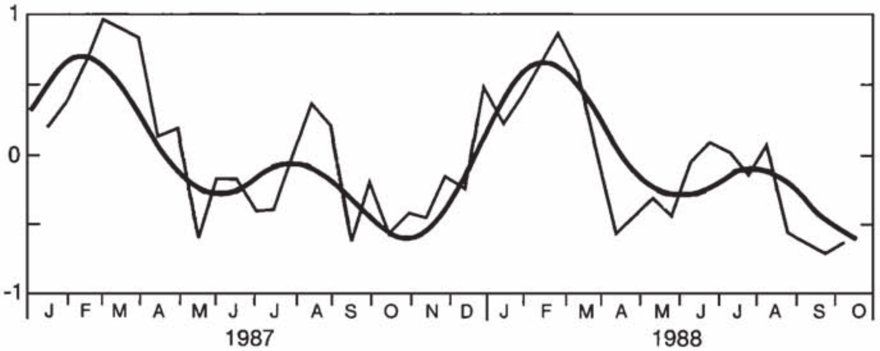

Fig. 6. The amplitude time series for the first EOF (solid line) in centimeters. The heavy solid line superimposed on the time series is the least squares fit of an annual and semiannual harmonic to the time series.

Drake Passage, a numerical simulation is beyond the scope of this study. It is, however, noteworthy that the seasonal cycle presented in Figure 7 is in good agreement with the calculation of *Semtner and Chervin* [1992] which shows a clear annual cycle in the mass transport of the Antarctic Circumpolar Current at the Drake Passage with phase opposite that of the variations in the mass transport of the Brazil Current at 40°S.

4. SUMMARY AND CONCLUSIONS

Satellite and hydrographic observations indicate that the latitude of the Brazil/Malvinas confluence changes seasonally, lying farther north during the austral winter than during the austral summer. The hypothesis considered in this study is that these north-south oscillations are related to changes in the transports of the Brazil and the Malvinas currents. We studied the changes in the Brazil Current transport produced by variations in the wind stress using a barotropic version of *Bryan*'s [1969] model. A numerical experiment using climatological wind stress data showed that the transport of the simulated Brazil Current is higher during the summer than during the winter. The model results were corroborated by Geosat altimeter data, which were also used to estimate the transport of the Malvinas Current and the seasonal variation of the latitude of the confluence.

During the austral summer, the southward displacement of the latitude of the confluence appears to be coincident with an acceleration of the flow in the subtropical gyre and a weakening of the transport of the Malvinas Current. This situation reverses during the winter when the Malvinas Current grows stronger, the Brazil Current transport decreases, and the latitude of the confluence between these two currents moves northward. These cycles are summarized in Figure 8, which displays normalized least squares estimates of annual and semi-annual components of seasonal variabilities of the latitude of the confluence, the acceleration of the Subtropical Gyre, and the transport of the Malvinas Current. Out-of-phase changes in the transport of the Brazil Current and the Malvinas Current, coupled with the north-south displacement of the wind stress patterns [*Peterson and Stramma*, 1991], can account for the large amplitude of the meridional excursions of the latitude of the confluence.

Although the seasonal oscillation of the confluence appears to be related to transport changes of the constituent currents, it is not necessary for both currents to have a well-defined seasonal component. In particular, although the evidence presented in this study strongly supports the existence of a robust annual component in the gyre-scale mass transport variations of the Brazil Current, it falls short of showing conclusive evidence for a similar cycle in the Malvinas Current transport near the region of the confluence. *Podesta et al.* [1991] and *Provost et al.* [1992] analyzed variations in sea surface temperature (SST) in the confluence region from satellite-derived data and found that the amplitude of the annual SST cycle decreases to the south. This observation was interpreted by *Provost et al.* [1992] as an indication of a reinforcement of the natural seasonal cycle associated with the heat flux from

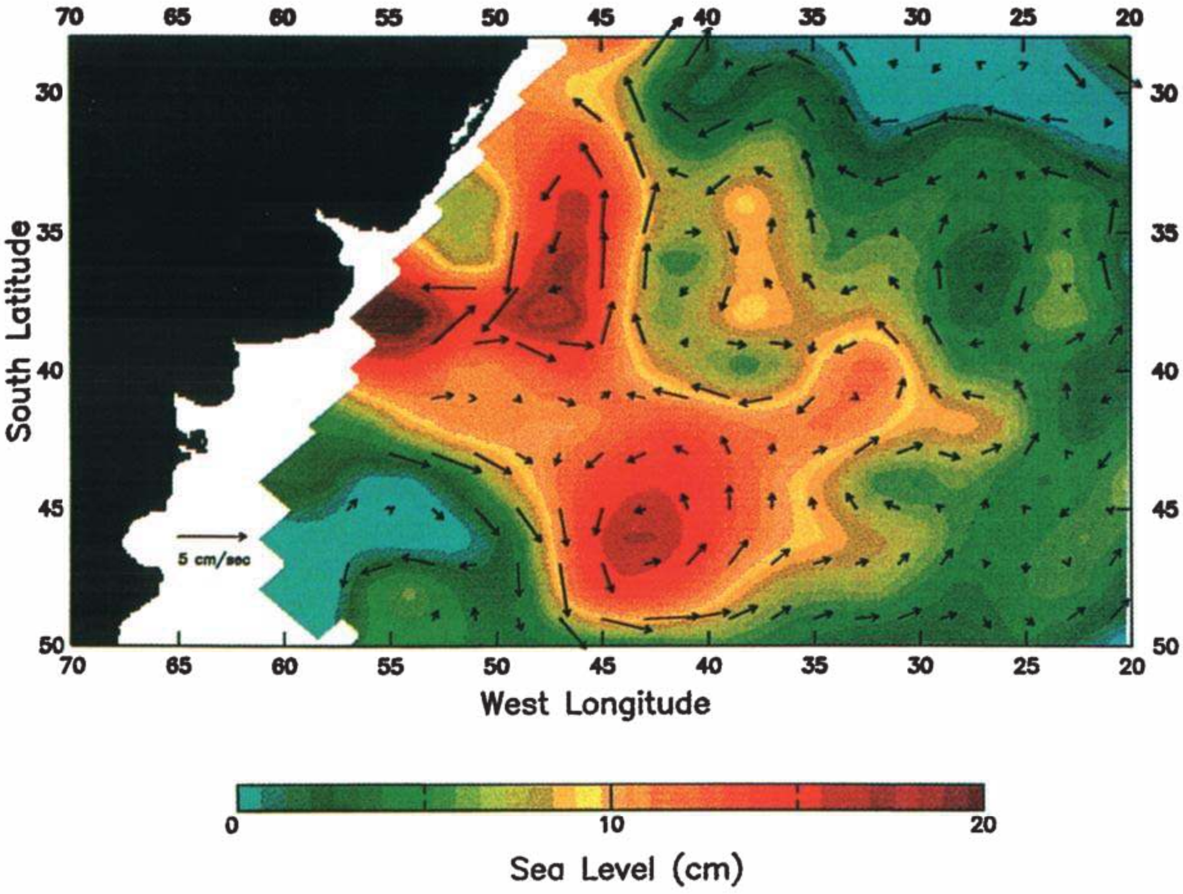

Plate 2. The first EOF (which accounts for 29.7% of the total variance) calculated from the synoptic sea surface elevation fields observed by the Geosat altimeter. The arrows indicate the geostrophic velocities associated with the surface elevation.

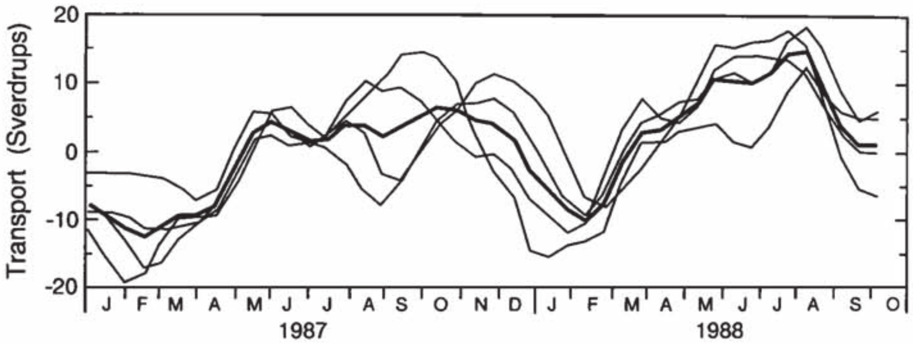

Fig. 7. Time series of the mass transport of the Malvinas Current, calculated from the synoptic fields of sea surface elevation. The locations of the points used in this calculation are shown in Figure 4. Thin lines represent individual calculations, the heavy line the average of the four transport estimates.

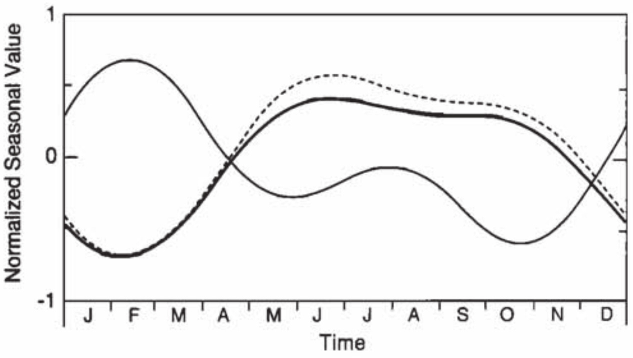

Fig. 8. Time series of the least squares fit of an annual and semi-annual harmonic to the first EOF of the synoptic fields of the sea surface elevation in the South Atlantic Ocean (thin solid line); transport of the Malvinas Current (dotted line); latitude of the Brazil/Malvinas confluence (heavy solid line). All the curves were normalized and plotted in nondimensional units.

the atmosphere by an annual component in the variability of the Brazil Current transport. Such a reinforcement is not obvious in the region dominated by the northward flow of the Malvinas Current. Whether this is an indication that the annual component of the confluence variability is mostly dominated by changes in the transport of the Brazil Current is a matter of further research.

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