GEOACTA, 22, 74-90, 1997

VARIABILITY AND MOTION OF THE BRAZIL-MALVINAS FRONT

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ABSTRACT

The temporal evolution of the thermal field associated with frontal motions in the South Western Atlantic is studied. The analysis is based on data collected with an array of inverted echo sounders (IES) deployed during the Confluence Program (1988-1990) at the Brazil/Malvinas Confluence. The travel time series obtained with the IES are scaled to mean temperatures of the upper 500 m (T_{500}) of the ocean and series of T_{500} horizontal distributions are constructed. A description of the evolution of the thermal field, emphasizing the frontal motions and some meso-scale features, is presented. Three well-defined northward penetrations of the Malvinas current with fairly variable periods of permanence (15-60 days) and mean frontal motion velocities of 0.2 m/s are observed. Cross-correlation of the T_{500} time series analysis leads to a plausible explanation of some features of the observed variability. Comparison with previous results in the area indicate a marked interannual variability and sources of variability are discussed.

RESUMEN

Se estudia la evolución temporal del campo de isotermas asociados con movimientos frontales en el océano Atlántico Sudoccidental. El análisis está basado en datos obtenidos de ecosondas invertidos (IES) fondeados durante la ejecución del Programa Confluencia (1988-1990) en la confluencia de las corrientes de Malvinas y Brasil. Las series de tiempo obtenidas con los IES fueron estandarizados con las temperaturas medias de los primeros 500 m (T_{500}) del océano y de esta forma se obtuvo la distribución horizontal de T_{500}. Se presenta una descripción de la evolución del campo térmico en relación con los movimientos frontales y las características de mesoescala de esa zona. Se observaron tres penetraciones bien definidas de la corriente de Malvinas con períodos variables de permanencia (15 -60 días) y velocidades del frente de 0.2 m/s. Del análisis de la correlación cruzada de la serie de T_{500} se obtiene una posible explicación de la variabilidad observada. La comparación con resultados previos indican una variabilidad interanual. Se discuten las fuentes de variabilidad.

1. INTRODUCTION

The most prominent feature of the upper circulation of the Western South Atlantic is the encounter of two boundary currents at the Brazil/Malvinas Confluence in the area of the Argentine Basin (Brennecke, 1921; Deacon, 1937). The Brazil Current flows poleward along the continental slope of South America. Between 35° and 3° S, this current converges with the Malvinas Current that flows northward along the continental margin, causing a sharp thermohaline front (Roden, 1986; Gordon, 1989). The Brazil Current is the western limb of the anticyclonic South Atlantic Subtropical Gyre while the Malvinas Current originates as a branch of the Antarctic Circumpolar Current (Deacon, 1933; Sverdrup *et al.*, 1942) downstream of the Drake Passage. After the encounter, both currents turn seaward, with the poleward momentum flux of the Brazil Current usually dominating (Gordon, 1981). Then, the Brazil Current executes an anticyclonic turn to the north, establishing a quasi-stationary meander of warm subtropical upper waters (Gordon and Greengrove, 1986), with its mean axis location along 53° W. Westward of this feature, a cyclonic trough of cold subantarctic water is enclosed by the Malvinas Current and its return.

High variability characterizes this region in a wide time and space range associated with strong baroclinicity due to the high horizontal density gradients. A large mesoscale variability related to the meandering nature of the Confluence area has been observed by satellite infrared imagery (Legeckis and Gordon, 1982; Olson *et al.*, 1988), surface drifting buoys (Piola *et al.*, 1987; Figueroa and Olson, 1989) and satellite altimetry (Cheney *et al.*,1983; Zlotnicki and Fu, 1990).

The subtropical upper water carried by the Brazil Current is characterized by temperatures higher than 10° C (up to 26° C in the surface layer during summer) and salinities higher than 35 (up to 36), while the subantarctic water carried by the Malvinas Current has temperatures lower than 10° C and salinities lower than 34.3 (Reid *et al.*, 1977; Bianchi *et al.*, 1993).

Dynamic height time series and a simple model assuming a mean profile of the 8 to 10° C isotherms across the front, were used to study frontal motions in the Confluence area. These time series are derived from a pilot experiment with inverted echo sounders (IES) moored during 16 months from 1984 to 1986 (Garzoli and Bianchi, 1987; Garzoli and Garraffo, 1989). Infrared satellite sensors were used to monitor sea surface temperature and to study temporal variations of the separation of Brazil and Malvinas Currents from 1984 to 1987 (Olson *et al.*, 1988). Both types of measurements provided information on the time-space variability of the front and demonstrated the importance of a regional survey based on long-term continuous observations. On these basis, an international (Argentine, French and U.S.A.) effort was initiated in 1988 to perform a high-resolution study of the frontal region: the Confluence Program (Confluence

Principal Investigators, 1990). As part of the Confluence Program, an array of 10 IES was deployed in November 1988 from R.V. Puerto Deseado and recovered in February 1990 from R.V. Le Suroit.

The IES data were analysed in terms of dynamic heights and geostrophic velocities and an estimate of the geostrophic transports associated to the main flows was obtained by Garzoli (1993). One of the main results of the study is that the large surface temperature variability (Olson et al, 1988) is also present in the dynamic height field of the surface relative to 1000 m. Most of this variability is due to the eddies generated between the two main flows and to the change in latitude where separation of the Brazil Current occurs. This in turn, is associated with a large frontal variability.

The objective of this paper is to analyse IES data to further study and quantify the frontal motions. In section 2, the data and methods used are presented. In section 3, a description of some features of the variability of the thermal field, due to the front location, is given. In section 4, association of pulses of Malvinas and Brazil Currents is studied using cross-correlation analysis. Finally, local dynamics of the area and time-space variability are discussed on the basis of the new results.

2. DATA AND METHODS

The location of the IES Confluence deployments (Garzoli, 1993) is shown in Fig. 1. Coordinates, depth of the moorings, and dates of deployment and recovery are given in Table 1. Hydrographic data (CTD and XBT) were obtained during the three Confluence cruises (Confluence Principal Investigators, 1990). The hydrographic information obtained during the first two cruises (Charo *et al.*, 1991), was used to scale the observed travel time (TT) to various oceanographic parameters.

2.1 Calibration to T_{500}

The travel time (TT) of an acoustic signal in sea water is a function of sound velocity, c:

$$TT= -2 \int dz/c(T,S,P)$$

TT is a function of the temperature (T), salinity (S) and pressure (P), a quantity directly related to the vertical structure of the temperature in the water column. In the Confluence area, where large changes in the depth of the thermocline are associated with frontal displacements, the variability in the TT record mainly represents the thermal variability of the upper layer. Therefore, the temperature averaged over the upper 500 m of the ocean (T_{500}), is directly related to the TT.

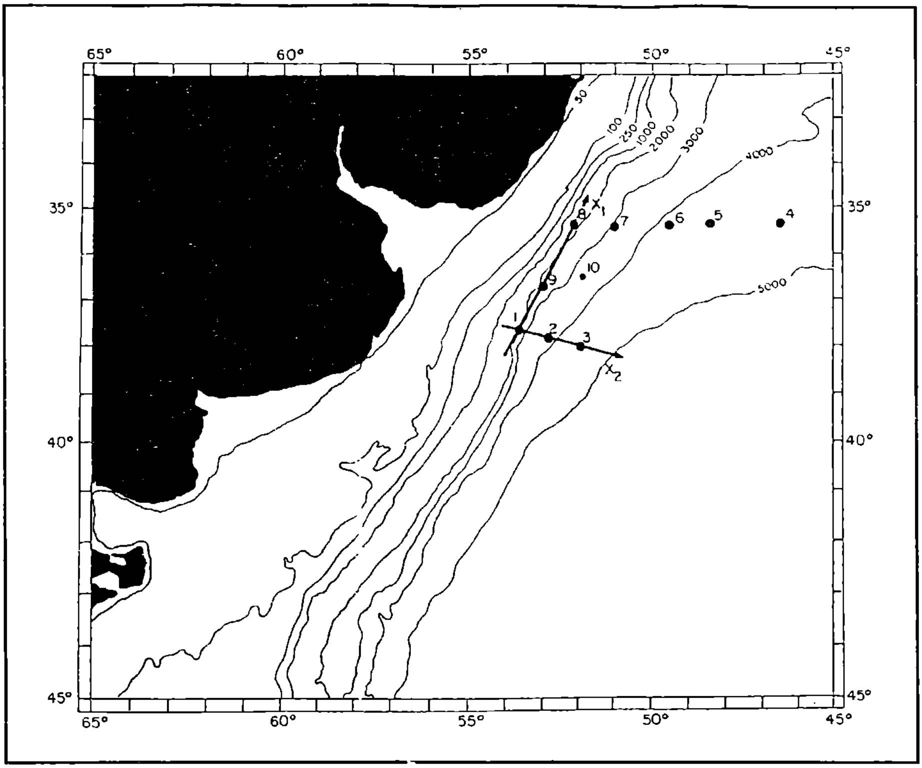

Fig. 1. The study area. The sites of IES moorings are indicated by dots. The solid lines, which were used to measure the frontal motions, indicate the axes along and normal the continental margin.

The CTD data collected during the first two cruises were used to calculate both parameters, TT and T_{500}. A linear regression fit of T_{500} as a function of travel time yields to the relation:

$$T_{500}\ (^{\circ}C) = 0.622\ TT\ (ms)$$

with a coefficient of determination $R^2 = 0.999$ and a standard error of the estimate of 0.118° C. This relation is used to calculate time series of T_{500}. The absolute value of T_{500} is then determined by adjusting the records to the vertically averaged values of temperature of the upper 500 m obtained from the CTD stations over the IES moorings in November 1988 and September 1989 cruises. In some cases (IES 8 and 10), additional data from XBT casts of February 1990 are used.

Differences between the values of T_{500} obtained from the CTD and IES data vary

TABLE I

IES Site #	Latitude	Longitude	Depth (m)	Deployment Date	Recovery Date
1	37°37.64'S	53°34.11'W	2852	11/14/88	02/23/90
2	37°48.10'S	52°45.20'W	3804	11/04/88	02/23/90
3	37°57.42'S	51°53.47'W	4346	11/05/88	02/24/90
6	35°22.90'S	49°30.40'W	4247	11/10/88	02/18/90
7	35°21.89'S	51°00.40'W	3018	11/10/88	02/17/90
8	35°27.39'S	52°16.94'W	1327	11/12/88	02/17/90
9	36°39.54'S	53°00.39'W	2231	11/13/88	02/21/90
10	36°29.56'S	51°52.35'W	3307	11/12/88	02/21/90

between 0.01° C and 1.2° C, with a mean value of 0.6° C and a standard error of 0.4° C. Examples of the resulting T_{500} series are given in Fig.2 (shown as the result of a 10-day running mean averages). The temperature differences between subantarctic and subtropical waters in the upper layer are of 11 to 14° C. Therefore, thermal variability in the area is one order of magnitude higher than the temperature estimate error. T_{500} changes of more than 10° C are observed for periods of 10-15 days at different moorings. Temperature changes of this magnitude, that occur in relatively short time, can only be explained by frontal motions and by eddies passing over the IES mooring sites. At IES stations 1, 2, 3 and 9 the wide range of thermal variability, more than 15° C in periods of 2 to 3 months, is essentially due to frontal motions. Local seasonal variability observed in the T_{500} series from summer to winter averages 2° C, never exceeding 4° C. This range is confirmed by historical CTD observations (Piola and García, 1993).

2.2 Horizontal Temperature distributions

A generalization of minimum-curvature giddying algorithms (Smith and Wessel,1990) was used to obtain instantaneous pictures of the integrated temperature distribution based on IES data. The minimum-curvature surface approximates the shape by a thin plate flexed to pass through the data points (for an analogy in elastic plate flexure). A grid with continuous curvature splines in tension and contouring programs is used to build a series of horizontal distributions of T_{500} using daily averages of the T_{500} series. Records obtained at IES stations 4 and 5 are excluded of the analysis because their locations induce extrapolation errors, specially in the area southward of these sites, where no data are available (see Fig.1). Computer contours accurately represent "freehand drawing" thermal distributions for different oceanographic conditions.

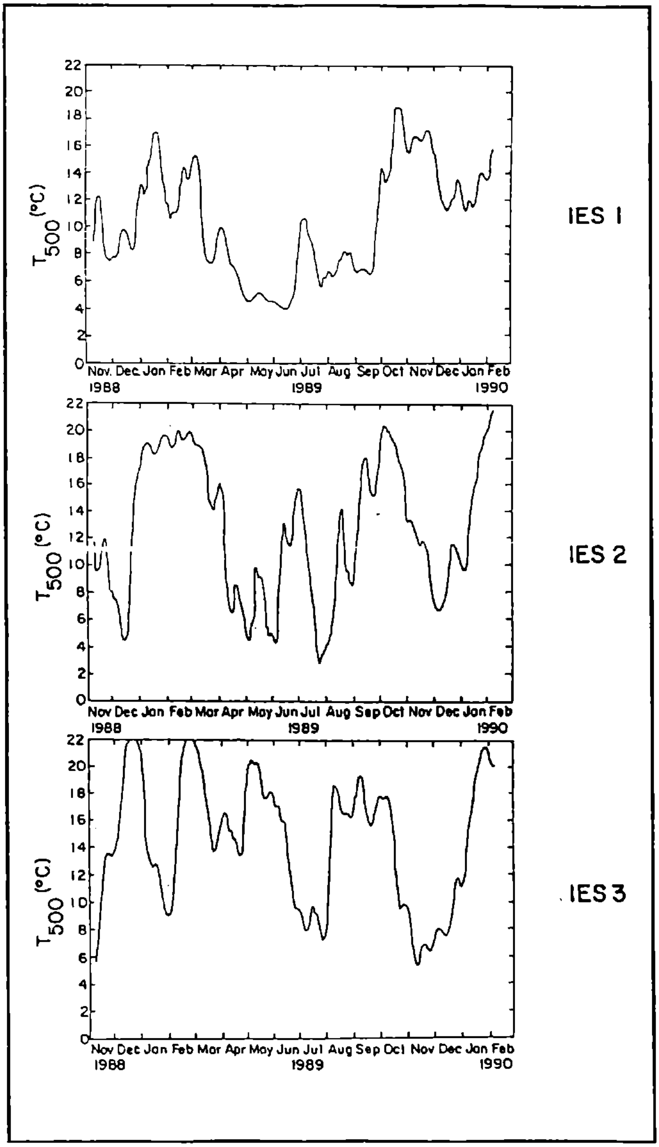

Fig. 2. A 10-day running mean time series of T_{500} corresponding to the first leg of IES (1,2 and 3) of the array.

2.3 Location of the front

Bianchi *et al.* (1993) estimated horizontal temperature gradients in the upper layer

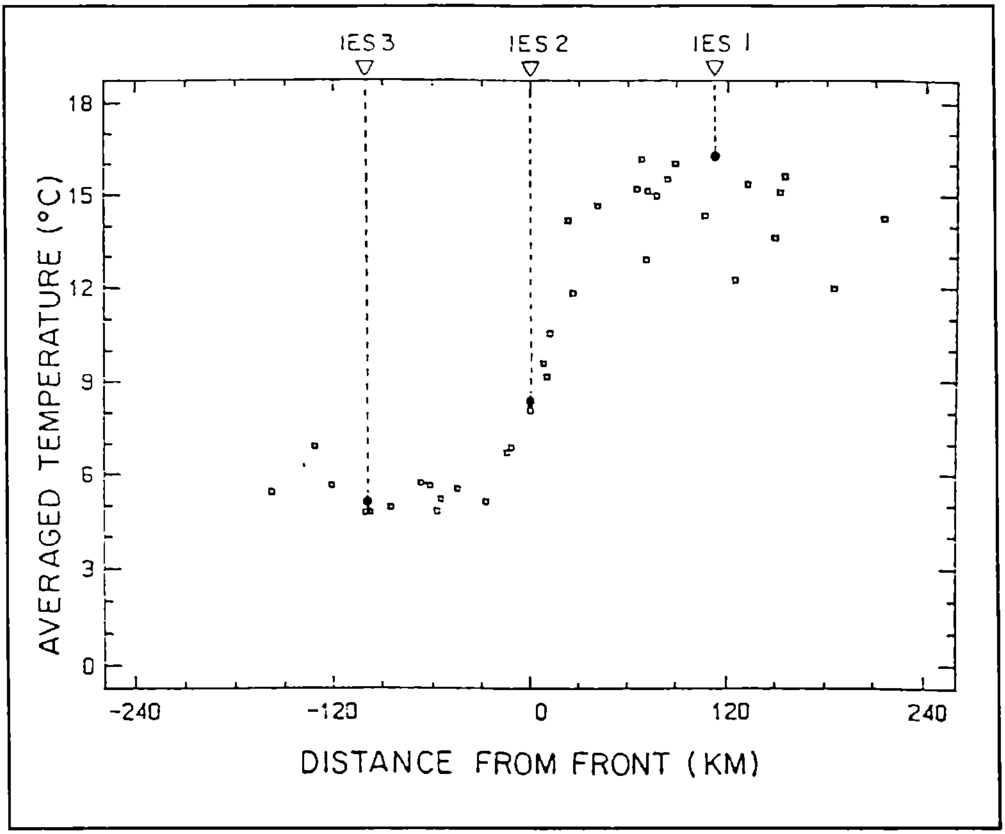

Fig. 3. This figure is extracted of Bianchi *et al.*(1993). T_{500} derived from IES 1, 2 and 3 have been plotted for a situation (December 22 of 1988) in which the temperature at the IES 2 site is the T_{500} representative of the front location (8.5° C). The figure shows the distribution of the vertically averaged temperatures (from hydrographic data) for the upper 500 m vs. distance to the front. The figure was constructed aligning individual profiles according to distance of the front. Large dots indicate T_{500} obtained from the IES sites for a situation in which the front was coincident with IES # 2.

of the Brazil-Malvinas Confluence based on the following scheme: the location of the front was defined where the 10° C isotherm is at 200 m depth (see Garzoli and Bianchi, 1987). Using a data set of the region (hydrographic cruises PD-02-84, OA-04-85, PD-02-88, and Confluence 1988 and 1989), different synoptic realizations of the front were obtained in front coordinates, i.e., shifted to align the front location of each section. The mean temperatures of the upper 500 m of the water column are calculated and plotted as function of the distance to the front (Fig. 3, adapted from Bianchi et al, 1993). IES temperatures agree well with CTD observations available in the area. Similar situations are obtained for other instants of the record (see Fig. 2) in which the front is located at

IES 2. Low values of T_{500} (generally about 4 to 5° C) correspond to subantarctic water and high values of T_{500} (generally higher than 15 °C) correspond to subtropical waters. In a band of 100 km (-50 to 50 km) T_{500} abruptly increases across the frontal region. Variability due to the mesoscale processes and the meandering nature of the front produce some T_{500} values lower than 12° C, at more than 100 km east. The location of the front is defined where the 8.5° C contour of T_{500} is observed. This criterion leads to similar results the 10° C isotherm at 200 m depth obtained in other analyses (Bianchi *et al.*, 1993).

In the pilot experiment (1984-1986) only front zonal displacement were resolved due to the geometry of the reduced array of IES deployed. The present array allows the detection of both, zonal as well as meridional front displacements. Then, this method permits to obtain the location of the front, by the analysis of horizontal distributions of vertically averaged temperatures in a larger array distributed zonally and also meridionally. This method avoids ambiguities and is more accurate than ones used in previous work (Garzoli and Bianchi, 1987; Garzoli and Garraffo, 1989).

3. VARIABILITY OF THE THERMAL FIELD AND FRONTAL MOTIONS

Based on the thermal field evolution, the frontal motions were investigated. Some features of the thermal field will be presented, emphasizing the frontal location related to local dynamic variability. It will be indicated, when possible, displacements of cold or warm eddies in the area. A more quantitative description is then given based on two time series of the frontal motion.

Four "snapshots" of the time series have been selected to depict particular features of the thermal field (Fig. 4). These snapshots were selected after inspection of the 91 5-day block averaged maps in order to represent oceanographic situations typical of the region. The infrared images collected by a satellite of NOAA (Olson & Podestá, personal communication) were visually compared with the T_{500} maps. Although the imagery is showing the skin temperature of the sea, and in most cases, the agreement with T_{500} is very good.

The thermal front is clearly depicted by the close meridional isotherms in December 22, 1988 (Fig. 4a). Due to the giddying scale and the smoothing techniques applied to the data, real gradients are probably are higher than the ones shown in the figure. The estimated cross-front horizontal temperature gradient, leads to an order of magnitude of 1 x 10-4 °C/m. This value is of the same order of magnitude as the estimates presented by Bianchi *et al.* (1993) based on hydrographic data. In December 22 of 1988 the front location reached 36° S , a latitude lower than the mean one for that time of the year (Olson et al, 1988). This anomaly was obviously observed in the geostrophic velocity field (Garzoli, 1993). The local wind forcing appears to be responsible of this northward penetration of the front (Garzoli and Giulivi, 1994).

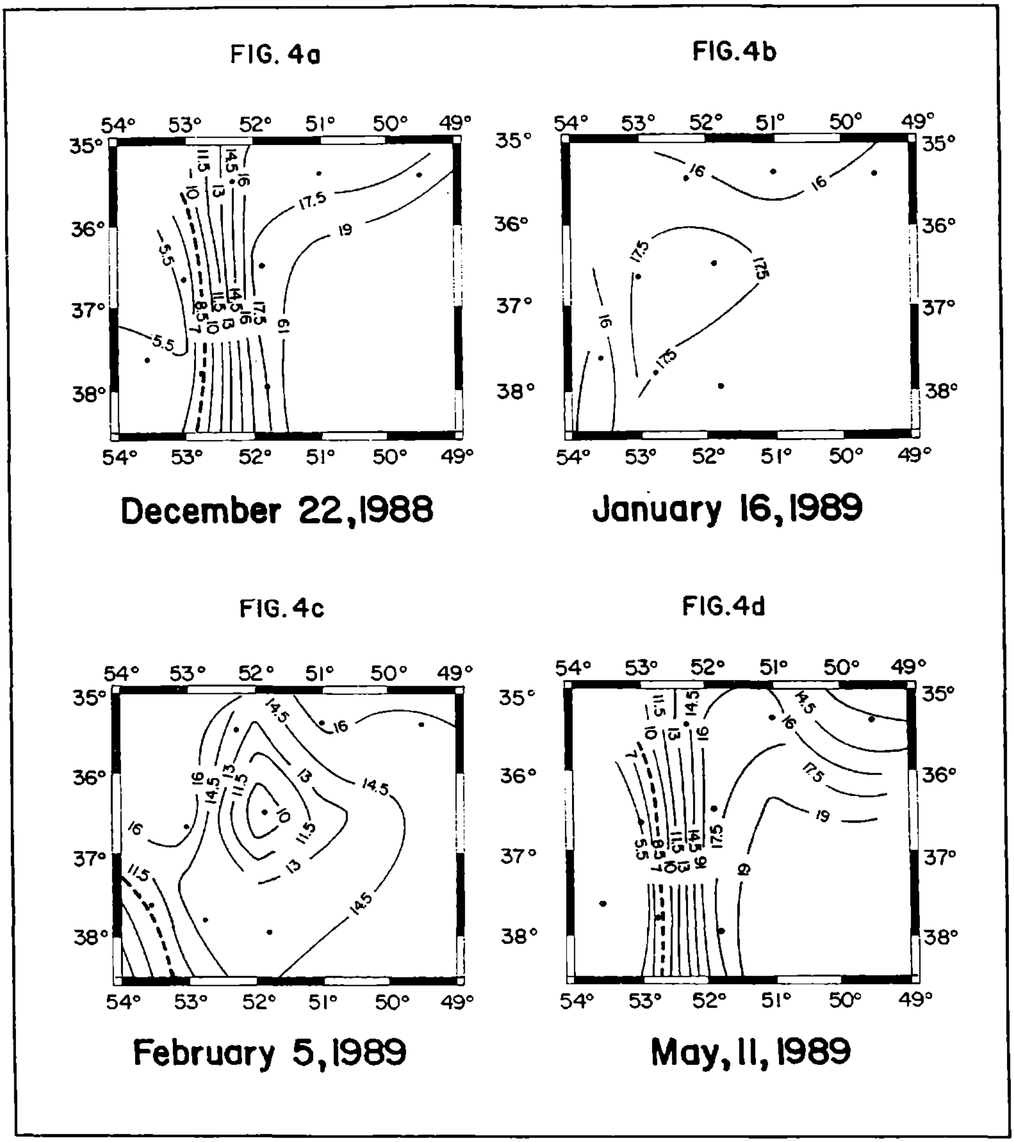

Fig. 4. Averaged temperatures of the upper 500 m contours for the study area. Maps are chronologically sorted. The 8.5° C contour(dashed) represents the location of the thermal front.

One month later, (January 16,1989, Fig. 4b) the front is no longer observed in the area. Most of the region is occupied by warm water preceding typical southern hemisphere summer conditions. The front has probably migrated southward, according to what it is expected to be the summer situation. This condition is confirmed by satellite imagery. A warm core of temperature higher than 17.5° C dominates the central part of the study region.

A situation showing a large-scale cold-core eddy of about 300 km of diameter centered at 52° W and 36° S is observed on April 6, 1989 (Fig. 4c). Malvinas water is found at 38° S and between 54-53° W (southwest corner of the map). Evidence of this cyclonic mesoscale feature is found in the geostrophic velocity field relative to 1000 dbar (Garzoli, 1993). Satellite imagery does not confirm the presence of the cold-core eddy. This is an example of a particular situation in which sea surface temperature does not represent the oceanographic conditions of the upper layer. Probably, due to large temperature differences between the sea and the atmosphere during the summer, air-sea heat fluxes increase and a thin, warm, stable surface layer develops, masking the cold eddy. An example of a similar situation is seen from hydrographic data in March 1986. At that time, a warm mixed layer over subantarctic waters was masking the presence of the front in the surface field for at least 80 km (Garzoli and Garraffo, 1989). Similar conditions have been recently observed at sea in the same region during a cruise performed at the end of March 1993 and 1994 (Piola, personal communication). In late April 1989, the observed cold eddy re-coalesced with the Malvinas waters. The eddy shedding and re-coalescing process are clearly depicted in a film made to represent the time evolution of the thermal field.

West of 53° W, maximum northward penetration of the Malvinas Current beyond 36°S is observed in mid May 1989 (Fig. 4d). The warmer waters of the area are centered in the southeast corner and maximum thermal gradients are present in a meridional band, between 52 and 53° W.

3.1 Frontal motion

According to the definition given in section 2.3, the front location is assumed to be at T_{500} = 8.5 °C. On the basis of this definition, a subset of 91 horizontal T_{500} distribution maps (one every 5 days) are used to quantify the position of the front. The location of IES 1 is used as the origin of the coordinates system. Distances to the front (to the 8.5° C isotherm) are measured over each map in two directions (see Fig. 1): along the continental slope, X_1 (in a line going from IES 1 to 8) and almost normal to the continental slope, X_2 (in a line from IES 1 to 3). Time series of the distances from the front to IES 1 are displayed in Fig. 5. Gaps in the series correspond to periods during which the front did not intersect one of the two axes. Peaks in Fig. 5 are associated to northward and eastward penetrations of the Malvinas Current.

Three northward penetrations of Malvinas Current are observed (Fig. 5a) for November-December 1988, May-June 1989 and August-September 1989. In less than ten days the front migrates about 200 km to the north. The mean front displacement velocity

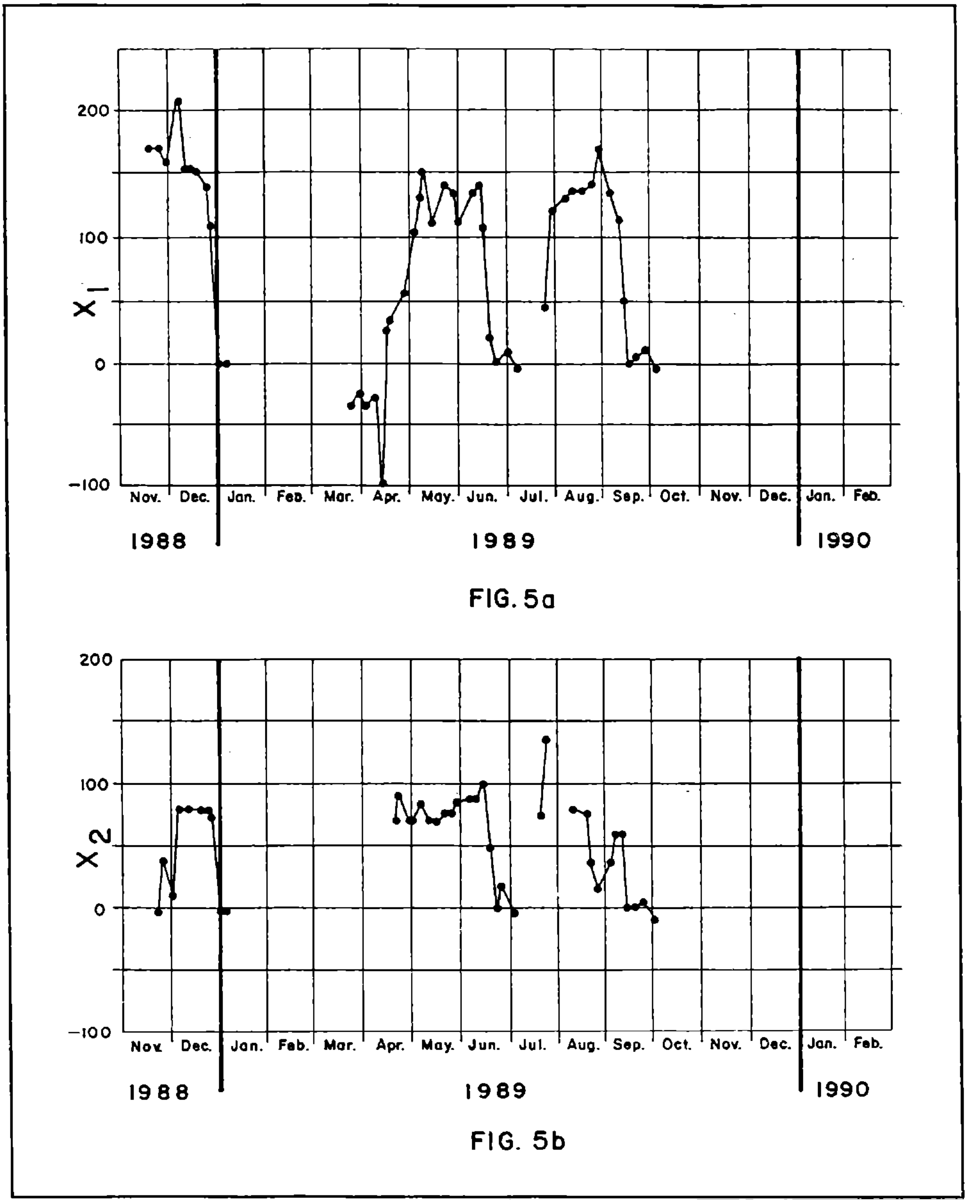

Fig. 5. Time series of the location of the front. a) along the slope, positive northward; b) normal to the slope, positive eastward.

is 0.2 m/s. The duration of the northward penetrations vary from 15 to 60 days.

The full extent of the along-slope penetrations of the Malvinas Current can not be estimated because subantarctic waters are repeatedly advected southward from the study area. The cold waters retreat as fast as they penetrate (5 to 10 days). During the summer of 1989 (January through March), in part of July 1989 and from mid-October to the end of the record (February 1990) subantarctic waters are displaced south of the domain of interest by pulses of warm subtropical waters (Brazil Current). Similar frontal behaviour is observed in Fig. 5b. It is reasonable to associate broadening areas covered by subantarctic waters to northward penetrations of Malvinas Current. Therefore, motions of the front in the eastward direction are related with northward penetrations of the Malvinas Current. According to density distributions and sea surface temperatures (Piola and García, 1993), Malvinas, as a boundary current, flows in a band of about 100 km.

4. SOURCES OF VARIABILITY

Sea surface temperature distributions suggest cyclical displacements of the Currents along the continental slope at semi annual and annual periods, although considerable interannual variability is present in the signal (Olson *et al.*, 1988). Similar frontal motion periods were derived from an array of 3 IES moorings in a zonal section at 38°S, at the same location of the southern leg of the data set presented here (Garzoli and Garraffo, 1989).

The late austral summer situations are very similar in 1989 and 1990. In the austral winter 1989, Malvinas water is observed during all the period except for 15-20 days of July 1989, because subtropical waters were present in the region. This feature, associated with a southward extension of Brazil Current during winter, suggests that seasonality is not the most important source of variability in the area. Unfortunately, the length of the record is too short to resolve annual fluctuations.

The inspection of the 91 T_{500} maps reveals that penetrations of relatively cold waters along the western boundary of the area, occur with penetration of warm waters in the eastern boundary. The enhancement of zonal temperature gradients suggests that instability processes are associated to the increased amplitude of the frontal variability. Thus, pulses in the Malvinas Current along the continental slope are associated to pulses of Brazil Current offshore. In order to further investigate this hypothesis, cross-correlation estimates were made between 5-day block averaged T_{500} time series of the western and eastern IES sites for the three sections (Fig.6).

For lags of 20-30 days, all the cross-correlations are negative and significatively different from 0, with the eastern series lagging behind the western series. Thus, when cold waters reach the western sites, warm water is present offshore 20 to 30 days later. This suggest that a Malvinas northward pulse enhances the baroclinicity of the

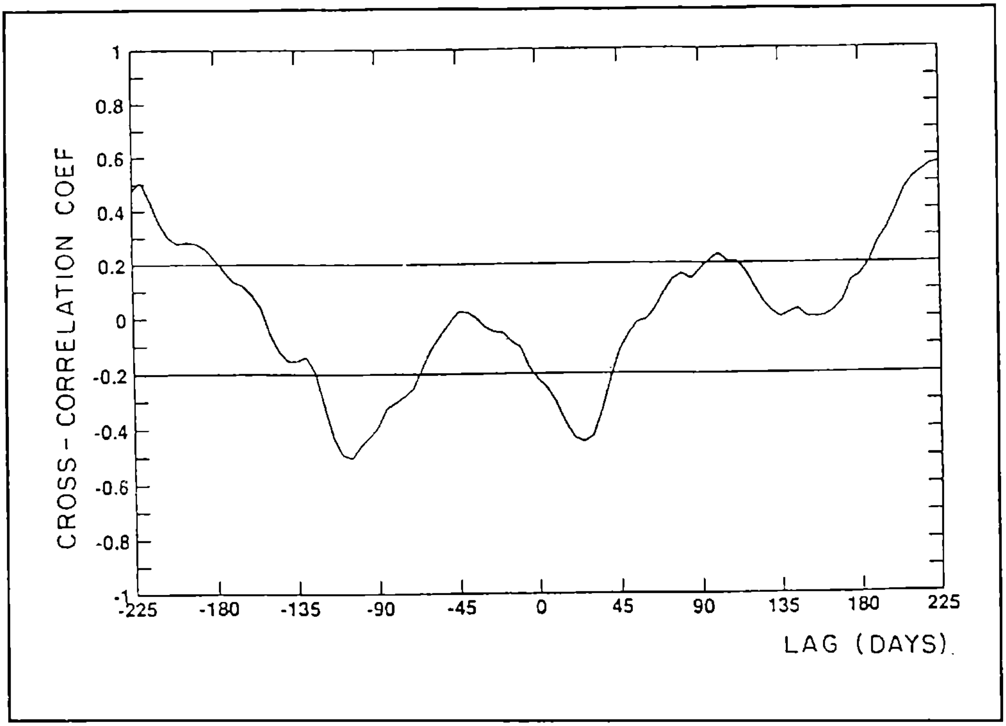

Fig. 6. Cross-correlation estimates between 5-day block averaged time series of the T_{500} corresponding to the IES 1 and 3. The record corresponding to IES 3 is lagging behind the corresponding to IES 1.

geostrophic jet. Significative correlation is also observed at periods centered at -110 days (Fig. 6) for the southern section. There are no significative correlation at this period for the other two sections. This time scale may be associated with the meridional motion of the front location and it is probably only observed in the southern border of the area because during most of the record, the front did not reach the central and northern IES sections.

Garzoli and Giulivi (1994) attempted to explain the observed frontal displacements in terms of the atmospheric forcing. They conclude that the main source of variability of the frontal location is the local wind forcing. In addition to the seasonal cycle in the latitude of separation of the Brazil current from the coast, a marked interannual variability was driven by wind forced pulses south of the Confluence. The "anomalous" northward penetration of the Malvinas Current during November 1988 and the southward extension of the Brazil Current during austral winter 1989 can be explained by these causes.

On the other hands, Gordon (personal communication) suggests that pulses of the

Brazil Current may be tied with eddies detached from the Agulhas Current that are then transported to the northwest. Once in the pathway of the South Atlantic subtropical gyre, the eddies would reinforce the Brazil Current.

Data from Geosat altimeter (Gordon and Haxby, 1990) reveals numerous transient anticyclonic Indian Ocean eddies penetrating into the South Atlantic subtropical gyre. Olson *et al.* (1988) suggested that variations in the Brazil-Malvinas Confluence might be driven by changes in the Malvinas Current forced by variability in the Antarctic Circumpolar Current (ACC). Besides, Campos (1988) suggests that the apparent intensification of Malvinas Current in the western part of the study area associated with southward penetrations of Brazil Current offshore should be related with overshooting of Rossby waves in the Confluence area.

The Brazil Current separation from the coast is determined where it meats the Malvinas Current. The latter could be affected by fluctuations of the ACC at the Drake Passage or by the forcing of winds in the Southern Ocean. Matano (1994) suggested that meridional migrations of the Subtropical Convergence, which are tightly associated with the North-South displacements of the Brazil-Malvinas Confluence, could control the thermohaline properties of the Atlantic Ocean. However, Garzoli and Giulivi (1994) did not observe a significant correlation between wind-forced pulses in the ACC and anomalous northward penetration of the Malvinas Current. Simultaneous monitoring of the variability in both regions (ACC and Brazil-Malvinas Confluence) is necessary to further understand this process.

5. SUMMARY AND CONCLUSIONS

It has been showed that the original method implemented to calibrate IES TT records in terms of T_{500} is an useful tool to monitor the evolution of the variability of the ocean upper layer in a frontal region. The main features of the mean upper ocean thermal field during the record period are evident in the different kind of representations used in this study.

In most cases, T_{500} maps are in good agreement with the satellite imagery showing sea surface temperature (excluding some mesoscale features that could not be resolved by images that represent the skin temperature of the ocean). Estimates of cross-front horizontal gradients derived from T_{500} maps are confirmed by hydrography data.

Northward penetrations of the Malvinas Current or southward extensions of the Brazil Current are also clearly observed. Mean front displacement velocities and the duration of currents penetrations are obtained from time series inspections. In other words, this study allows to have a first order approximation to space and time range scales of frontal motion. Cross-correlation analysis of time series showed that when Malvinas cold waters reach the IES western sites of the array, warm water appears 20/30 days after in the eastern sites. This fact induces an enhancement of horizontal temperature gradients and reinforce the baroclinicity of the frontal geostrophic jet.

This study has shown that the strong variability of the Brazil- Malvinas System is not dominated by the annual or semi-annual cycle. The larger component of the observed variability in the time-frame covered by the IES array is forced by local winds as was shown by Garzoli and Giulivi (1994) in a companion paper. Probably, the intense cross-frontal mixing processes in the area (Bianchi *et al.*, 1993) are important in the relaxation and dissipation of the front after it has been intensified by horizontal advection. This hypothesis is matter of study of ongoing research in the region (Piola & Bianchi, 1992).

Acknowledgements

The authors are indebted to the crews on board BOARA Puerto Deseado, BIP Oca Balda and R/V Le Suroit, for different stages of field work. To the authorities of Servicio de Hidrografía Naval (SIHN) and Instituto de Investigación y Desarrollo Pesquero(INIDEP) from Argentina, for their support during the preparation and logistics of the cruises. To the government of Uruguay who granted permission to work in territorial waters. To Alberto Piola for his careful reading and useful comments on the manuscript. D. Olson, G. Podestá and O. Brown kindly provided the processed images for the present study. M. Charo and A. P. Osiroff were responsible of hydrographic data processing. M. Macció was in charge of the IES from preparation for deployment to recovery. He was assisted during the cruises by M. Ferrario. The IES data processing and computer programming was performed by A. Martino. Silvia Damiani prepared the final figures. The field work was supported by NSF through grant OCE-87-11529, by SIHN and CNRS (French National Research Council). Data collection and analysis were partially supported by NSF grants OCE-87-11529 and OCE-91-02541. The satellite images were collected by the Servicio Meteorológico Nacional (SMN) of Argentina and processed at the University of Miami under NSF grant OCE-91-02112. A grant from the TINKER Foundation, a grant of the International Division of the NSF, INT-89-14536, and Consejo Nacional de Investigaciones Científicas y Técnicas, supported part of the cooperative work between the authors.

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