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Geostrophic velocity and transport variability in the Brazil–Malvinas Confluence

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Abstract—This paper presents the results from a study of the dynamics of the Brazil–Malvinas Confluence in the southwestern Atlantic based on data collected with an array of inverted echo sounders. Dynamic height series were obtained at 10 different sites for a period of 15 months The data are analyzed in terms of dynamic height, geostrophic velocities and transports The large variability previously inferred from satellite observations is observed in the dynamic height field of the surface, relative to 100 m, and is attributed to changes in the latitude of separation, the meandering of the Confluence front towards the east, and eddy generation. The eddy circulation observed is both cyclonic and anticyclonic. These eddies are observed both between the southward edge of the Brazil Current and the northward edge of the Malvinas Current and superimposed to the main flows The diameter of the eddies is two to three times the Rossby Radius of deformation

The highest observed values of the geostrophic velocities (102 cm s^{-1} at 36 5°S and −61 to −62 cm s^{-1} at 37.6°S) are associated with the large shear in frontal situations. The northward penetration of the Malvinas Current occurs during 1988 and 1990 during the southern hemisphere winter This is in agreement with results from a previous deployment, satellite observations and model results The Brazil Current transport is at 35.2 and 36.5°S, −24 Sv towards the south and −20 Sv between 37.7 and 38°S (reference 1000 m). The transport of the Brazil Current return at 35 2°S is of the same value as the southward flow· 24 Sv. For the Malvinas Current, the estimates indicate a northward transport of 5 Sv at 37 7°S (reference 1000 m) These values are considered as a lower limit The array captured only about half the flow due to the location of the deployments, and only the baroclinic component. The transport should be at least doubled to compensate the value obtained for the Malvinas return flow at the same latitudes, −24 Sv.

INTRODUCTION

ONE of the unique features of the South Atlantic lies in the fact that it is the only ocean with equatorwards meridional heat flux (BRYAN, 1962). Possibly as a consequence, the western boundary currents system does not follow the classical pattern. At the western boundaries elsewhere strong poleward flow (in the Gulf Stream and the Kuroshio Current) encounters weaker currents flowing equatorwards (the Labrador and the Oyashio currents in the above-mentioned examples). In the southwestern Atlantic, all estimates of the Brazil Current transport indicate that this western boundary current transports less than half of the volume carried for its peers in the other oceans. On the other hand, the Malvinas (Falkland) Current, a northern branch of the Circumpolar Current, is apparently stronger than equatorward flows such as the Labrador or Oyashio

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currents. This last result is based mostly on theoretical model. No direct measurements have been made.

If the circulation is explained based on the Sverdrup closure of the wind stress, all western boundary currents should have the same intensity. As early as 1965 STOMMEL (1965) suggested that the cause of the difference between the Brazil Current and Gulf Stream transports could be found in the thermohaline circulation. Thermohaline circulation will enhance the Gulf Stream transport in the North Atlantic and diminish the one carried by the Brazil Current in the South Atlantic.

The encounter of the Brazil and Malvinas currents, which has been called the Confluence (GORDON and GREENGROVE, 1986), occurs between 40 and 35°S. The latitude at which the current separates from the coast varies seasonally (OLSON *et al.*, 1988; GARZOLI and GARRAFFO, 1989) with a northward penetration of the Malvinas Current during the southern hemisphere winter and a southward advection of the Brazil Current during the southern hemisphere summer. GARZOLI and GARRAFFO (1989) suggested that the cause of this variability could be two-fold: due to an intensification of the winds in the southern ocean or to a variability in the South Equatorial Current, which will result in a weaker Brazil Current. OLSON *et al.* (1988) suggested that variations in the Brazil–Malvinas Confluence might be driven by changes in the Malvinas forced by variations in the Antarctic Circumpolar Current.

The transports associated with the currents are still not well defined. An excellent review of observational results in the southwestern Atlantic is given by PETERSON and STRAMMA (1991). According to STRAMMA *et al.* (1990), the southern branch of the South Equatorial Current carries about 16 Sv across 30°W in the upper 500 m. Of these 16 Sv, 12 feed the North Brazil Current and only 4 Sv flow south. As the Brazil Current flows south it intensifies at a rate of about 5%, similar to the Gulf Stream (PETERSON and STRAMMA, 1991). This downstream intensification appears to be related to a recirculation cell (GORDON and GREENGROVE, 1986). North of the Confluence, at 33°S, the Brazil Current transport is estimated to be 17.5 Sv (STRAMMA, 1989). At the Confluence, and across 38°S, estimated transports range from 19 to 22 Sv (GORDON and GREENGROVE, 1986; GARZOLI and GARRAFFO, 1989). All these estimates have been obtained using reference levels between 500 and 1000 m. MCCARTNEY and ZEMBA (1988) and PETERSON (1990) estimated a total southward transport from the surface to 3000 m of 76 Sv at 37°S and 70 Sv at 38°S, respectively. An intensive study of the Brazil Current by ZEMBA (1991) concluded that, when considering all the water masses, the Brazil Current transport increases considerably but it never reaches the Gulf Stream values. The problem that this poses is how to define the Brazil Current. If it is defined as the warmer (T = 15–25°C) and saltier (S = 35.8–36.0‰) water confined above the thermocline, then the transport at its southward position is about 20 Sv.

As a branch of the Circumpolar Current, the Malvinas Current Flows northward along the continental shelf of South America. It is assumed to be a stronger current, but actually very few estimates of the volume transport exists in literature. These estimates have a large range of variability depending on the differences of opinions concerning the reference level. Currently it is accepted that the Malvinas Current has a strong barotropic component and that non-zero bottom velocities must exist. The first assumption is based mostly on both hydrographic data and on differences between geostrophic surface velocities obtained from those data and surface drifter observations (PETERSON and STRAMMA, 1991). In any case, using a reference level of 1400 m, GORDON and GREENGROVE

(1986) obtained from CTD data northward transports of about 10 Sv between 42 and 46°S; the authors considered that their estimates represent a lower limit of the real flow. Similar values were obtained by PIOLA and BIANCHI (1990) in the area: 10–12 Sv, also reference 1000 m. That non-zero velocities occur near the bottom has been directly verified by HARKEMA and WEATHERLY (1989) whose bottom current meters observed velocities up to 10 cm s^{-1}. In a recent publication, PETERSON (1992) estimated the depth-integrated northward transports in the Malvinas Current region as a mass balance residual between 38 and 42°S. This calculation leads to values for the northward transport of 75 Sv at 42°S and 88 Sv at 46°S. These numbers are much larger than previously found in the literature but, according to PETERSON (1992), consistent with velocities of surface drifters in the Malvinas Current (40 cm s^{-1}).

Results from numerical models confirm the observational results obtained for the Brazil Current but disagree with the values of Malvinas transport. The transports for both currents were calculated from the global ocean eddy resolving general circulation model of SEMTNER and CHERVIN (1992) by GARZOLI *et al.* (1992). In order to compare with observations, transports were calculated from the model velocities assuming a reference level of 1000 m. Results indicate a southward transport associated with the Brazil Current of 12 Sv at 34°S and 16 Sv at 40°S, in agreement with the observations and, a northward transport associated with the Malvinas Current of 28 Sv at 47°S, two times larger than estimated from the observations. Malvinas model transports to the bottom are of about 50 Sv. The most generalized theory for this disagreement is that the modeled Circumpolar Current is overestimated and that this results in a stronger than "real" Malvinas Current. GARZOLI *et al.* (1992) suggest that another cause for the disagreement might be due to a poor resolution of the topography in the Drake Passage and in the region where the Malvinas Current separates from the Circumpolar Current. The fact is that the "real" transport of the Malvinas Current remains unknown.

Following the pilot experiment performed in the area (GARZOLI and BIANCHI, 1987; GARZOLI and GARRAFFO, 1989) an international program, Confluence (CONFLUENCE PRINCIPAL INVESTIGATORS, 1990), was organized to study the time–space variability of the associated flows in the region. As part of this program, an array of 10 inverted echo sounders (IES) was designed to obtain an estimate of the geostrophic velocities and

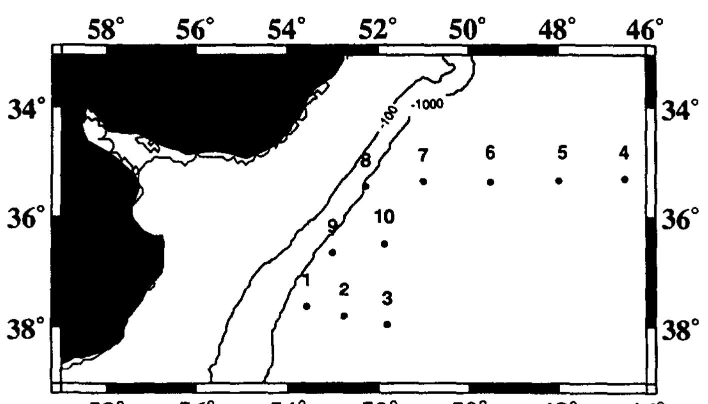

Fig 1 Location of the 10 IES deployments during the Confluence 1988–1990 program

transports associated with the Brazil Current at the Confluence and to study the time–space variability of the Confluence front (Fig. 1).

In this paper, the data collected with the IESs are analyzed in terms of dynamic height, geostrophic velocities and volume transports. A general picture of the flows, their intensity and variability during the 15 months of the experiment, is given. In a companion paper (BIANCHI and GARZOLI, 1992) the location of the front and its motions are analyzed.

THE DATA

The IESs (manufactured at Pacer and tested and prepared for deployment at the Lamont-Doherty Geological Observatory) are bottom-deployed instruments that internally record the time it takes for an acoustic signal to travel to the surface and return. This travel time is a function of the sound velocity, which in turn depends on the thermodynamics of the water column (temperature, salinity and pressure). Therefore, monitoring changes in travel time, it is possible to determine changes in variables such as the depth of the thermocline, the integrated temperature or the dynamic height.

The instruments were deployed from the Argentine R.V. *ARA Puerto Deseado* between 4 and 14 November 1988. A hydrographic cruise took place during September 1989 as part of the program from the Argentine R.V. *BIP Oca Balda*. The objective of the cruise was to survey the hydrographic conditions of the area between the deployment and recovery cruises. During this cruise, in addition to the main CTD work, the performance of the IES was tested through "listening" stations in which the IESs were interrogated from the ship. CTD stations obtained during these stations provided a new point for calibration of the series. The 10 instruments were successfully recovered from the French R.V. *Le Suroit* between 17 and 24 February 1990. All of the data collected were in excellent condition, and 10 15-month-long series of travel time were obtained. The co-ordinates of the deployment sites, as well as the depth, time and date of deployment and recovery, are given in Table 1. The time interval between observations is $\Delta t = 1$ h. During the whole extension of the observation, and as part of the program, satellite infrared images of the sea surface temperature were collected at the station operated by the Argentine Meteoro-

Table 1 Location of the IES sites (Lat., Long.), depth in meters, and dates of deployment and recovery

IES site	Lat.	Long	Depth (m)	Deployment date (Nov. 1988)	Recovery date (Feb. 1990)
1	37°37 64′S	53°34.11′W	2852	14	23
2	37°48.10′S	52°45.20′W	3804	4	23
3	37°57.42′S	51°53.47′W	4346	5	24
4	35°19 00′S	46°29.00′W	4824	8	19
5	35°21.18′S	47°59.08′W	4688	9	19
6	35°22.90′S	49°30.40′W	4247	10	18
7	35°21.89′S	51°00.40′W	3018	10	17
8	35°27.39′S	52°16.94′W	1327	12	17
9	36°39.54′S	53°00 39′W	2231	13	21
10	36°29.56′S	51°52.35′W	3307	12	21

logical Service at Villa Ortuza (Buenos Aires) and processed at the Rosenstiel School of Marine Sciences (University of Miami, Florida). The images have been made available for inspection while analyzing the IES data and some of them are published in the present paper (courtesy of Podesta, Olson and Brown).

DATA REDUCTION

Calibration to dynamic height

The travel time integrated through the water column has proven to be directly related to the dynamic height (WATTS and ROSSBY, 1977). This relation is characteristic of each region of the world ocean. At the Confluence, previous estimates (GARZOLI and BIANCHI, 1987; GARZOLI and GARRAFFO, 1989) obtained from CTD casts lead to a linear regression between dynamic height (reference 800 m, DH_{800}) and travel time (TT) of the form ΔDH_{800} (dyn m) = $-0.01576\ \Delta TT$ (ms). The present array covered a larger area and, on the basis of the observations (PIOLA, personal communication), the reference level chosen is 1000 m. A new relation is obtained by using the hydrographic data collected during the first two cruises (CHARO *et al.*, 1991) between dynamic height reference 1000 m and travel time (both parameters calculated from the data collected with the CTD casts) leads to the relation:

$$\Delta DH_{1000}\ (\text{dyn m}) = -0.0179\ \Delta TT\ (\text{ms}). \tag{1}$$

The correlation coefficient is $R^2 = 0.962$ and the error of the estimate, $e = \pm 0.0305$ dyn m ms^{-1}. The observed changes in travel time range from 30 to 60 ms. These changes correspond, according to equation (1), to changes in DH from 54 to 107 dyn cm. Therefore, the error incurred by estimating dynamic height from the observed travel time using relation (1) is, at worst, 5.5% of the total signal and, at best, 2.8%.

Relation (1) establishes the relative change in dynamic height inferred from an observed relative change in travel time. To obtain an absolute value for the dynamic height, the information collected through the CTD casts is used. The procedure applied is the following: after one instrument is deployed, this is to say when it has reached the bottom of the ocean and has already started to internally record the travel time, a CTD cast is obtained. From the vertical profile of temperature and salinity, dynamic height from the surface to 1000 m is calculated. In this way, the absolute value of dynamic height at the time of deployment is established. The process is repeated during the intermediate cruise and, with these two points, the series of relative dynamic height are adjusted to absolute values by simply adding a constant that best matches the series with the CTD data derived values. (Unfortunately the CTD data obtained during the third cruise was not made available for this study.) The resulting 10 dynamic height series obtained throughout this procedure are shown in Fig. 2. Also shown are the values for dynamic height obtained with the CTD casts overlapped to the series.

Geostrophic velocities and transports

From the dynamic height series, geostrophic velocities can be calculated by using the equation:

$$v_g = (g/f)\ \Delta DH/\Delta x, \tag{2}$$

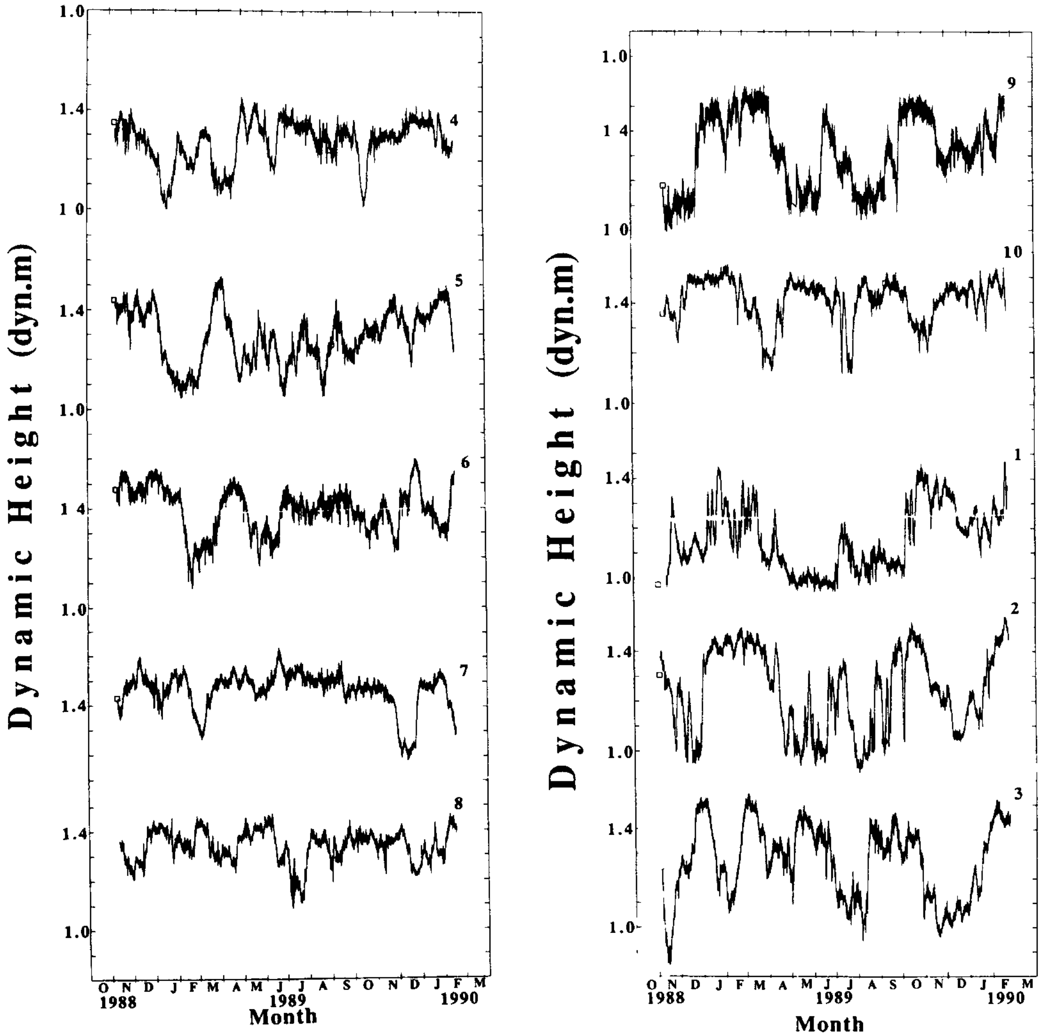

Fig. 2. Series of dynamic height (reference 1000 m) as obtained from the 10 travel time series. Overlapped (□) are the values of dynamic height from the CTD data collected during the first and second Confluence cruises

where g is gravity, f the Coriolis parameter and ΔDH is the difference in dynamic height between two stations separated by a distance Δx. Assuming no error in the distance between the stations, the error incurred by equation (2) is due to errors in dynamic height. The error in the estimate of dynamic height is ± 0.0305 dyn m, and this is translated into errors in geostrophic velocity that vary at each location. The estimated errors are ± 2.4 to ± 3.1 cm s^{-1} at 35°20′S; ± 3.4 cm s^{-1} at 36°30′S and ± 4.5 at 37°50′S. They are represented in the figures as horizontal lines and should be considered as the upper level. This is because, to minimize the errors, the series of V_g obtained through relation (2) are adjusted to the values of geostrophic velocities obtained with the CTD data following the same procedure applied to obtain the absolute dynamic height series, and this procedure reduces the errors Once the geostrophic velocities are obtained, the transport between the stations can be estimated. IES data do not provide information on the vertical structure of the water column. Therefore, to calculate transports, assumptions on the vertical velocity profile must be made. In a previous paper GARZOLI and GARRAFFO (1989) have demonstrated the validity of the assumption that the velocity decreases linearly with depth. On this basis, transports are calculated using the equation:

$$Tr(\mathrm{Sv}) = 0.5V_g\,\Delta x\,\Delta z, \tag{3}$$

where Δx is the distance between the stations and $\Delta z = 1000$ m, the depth of the layer. Nevertheless, the transports obtained through relation (3) are adjusted afterwards, if necessary, to the value of transports obtained with data from the CTD casts in a similar fashion as was done for the dynamic height and geostrophic velocities. Results (Fig. 3) show the series obtained from differences in dynamic height scaled at geostrophic velocity (left) and transport (right). Oscillations with periods less than 2 days are eliminated through a filter with a cut-off frequency 0.5 c.p.d. and a termination frequency of 0.85 c.p.d.

DATA ANALYSIS AND INTERPRETATION

Circulation

The present data set confirms that the large surface variability of the area, previously observed through satellite infrared imagery (OLSON *et al.*, 1988), satellite tracked drifting buoys (PATTERSON, 1985; PIOLA *et al.*, 1987; FIGUEROA and OLSON, 1984) and satellite altimetry (CHENEY *et al.*, 1983; LEGECKIS and GORDON, 1982), is also observed throughout the water column (up to 1000 m).

Across the northern leg, along 35.2°S (Fig. 1), the dynamic height varies from 1.0 to 1.6 dyn m. A picture of this variability in the dynamic topography (of the surface relative to 1000 m; Fig. 4) shows the series of dynamic height as a function of time and longitude for (a) across 35.2°S (IES Stas 4–8), and (b) across 37.7°S (IES Stas 1–3). A large variability is observed in both sections. As will be shown, in the northern section this variability is due mostly to the return of the Brazil Current and to eddy formation, and in the southern leg, to the advection of the Brazil Current that results in frontal motions.

From the slope in dynamic topography, which gives the direction of the geostrophic flow or geostrophic velocities (Fig. 3), it can be inferred that across 35.2°S, for most of the observed period at the western side of the section (between IES Stas 7 and 8), the flow is southward. This southward flow is generally associated with the Brazil Current. Only twice during the entire observed period, the flow between IES Stas 7 and 8 is directed towards the north (Fig. 3): from 26 February to 16 March 1989 and from 2 to 26 December 1989, perhaps indicating a northward penetration of the Malvinas Current. If so, it will indicate, in the case observed during February, a contradiction (or a marked interannual variability) with previous results (OLSON *et al.*, 1988; GARZOLI and GARRAFFO, 1989), which indicated that the Malvinas Current is at its southward location during February. A closer look at the circulation in the entire observed area, however, shows that this is not the case.

The direction and magnitude of the geostrophic flow between station pairs (Fig. 5) shows that the circulation is characterized by a system of cold and warm eddies. On 2 March (Fig. 5a), south of 37°S, the observed values of dynamic height (1.2, 1.4 and

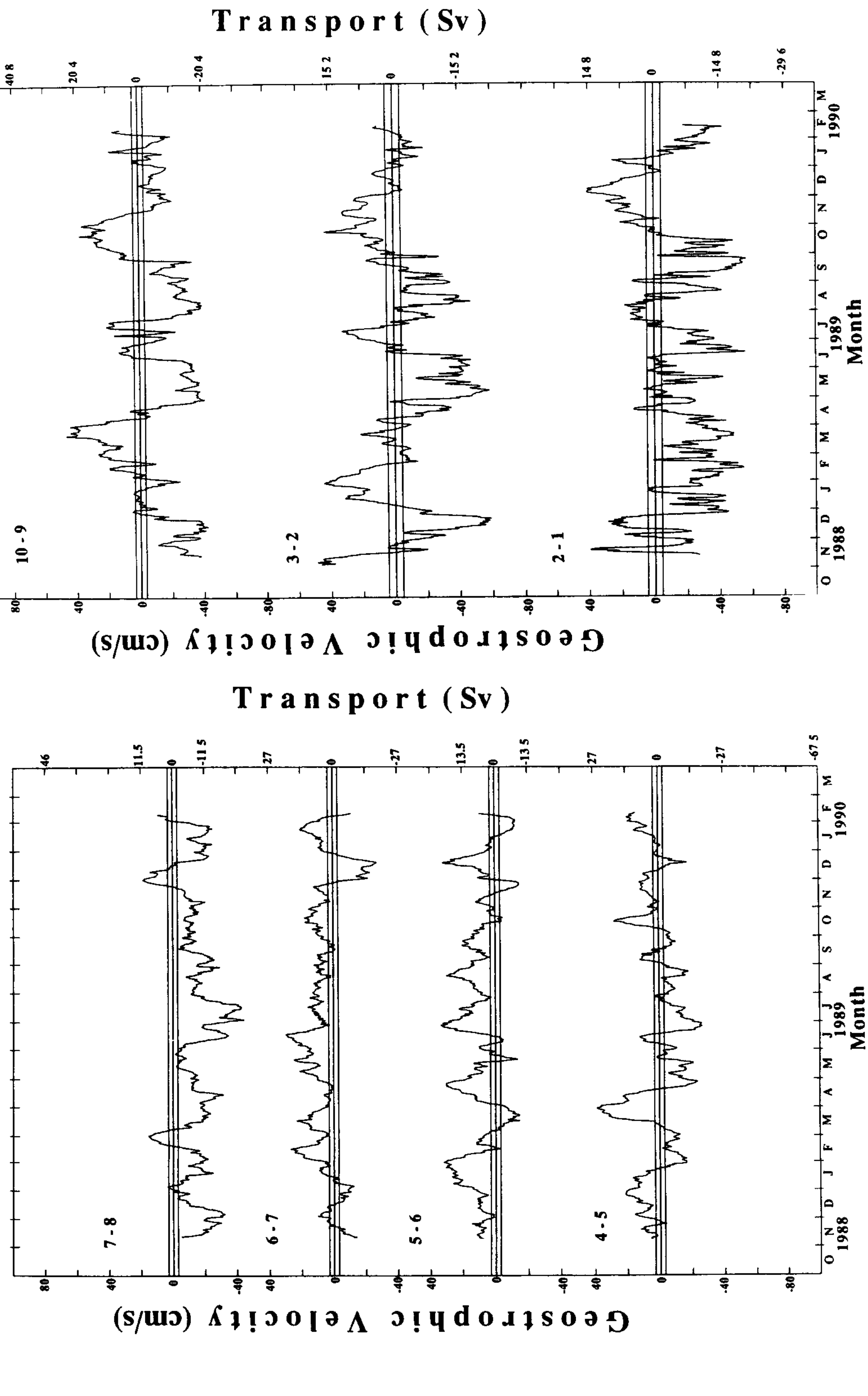

Fig 3 Series of geostrophic velocities (left scale) in cm s^{-1} and transports (right scale) in Sv ($=10^6$ m^{-3} s^{-1}) obtained from the gradient in dynamic height Oscillations with periods less than 2 days are eliminated through a low pass filter (see text)

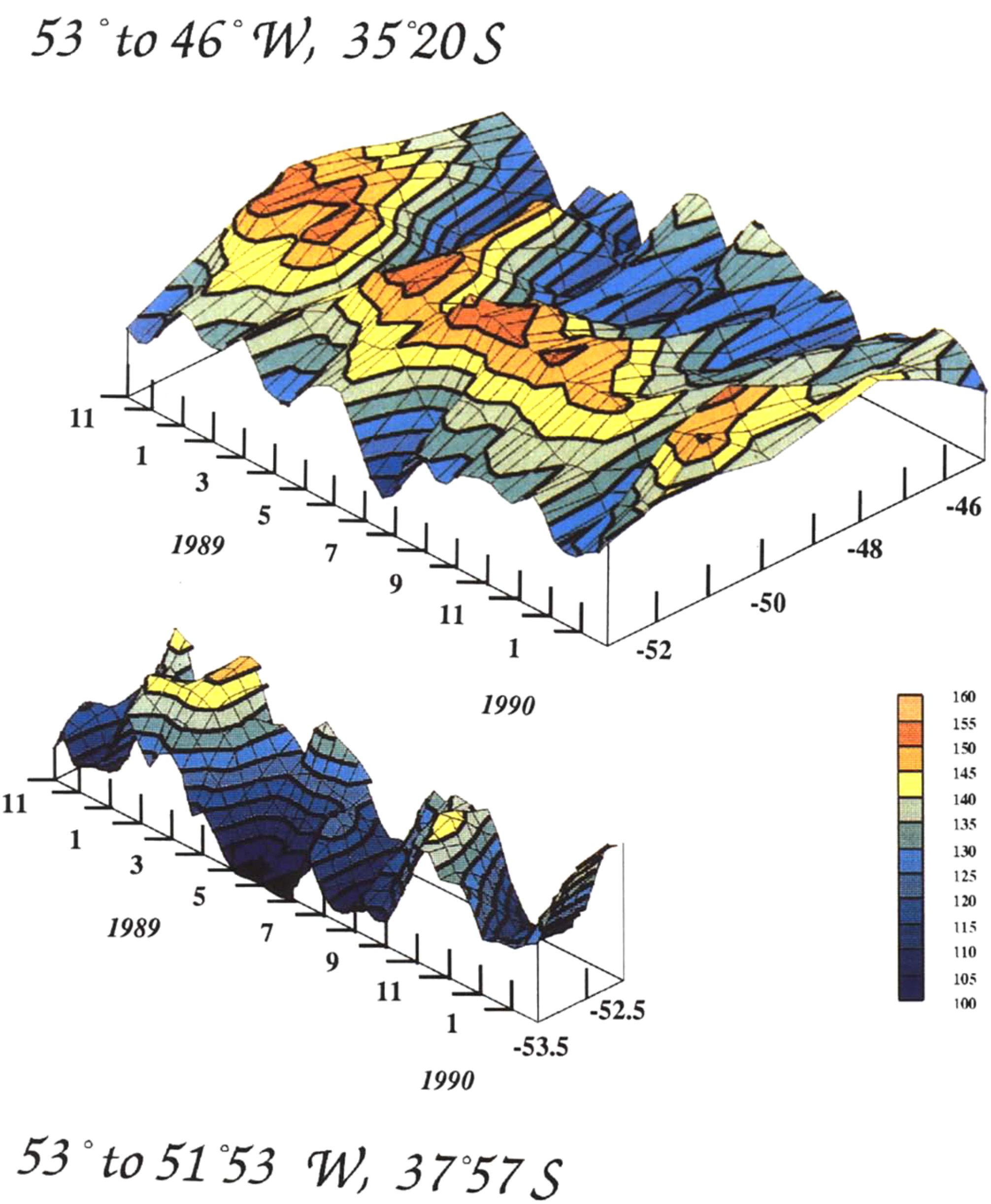

Fig 4. Dynamic height as a function of time and longitude for series across 35.2°S (IES Stas 4–8) and across 37 7°S (IES Stas 1–3) These data are the result of a 10-day running mean of the original hourly values. Yellow to green values (>1 30 dyn m) are associated with the Brazil Current while dark blue colors (<1 05 dyn m) are associated with the Malvinas Current

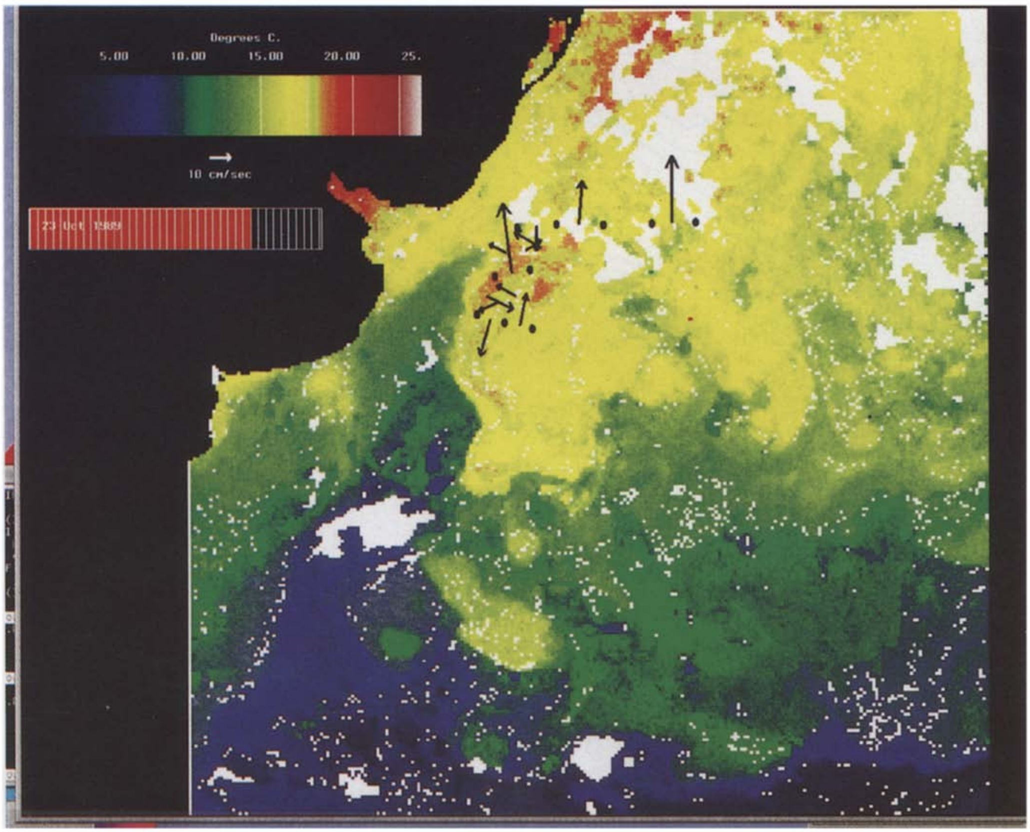

Fig. 7. NOAA AVHRR satellite image for 23 October 1989 collected by the Argentine Hydrographic Service and processed at RSMAS, University of Miami (PODESTA, OLSON and BROWN, personal communication) Superimposed are the location of the IES stations and the direction and magnitude of the geostrophic velocities (cm s^{-1})

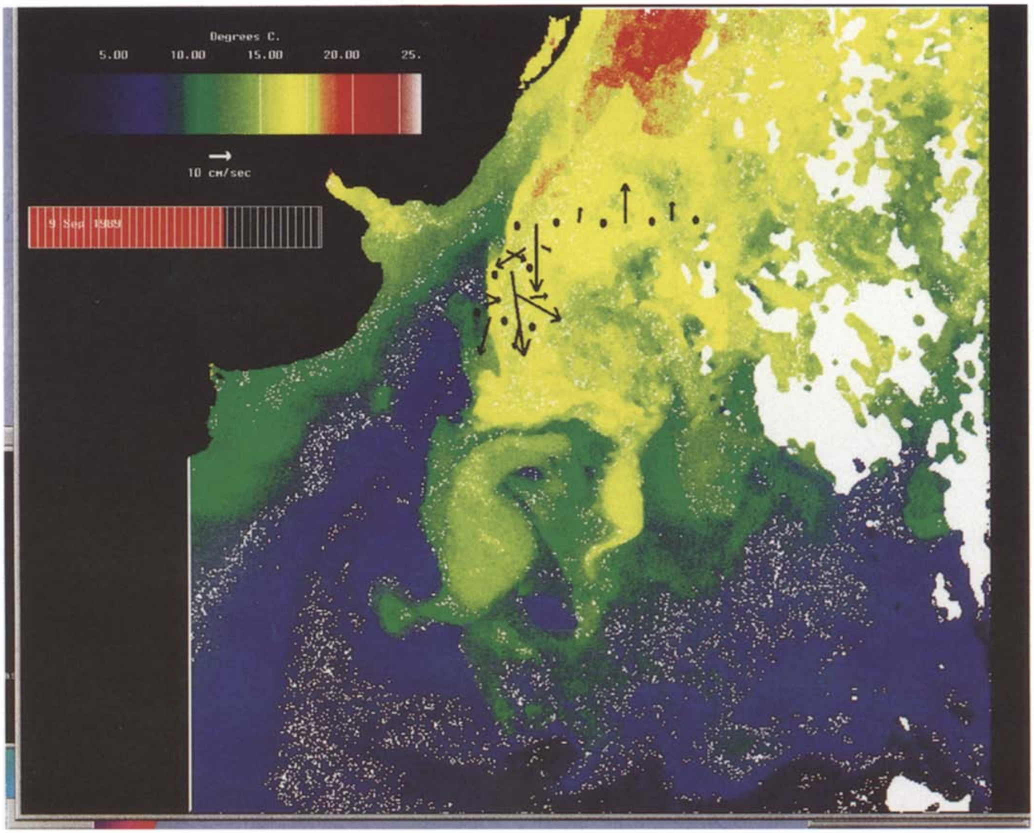

Fig 9. NOAA AVHRR satellite image for 9 September 1989 collected by the Argentine Hydrographic Service and processed at RSMAS, University of Miami (PODESTA, OLSON and BROWN, personal communication) Superimposed are the location of the IES stations and the direction and magnitude of the geogstrophic velocities (cm s^{-1})

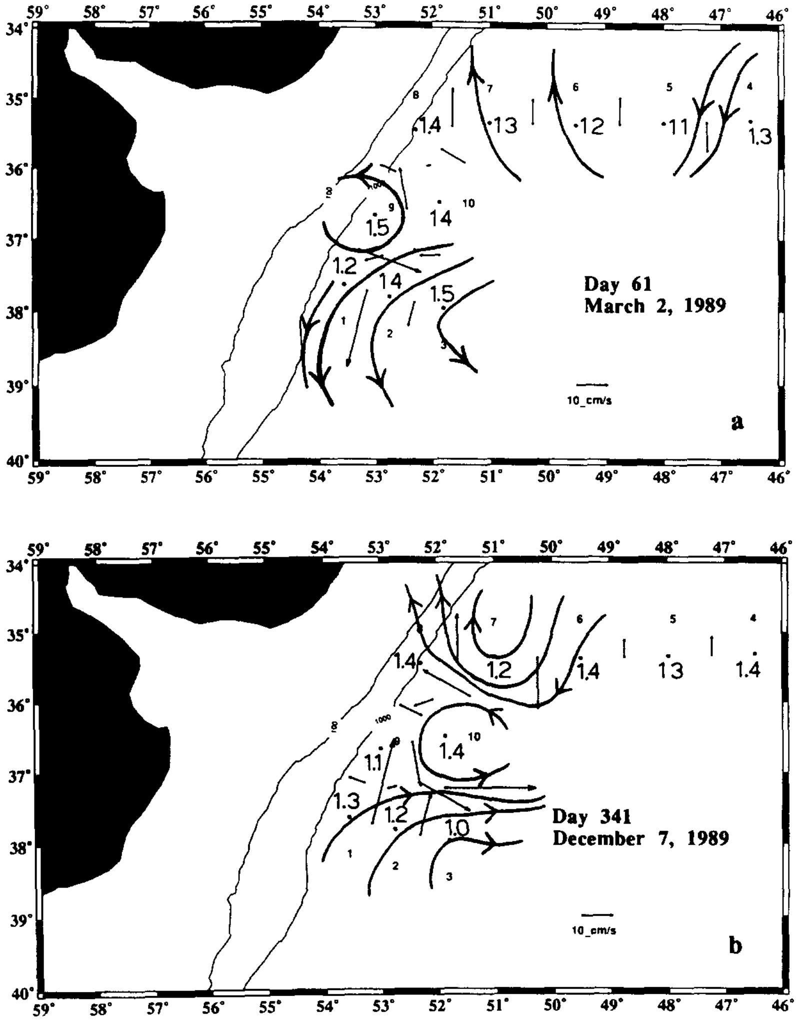

Fig. 5 Direction and magnitude of the geostrophic velocities (cm s^{-1}) between station pairs for (a) day 61 (2 March 1989) and (b) day 341 (7 December 1989) Numbers from 1 to 10 indicate the IES station number. Values near the station are dynamic height in dyn m. The lines indicate the circulation pattern

1.5 dyn m at IES Stas 1, 2 and 3, respectively) indicate that the Brazil Current occupies the entire area while the Malvinas Current does not reach the latitude of the southern leg. The direction of the geostrophic flow indicates an anticyclone circulation in the southern leg and a cyclonic circulation in the northern leg. This results in a northward flow observed between IES Stas 7 and 8. The scale of these cyclonic and anticyclonic circulations is too large to assume that it corresponds to eddies shed by the main flows. Satellite images for this period of time are not very clear due to a storm system in the area. Nevertheless, they indicate the presence in the atmosphere of two large cyclons (cyclonic and anticyclonic; Olson and Podesta, personal communication). The question remains if the atmospheric cyclons system had remained in the area long enough to force the ocean.

On day 341 (7 December) the situation is somewhat different (Fig. 5b), but again, the northward flow between Stas 7 and 8 is due to a system of eddies. Centered at Sta. 7, there is a colder eddy embedded in Malvinas waters (1.23 dyn m at the center); a warm eddy centered at Sta. 10, (1.45 dyn m) and a cold eddy (1.0 dyn m) centered at Sta. 3. The lower value of dynamic height at Sta. 3 suggests that the southern eddy has been shed from the Malvinas Current main flow while the warm anticyclonic eddy, centered at Sta. 10, apparently has been shed from the Brazil Current. Satellite images for the two analyzed periods of time confirm (Podesta and Olson, personal communication) the presence at the surface of cold cyclonic and warm anticyclonic eddies previously described. That is to say, in both cases the northward flow observed in the western side of the section, across 35°20′S, is not due to a northward penetration of the Malvinas Current but to eddies originating at the Confluence. These eddies are the result of the local dynamics; eddies are shed from the main flows by a pinching of the meander.

Further east, between Stas 5 and 7 (Fig. 3), the flow is northward most of the time. This is due to the return of the Brazil Current. It is interesting to note (Fig. 3) that occasionally when the flow between IES Stas 6 and 7 is southward (December 1988 and December 1989), the flow between Stas 5 and 6 is towards the north. The same holds true for negative flows between Stas 5 and 6. This is due to both the generation of eddies and the zonal meandering of the Confluence. Oscillations from positive to negative between this last station pair are mostly out of phase with those observed between IES Stas 4 and 5. A clear example is during December 1989; the flow between IES Stas 6 and 7 is negative during the whole month (-22 cm s^{-1}) and positive during the same period of time between IES Stas 5 and 6 ($+ 22$ cm s^{-1}). This is a clear indication of a cyclonic circulation or eddy.

The extreme values of the geostrophic velocities (maximum and minimum) across the section along 35.2°S are given in Table 2 along with the mean values and standard deviation. At the western side of the section, along 35.2°S between IES Stas 7 and 8, the mean flow is negative (-13.1 cm s^{-1}). This indicates the presence of the southward flowing Brazil Current with the exception of the two situations previously described in which, due to cyclonic circulations, the flow was towards the north. It is at this location where the maximum negative value of geostrophic velocity is observed: -46.3 cm s^{-1}. In the center of the section (IES Stas 5–7) average flows are positive, indicating northward motion. This northward flow is associated with the return of the Brazil Current. The largest positive

Table 2. Geostrophic velocities between IES station: minimum (min), maximum (max), mean and standard deviation (S.D)

	Geostrophic velocity (cm s^{-1})			
IES Sta	Min	Max	Mean	S D.
2–1	−61 3	43 6	−12 0	22.4
3–2	−62.3	77 6	−2.8	23.5
4–5	−29 6	41 2	1 6	12.5
5–6	−20 0	35 5	9 1	11.1
6–7	−28 9	33 6	6 2	10.1
7–8	−46 3	19 9	−13 1	11 7
10–9	−47 2	102 7	−6 2	21 1

velocity, between IES Stas 5 and 6 (35.5 cm s^{-1}; Table 2), is not statistically different from the one observed between IES Stas 6 and 7: 33.6 cm s^{-1}. In both cases the value of the standard deviation is smaller, indicating that less variability is observed between Stas 5 and 7.

Maximum positive values along 35.2°S are observed at the eastern side of the section (IES Stas 4 and 5): 41.2 cm s^{-1}. Nevertheless, the mean during the entire monitored period is statistically zero (1.6 cm s^{-1}). This is an indication of the meandering of the Confluence at this location.

For the two IES stations in the middle of the array (Stas 9 and 10) the flow changes direction from northwest to southeast periodically (Fig. 2ii). The most stable northward flow is observed during March/April and October/November 1989. In both cases the circulation is apparently very similar. Along the northern leg, an alternating series of low and high values of dynamic heights result in an eastward meandering type circulation. High values of dynamic height (1.4–1.67 dyn m) are observed at Sta. 9 and a very low value (1.1–1.2 dyn m) is observed at Sta. 10, due to the presence of a cold cyclonic eddy between the two main flows (Figs 6a and b). While there are similarities in Fig. 6 in the circulation at the central and northern legs, differences are observed in the south. In the first example (27 March, Fig. 6a), the low value of dynamic height at Sta. 1 (1.09 dyn m) and the large shear between Stas 1 and 2 indicate the presence of the Malvinas Current and its return. In the second example, the observed dynamic height at Sta. 1 is high (1.5 dyn m) and related to the Brazil Current. A warm eddy composed of Brazil waters is centered at this location. To better illustrate this part of the discussion, the SST, as derived from the satellite images for 23 October 1989, is shown in Fig. 7.

The sites along 37.5°S (Fig. 1, IESs 1–3) were previously occupied during the pilot experiment (Garzoli and Garraffo, 1989). Therefore, the analysis of the present data will provide additional information on interannual variability. At these latitudes, the main variability in dynamic height, and therefore in geostrophic velocities, was shown to be due in 1985–1986 (Garzoli and Garraffo, 1989) to the east–west displacement of the front that originates between the two opposite flows (Brazil and Malvinas Currents). These motions are mostly due to a northward penetration of the Malvinas Current during the southern hemisphere (SH) winter (July–September) or to the southward advection observed in the Brazil Current (SH summer, January–March). Additional variability is due to the presence of eddies formed at the Confluence.

During 1988–1990 the flow between IES Stas 1 and 2, at the western location of the southern leg, is towards the south (Fig. 3) for most of the observed period. This southward flow can correspond either to the Brazil Current or to the return of the Malvinas Current. The way to differentiate between these two cases is by analysis of the dynamic height values at Stas 1, 2 and 9. If the values of dynamic height at these locations are higher than 1.2 dyn m, then the southward flow will correspond to the Brazil Current. If the values are lower than 1.1 dyn m, then this could be an indication that the Malvinas Current is flowing north, west of IES Sta. 1 and the southward flow observed is due to its return. For example, the low values of dynamic height observed at IES Sta. 1 from May through 1 October indicate the presence of subantarctic waters up to 37°S. If low values of dynamic height are also observed at IES Sta. 9, the Malvinas Current probably penetrated farther north at that time. In this case the southward flow is associated with the return of the Malvinas Current. This second case is illustrated in a typical example shown for day 251 (8 September 1989) in Fig. 8a. Across 35.2°S, the Brazil Current flows south, west of 49°W up

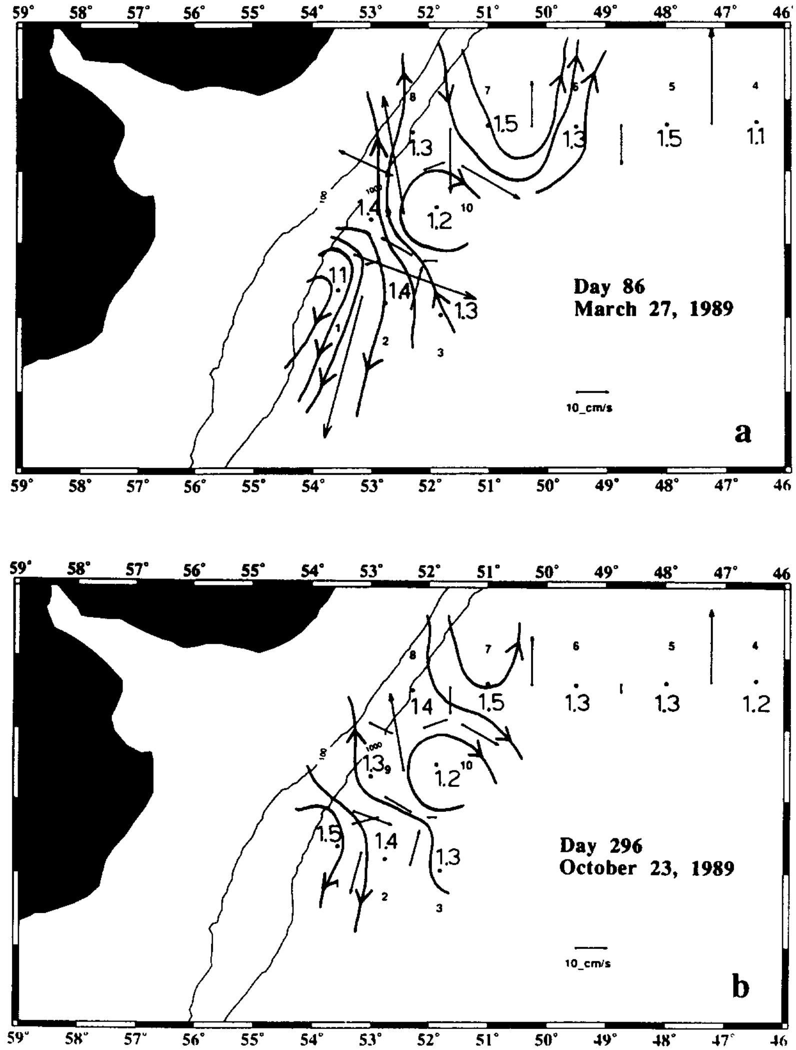

Fig 6. Direction and magnitude of the geostrophic velocities (cm s^{-1}) between station pairs for (a) day 86 (27 March 1989) and (b) day 296 (23 October 1989). Symbols as in Fig 5

to 37°S, where it turns towards the east and returns towards the north at 35.5°W east of 49°W. The low values of dynamic height at IES Stas 1 (1.09 dyn m) and 9 (1.0 dyn m) indicate that the Malvinas Current is flowing on the continental shelf west of 53.5°W, encountering the Brazil Current at around 37°S, and returning south between 53 and 54°W. The southeastward flow between IES Stas 10, 2 and 3 indicates the Brazil Current flowing south. This pattern agrees with the previous results that show the Brazil Current reaching its southward extension during the SH summer. The example shown for 8 September 1989 was chosen because it corresponds to the period of time of the second Confluence cruise when hydrographic casts had been collected. A comparison with the satellite images (Fig. 9) and with the hydrographic data collected during this cruise (PIOLA

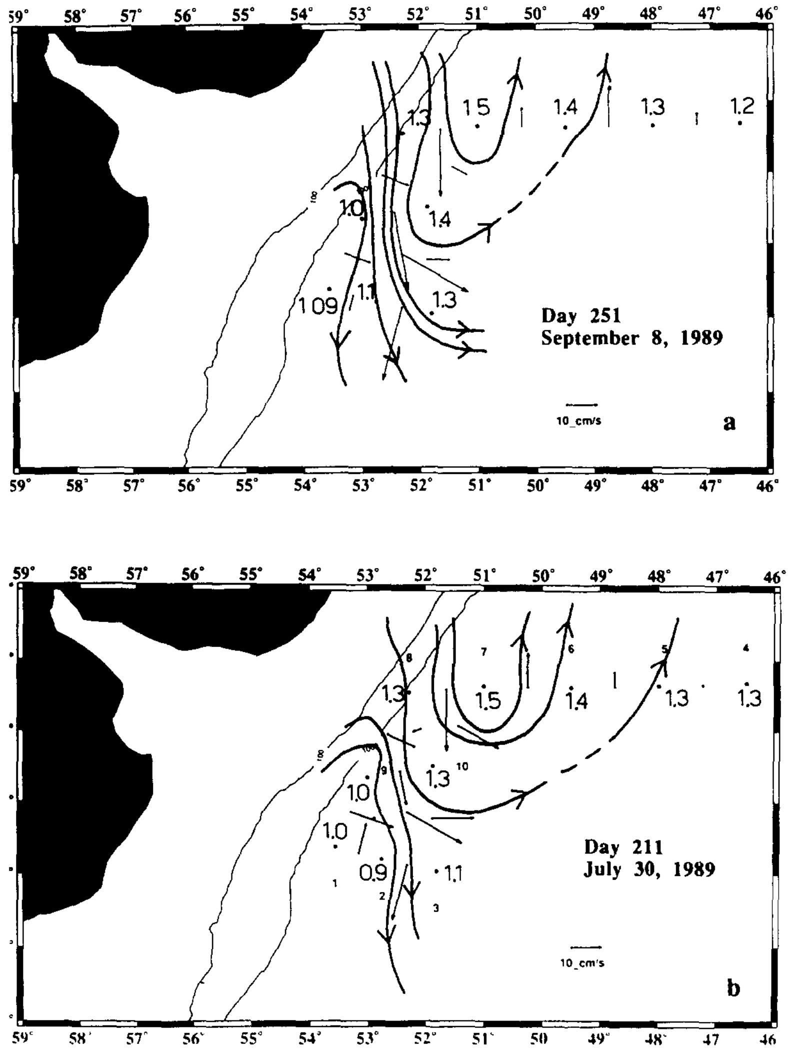

Fig 8. (a) Direction and magnitude of the geostrophic velocities (cm s^{-1}) between station pairs for day 251 (8 September 1989), (b) direction and magnitude of the geostrophic flow between station pairs for day 211 (30 July 1989) Symbols as in Fig. 5

et al., in preparation), confirms our interpretation. Another example is shown in Fig. 8b for day 211 (30 July 1989).

Significant northward flow is observed between IES Stas 1 and 2 at the end of 1988 and during November and December 1989 (Fig. 3). This is due to the presence of anticyclonic warm eddies shed from the Brazil Current. The direction and magnitude of the geostrophic flow for day 22 (22 December) 1988 (Fig. 10) show that the low values of dynamic height observed at Sta. 9 (0.96 dyn m) along 36.5°S indicate the presence of the Malvinas Current flowing west of 53°W. The Brazil Current flows south at 35.2°S between 50 and 53°W and returns north east of 50°W. The anticyclonic circulation observed at IES Sta. 1 is due to a warm eddy (1.15 dyn m) superimposed to the Malvinas Current (the value of

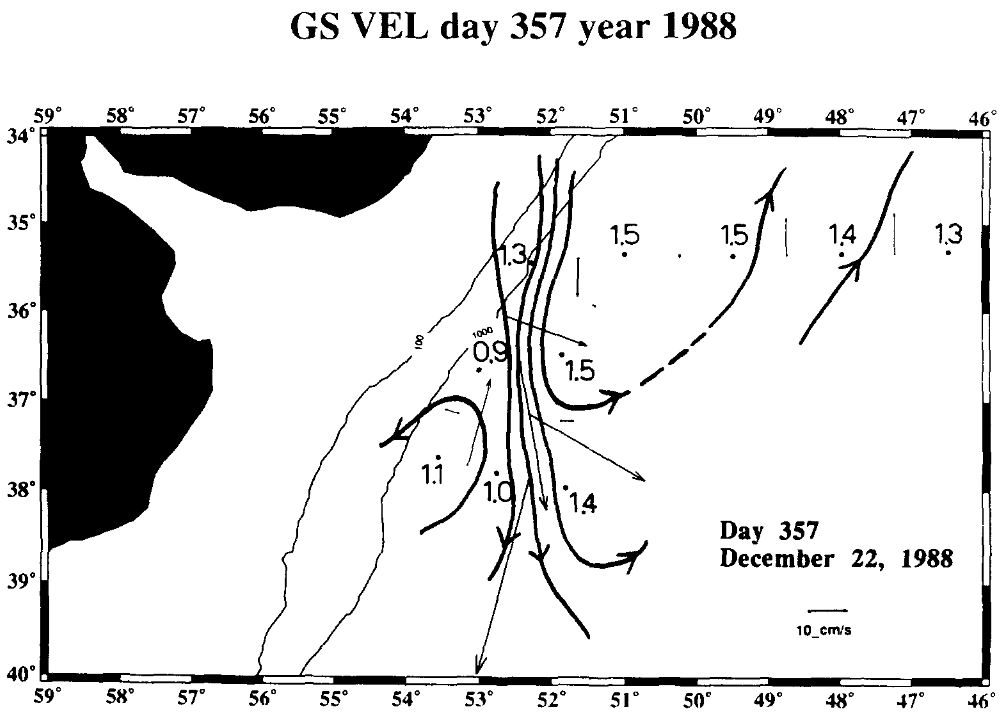

Fig. 10 Direction and magnitude of the geostrophic velocities (cm s^{-1}) between station pairs for day 357 (22 December 1988) Symbols as in Fig. 5.

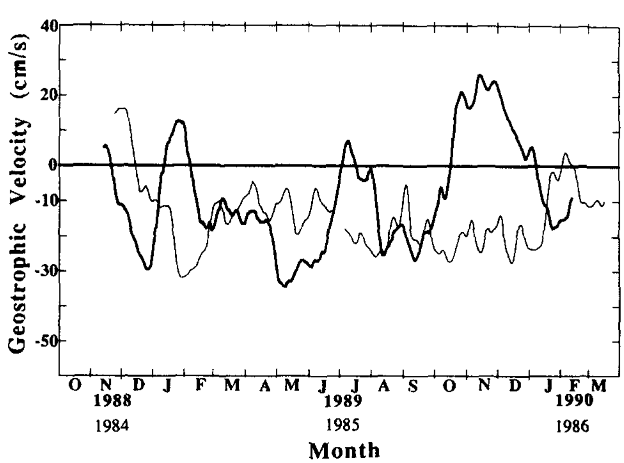

Fig. 11 Geostrophic velocities obtained from the gradient in dynamic height between IES Stas 1 and 3 (thick line) overlapped with the similar calculations obtained at the same location during 1984–1985 (thin line, from GARZOLI and GARRAFFO, 1989) These data are the result of the 10-day running mean of the original hourly series to eliminate the high frequency oscillations to the effect of the comparison. As it can be seen, even though the range of velocities is of the same order of magnitude, a large variability is observed in both observed periods.

dynamic height at IES Sta. 2 is 1.0 dyn m). The northward velocities observed between IES Stas 1 and 2 at the end of 1989 (Fig. 3) are due to a situation similar to the one just described or to the two cyclonic circulations shown in Fig. 5.

Between Stas 3 and 2, the flow changes from positive to negative due to the motions described in the previous paragraphs (Figs 5–8). On average, the total flow is almost zero (-2.8 cm s^{-1}, Table 2) The value of the standard deviation for the series along 37.7° (1–3) is high (21.1 cm s^{-1}), indicating the large variability.

To compare with the series of geostrophic velocities obtained at these locations during 1984–1986, the geostrophic velocity between IES Stas 1 and 3, are obtained and overlapped to the series obtained during 1984–1985 (Fig. 11). The comparison shows that the pattern does not repeat from 1 year to the next even though the range of velocities is of the same order of magnitude and a large variability is observed in both observations. Interestingly, at the beginning of the series, there is a similar pattern with a 1-month lag. After that, the flow is toward the south for most of the time until October of the second year when a serious discrepancy is observed. This discrepancy occurred during the situation described in Fig. 5 in which two cyclonic circulations result in northward flow.

Transport

Transports are calculated following the procedure described in the data reduction section and the results are given in Table 3. The first line of Table 3 corresponds to the

Table 3 Transport in Sv (m^3 s^{-1}) *between station pairs calculated.* (1) *from the approximation given in equation* (3), *and* (2) *adjusted to the transport obtained from* CTD *data*

	Transport (Sv)			
IES Sta	Min	Max	Mean	S D
Approx (2–1)	−22 8	16.2	−4 5	8 3
Adjusted (2–1)	−25 8	13 1	−7 5	8 3
Approx (3–2)	−24 2	20.8	−1.0	9 1
Adjusted (3–2)	−24 2	20.8	−1 0	9 1
Approx (4–5)	−20 1	28 0	1 1	8 5
Adjusted (4–5)	−21 8	26 3	−0 6	8 5
Approx (5–6)	−13.8	24 4	6 3	7.7
Adjusted (5–6)	−13 6	24 6	6 5	7 7
Approx (6–7)	−19 6	22 7	4 2	6.9
Adjusted (6–7)	−21 3	20 9	2 4	6 9
Approx (7–8)	−26 9	11 6	−7 6	6 8
Adjusted (7–8)	−26 8	11 8	−7.5	6 8
Approx. (10–9)	−24 2	25 6	−3 2	10 8
Adjusted (10–9)	−26 3	23 5	−5 3	10 8
Approx Σ (1 to 3)	−23.9	21.7	−5 9	10 5
Adjusted Σ (1 to 3)	−26.9	18 7	−8 9	10.5
Approx Σ (8 to 4)	−20 6	25.1	3 9	7 3
Adjusted Σ (8 to 4)	−23 6	22 0	0 9	7 3

transport obtained by using the approximation given in equation (3); the second line is the transport adjusted, when necessary, at the beginning and middle of the series to the values obtained from the CTD data. For IES Stas 3 and 2, there is no evident adjustment to apply to the transport series and therefore it is not adjusted. At some locations (like Stas 5 and 6 or 7 and 8) there is no difference between the approximated and adjusted transport (differences in the mean are 0.23 and 0.18 Sv, respectively). At the other locations, where there is a larger variability in the direction of the flow, differences between the mean adjusted and approximated transport vary from 1.7 Sv for IES Stas 4 and 5 to 3 Sv at IES Stas 2 and 1. The following discussion will be based on adjusted transports.

Across 35.2°S, this is to say across the northern leg of deployments (Table 3), the net transport is almost zero: Σ (8 to 4) = 0.9 Sv. Further south between 37.5 and 38°S (IES Stas 1–3) the net flow is 8.9 Sv towards the south (Table 3, Σ (1 to 3) = −8.9 Sv).

For those situations in which the circulation pattern allows distinction between the main flows and eddy-generated circulation, it is possible to obtain an estimate of the transport of the Brazil and Malvinas Currents, as well as the return flow across the different legs. The analysis of Fig. 3, in terms of transports (right side scale), allows us to obtain the following estimates:

(1) The largest southward flow associated with the Brazil Current is observed during 17–22 July between IES Stas 8 and 7 across 35.2°S; the value is −23 Sv. (2) The northward flow associated with the return of the Brazil Current across 35.2°S is maximum on 1 April 1989 between IES Stas 4 and 5, with a value of 23 Sv. (3) Further south, between IES Stas 9 and 10, the southward flow associated with the Brazil Current reaches values of −20 Sv. (4) Between 37.5 and 38°S (southern leg), at the beginning of November 1988, the Brazil Current transport reaches a value of −20 Sv between IES Stas 1 and 2. (5) Northward flow, clearly associated with the Malvinas Current, is observed for the period 23 July to 12 August and reaches a value of 5 Sv between Stas 1 and 2. The Malvinas return flow for that period of time is −10 Sv between Stas 2 and 3. (6) Southward flow, associated with the Malvinas return, is observed at the two southern legs between May and September. The maximum values are obtained from 4 May to 18 June. They reach a value of 24 Sv from 9 to 14 May.

These results indicate that at 35.2°S the transport associated with the Brazil Current (−24 Sv) is of the same order of magnitude (24 Sv) as its return. The Brazil Current is stronger at 35.2°S (−25 Sv) than at 37.7°S (−20 Sv). The northward Malvinas Current transport at the Confluence is, according to these results, considerably weaker than the Brazil Current (5 Sv). These values might be underestimated for a number of reasons. The most obvious is that most of the transport occurs west of Sta. 1, on the slope of the continental shelf. The present array was not designed to measure the Malvinas transport. In addition, given the characteristics of barotropicity of the Malvinas Current, the IES might detect only a small portion (the baroclinic portion) of the transport. The estimated transport for the Malvinas return reaches values of −24 Sv. This result supports the assumption that the array is not capturing the total Malvinas transport.

Results from the previous discussion are compared with those previously obtained in the region in Table 4. It should be noted that differences in the values are due to differences in the reference levels.

A more qualitative picture of the observed transports (Fig. 12) shows the monthly averages of transports across the station pairs. This picture is more qualitative because, as it was shown before, there is a large mesoscale variability in the area and straight

Table 4 Comparison between the estimated transports and those previously obtained in the area

	Transport (Sv)	Reference (m)	Source
Brazil Current			
33°S	−17 5	1000	Stramma (1989)
35 2°S	−23	1000	This paper
36 5°S	−23	1000	This paper
37°S	−76	3000	McCartney and Zemba (1988)
37 7 to 38°S	−20	1000	This paper
	−22	1400	Gordon and Greengrove (1986)
	−18	800	Garzoli and Garraffo (1989)
	−70	3000	Peterson (1990)
38°S	−28	thermocline	Peterson (1992)
Brazil Return			
35 2°S	24	1000	This paper
Malvinas Current			
37 7°S	>5	1000	This paper
42°S	75	4600	Peterson (1992)
Malvinas Return			
37 7°S	−24	1000	This paper
	−4	800	Garzoli and Garraffo (1989)

monthly means, in some cases, average out the previously discussed particular circulation patterns.

The monthly mean values of transports across 35.2°S (Fig. 12, upper panel) show, for the months of November and December 1988 and January 1989, a southward flow associated with the Brazil Current at the two western locations and return at eastern locations. This pattern does not repeat itself during the course of the observed period. In all 3 months the flow between Stas 9 and 10 is southward. The pattern more reproduced in this section is the one observed during February, May, June, July, August and September 1989: southward flow between the two stations at the section's edge and northward in between. The flow between Stas 9 and 10 is towards the south as in the previous case. A third pattern is observed during April, October and November 1989 and January 1990, in which the southward flow is restricted to the western station pairs; towards the east the flow is northward. In this case, northward flow is observed between Stas 9 and 10 in all cases but January 1990.

Single patterns are observed during March and December 1989. In the first case, there is a meandering circulation with southward flow at the westernmost location and in the second one, the meandering is repeated with northward flow at the westernmost stations. This last case corresponds to the anomalous situation described in Fig. 5. Finally, during February 1990, the pattern is similar but opposite to the second one described: northward flow at the edges and southward in between.

Across 37.5°–38°S (Fig. 12, lower panel; IES Stas 1–3), the dominant pattern is southward flow between the two station pairs. This is the case for December 1988, January 1989, April–June, and September 1989 and January–February 1990. The second typical situation at these latitudes is observed during November 1988, January–March, June and October 1989. In this case, southward flow is observed in the west and northward flow in

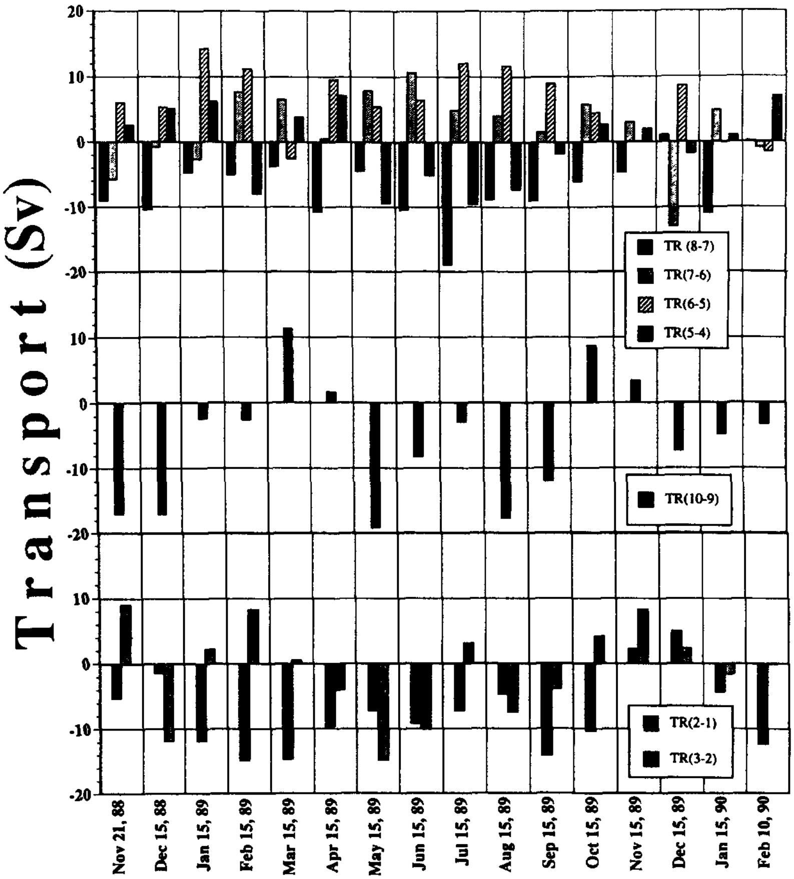

Fig. 12 Monthly average of the transports across the three different sections: (a) 35.2°S (IES station pairs 8–7, 7–6, 6–5 and 5–4); (b) 36 5°S (IES station pairs 9–10) and (c) 37.7°S (IES station pairs 2–1 and 3–2)

the east. November and December 1989 are, again, atypical. The flow across the section is northward with a mean total flow than ranging between 10 and 12 Sv.

CONCLUSIONS

The data collected with the array of IESs deployed at the Confluence allow us to obtain a picture of the variability and intensity of the flows in the area. The large variability previously observed at the surface was also present in the dynamic height field of the surface relative to 1000 m. This large variability was due to the changes in the latitude of separation, i.e. to a northward penetration of the Malvinas Current, which resulted in a northward retreat and, therefore, a lower latitude of separation of the Brazil Current from the coasts, to the meandering of the Confluence front towards the east and to eddy generation.

The eddy type circulation observed was both cyclonic and anticyclonic. These cold and warm eddies could be located between the southward edge of the Brazil Current and the northward edge of the Malvinas Current, or superimposed to any of the two main flows. The diameter of the eddies ranged between 100 and 150 km, that is to say, of the order of two to three times the Rossby Radius of deformation, which for this area is 57 km (GARZOLI and BIANCHI, 1987).

Cold cyclonic eddies have been observed previously at the convergence of the flows (GORDON and GREENGROVE, 1986; LEGECKIS and GORDON, 1982; OLSON *et al.*, 1988), but in most of the cases observed as a pinch of the second meander one or two degrees to the east. In the present work, cold eddies with values of dynamic height slightly higher than the ones currently associated with the Malvinas Current are observed close to the continental shelf. The presence of a cold cyclonic eddy at this location might be due, as suggested by GORDON (1989), to the result of the Malvinas Current flowing on the continental shelf, dragging eastward low salinity shelf water and shedding an eddy. This eddy therefore will have a dynamic height similar to the one related to the Malvinas Current, but slightly higher due to the superficial layer of low salinity water from the shelf. On the other hand, the shelf water is very warm (GORDON, 1989) and will mask the presence of this eddy at the surface. That is to say, in a satellite image it will be difficult to distinguish the eddy from the Brazil Current.

Comparisons between observations obtained during the same months at different years, and with those obtained during a previous deployment in the southern leg, indicate that the patterns do not repeat. At the end of 1989, a significant northward flow is observed at this location, while during at the same time of the year in 1986 the flow was consistently southward for the same location. Information provided by the National Institute of Fisheries (INAPE; Montevideo, Uruguay) leads to the conclusion that this situation is anomalous. During December 1989, the hake reached a location further north than usual and arrived to the area 2 months in advance (M. ORIBE, Director INAPE, personal communication).

Nevertheless, the timing for the northward penetration of the Malvinas Current is the same in both observed periods.

The geostrophic velocity field depicts the complex circulation of the area. Highest values are observed in the two southern lines of deployments (a maximum of 102 cm s^{-1} at 36.5°S and −61 to −62 cm s^{-1} at 36.6°S) and are associated with the shear between the northward flowing Malvinas Current and the southward flow related to its return. For most of the observed period, the Malvinas Current flows north close to the continental shelf, south and west of IES Sta. 1 (Fig. 1). The northward penetration of the Malvinas Current is observed during mid-July and August 1989.

Estimations of geostrophic transports add new information on the intensity of the currents. Previous results indicate that the Brazil Current transport increases as the current flows south. The present study tends to support this statement (−23 Sv at 35.2 and 36.5°S) but also indicates a decrease in the transport at the Confluence (−20 Sv at 38°S). The present array also allowed estimation of the transport of the Brazil Current return at 35.2°S which is of the same value as the southward flow: 23 Sv. Concerning the Malvinas Current, the estimates indicate a northward transport much higher than what was previously obtained. The estimate (larger than 5 and in the order of 24 Sv) is based on the values obtained for the Malvinas return flow: −24 Sv at 37.7°S. The lower value obtained for the Malvinas northward transport (5 Sv) is due to the fact that the array captures, at most, half of the northward flowing current and that, in addition, the IES provides only the baroclinic transport. The Malvinas Current is known to be strongly barotropic.

These are the results from the first analysis of the data. In a companion paper (BIANCHI and GARZOLI, 1992), the data are analyzed to study the motions and variability of the Confluence front.

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