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Satellite observations of the Brazil and Falkland currents—1975 to 1976 and 1978*

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Abstract—Satellite infrared observations of the Brazil and Falkland currents were made from September 1975 to April 1976 and from January to July 1978. The warm water associated with the Brazil Current fluctuates southward and northward between 38 and 46°S with a time scale of about two months. Warm core eddies are formed during the northward phase at intervals of about one week. These eddies are elliptical with a mean major axis of 180 km and a minor axis of 120 km. The eddies drift southward at speeds of 4 to 35 km day^{-1}, and the higher speeds are associated with the more recently formed eddies. Hydrographic surveys during 1978 on the ARA *Islas Orcadas* revealed the subsurface structure of the warm core eddies and the Brazil Current. The surface thermal patterns detected by satellite were correlated with the subsurface thermal structure and the mixed layer depth.

INTRODUCTION

THE Brazil Current flows poleward along the continental margin of South America as part of the western boundary current of the South Atlantic subtropical gyre. The Falkland (Malvinas) Current flows northeastward along the coast of Argentina from its origin as a branch of the Antarctic Circumpolar Current. Recent satellite infrared (i.r.) images have revealed the sea surface temperature (SST) patterns associated with these currents. In this report we describe the satellite observations as they relate to the general circulation patterns in the western South Atlantic and provide some confirmation of the subsurface thermal structure coincident with the satellite observations.

The confluence of the Brazil and Falkland currents was described by BRENNECKE (1921) and DEACON (1937). Both DEACON (1937) and SVERDRUP, JOHNSON and FLEMING (1942) refer to the confluence as the subtropical convergence. BALECH (1949) showed that the location of the convergence varies with the major wind systems. BOLTOVSKOY (1970) used biological tracers to study the circulation of the western South Atlantic. The 0/1000 dynamic topography of the western South Atlantic presented by REID, NOWLIN and PATZERT (1977) indicates that the Brazil Current extends poleward, after confluence with the Falkland Current, and then returns to 40°S to follow an easterly course. LUTJEHARMS and BAKER (1980) presented a statistical analysis of the spatial variability of mesoscale turbulence in the Southern Ocean.

The advent of environmental satellites introduced a capability for making nearly instantaneous observations of the Earth. Infrared scanners were first introduced to allow

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meteorologists to make night-time observations of cloud patterns and storm systems. The improvements of the signal-to-noise ratio and of the spatial resolution of i.r. scanners have allowed oceanographers to recognize the sea surface temperature (SST) patterns associated with major currents and fronts: BERNSTEIN, BREAKER and WHRITNER (1977), LEGECKIS (1978), MAUL, DEWITT, YANAWAY and BAIG (1978), LEGECKIS (1979), and EMERY and MYSAK (1980) among others.

There appear to be few studies of the Brazil and Falkland currents using satellite measurements. For example, CHI (1976) and TSENG (1974) used the NIMBUS V data to describe the zonal shift of the western boundary of the Brazil Current. JOHNSON and NORRIS (1977) presented a high resolution i.r. view from SKYLAB of the Brazil Current boundary and found surface temperature gradients of 1°C each 67 m. The present study extends some of the previous satellite observations of the time-dependent fluctuations associated with the Brazil Current and compares the satellite data to hydrographic measurements.

DATA AND METHODS

In the present study, the Very High Resolution Radiometer (VHRR) on the National Oceanic and Atmospheric Administration (NOAA) operational polar orbiting satellite system is used to monitor the position of the SST boundaries associated with the Brazil and Falkland currents. The VHRR was able to resolve temperature changes of 0.5°C at a spacial resolution of 1 km. Measurements can be made over a given area of the Earth at intervals of 12 h. Further description of the VHRR instrument is given by SCHWALB (1972).

The VHRR i.r. data were collected during two periods. The first was from September 1975 to April 1976 (Table 1) and the second from January to July 1978 (Table 2). Some of the data were obtained in digital form and for these cases the i.r. images were corrected for geometric distortions according to an algorithm described by LEGECKIS and PRITCHARD (1976). The images were also computer enhanced so that the SST boundaries could be more easily recognized visually. A transparent overlay map was used to transfer the location of the SST boundaries to a map base and the uncertainty in the position measurements was about 10 km. Image data that were not available in digital form were transferred to a map base with a zoom transfer scope and the measurement uncertainty associated with this method varied between 10 and 25 km.

Four examples of i.r. images obtained in the western South Atlantic during the austral spring and summer are shown in Figs 1 to 4 for 17 October and 20 December 1975, 16 January 1976, and 10 March 1978, respectively. The darker shades of gray represent the warmer water. Because clouds are usually colder than the water, they appear nearly white in the i.r. images. Representative surface temperatures recorded at the satellite radiometer are also shown in Figs 1 to 4. The temperatures are not corrected for the effects of atmospheric absorption of the i.r. radiation and may be several degrees lower than *in situ* temperatures (LEGECKIS, LEGG and LIMEBURNER, 1980). Each value is an average in a 10-km square.

FALKLAND CURRENT

The satellite i.r. images reveal a relatively cold band of water, approximately 100 km wide, over the continental slope in the western South Atlantic mainly during the austral spring and summer. The western SST boundary of this cold water is nearly parallel to the

Table 1. A summary of the NOAA VHRR i.r. images obtained between September 1975 and April 1976

ORBIT	DATE	F	B	EDDY		M
NOAA-4				C	W	
3805	09/15/75		✓	✓	✓	✓
3999	10/10		✓			✓
4200	10/17	✓			✓	✓
4275	10/23	✓	✓		✓	
4375	10/31	✓	✓		✓	✓
4400	11/02	✓	✓		✓	✓
4576	11/16	✓	✓		✓	
4675	11/24	✓	✓		✓	
4700	11/26	✓	✓	✓		✓
4763	12/1		✓		✓	✓
4875	12/10	✓	✓		✓	
4951	12/16	✓	✓		✓	
5001	12/20	✓	✓		✓	✓
5339	01/16/76	✓	✓		✓	✓
5677	02/12	✓	✓		✓	
5702	02/14	✓	✓		✓	
10502 +	03/03	✓	✓	✓	✓	✓
5965	03/06	✓				
6090	03/16	✓	✓		✓	
6353	04/06	✓	✓		✓	✓
6466	04/15		✓		✓	✓
6616	04/27	✓	✓			

The observed ocean surface features are identified as follows: F, Falkland Current; B, Brazil Current; C, cold core eddy; W, warm core eddy; M, zonal meanders of the Brazil Current. All images were geometrically corrected to remove distortions introduced by satellite scanning geometry. Orbit 10502 is from the NOAA-3 satellite.

Table 2. A summary of the NOAA AVHRR i.r. images obtained between January and July 1978

ORBIT	DATE	F	B	EDDY		M
NOAA-5				C	W	
6639	1/17/78	✓	✓			✓
6726	1/24	✓	✓			
6763	1/27	✓	✓			
6800 *	1/30	✓	✓			✓
6825 *	2/1	✓	✓			
6949	2/11		✓			
7085 *	2/22	✓	✓			
7184	3/2		✓			
7258	3/8	✓	✓			
7283 *	3/10	✓	✓		✓	✓
7382	3/18	✓	✓		✓	
7419	3/21	✓	✓			
7518 *	3/29	✓	✓		✓	
7543	3/31		✓			
7741	4/16	✓	✓			
7877	4/27	✓	✓		✓	
8100	5/15		✓			
8137	5/18		✓			
8471	6/14		✓		✓	
9016	7/28		✓		✓	

The observed ocean surface features are identified as follows: F, Falkland Current; B, Brazil Current; C, cold core eddy; W, warm core eddy; M, zonal meanders of the Brazil current. Only images identified by an asterisk (*) were geometrically corrected.

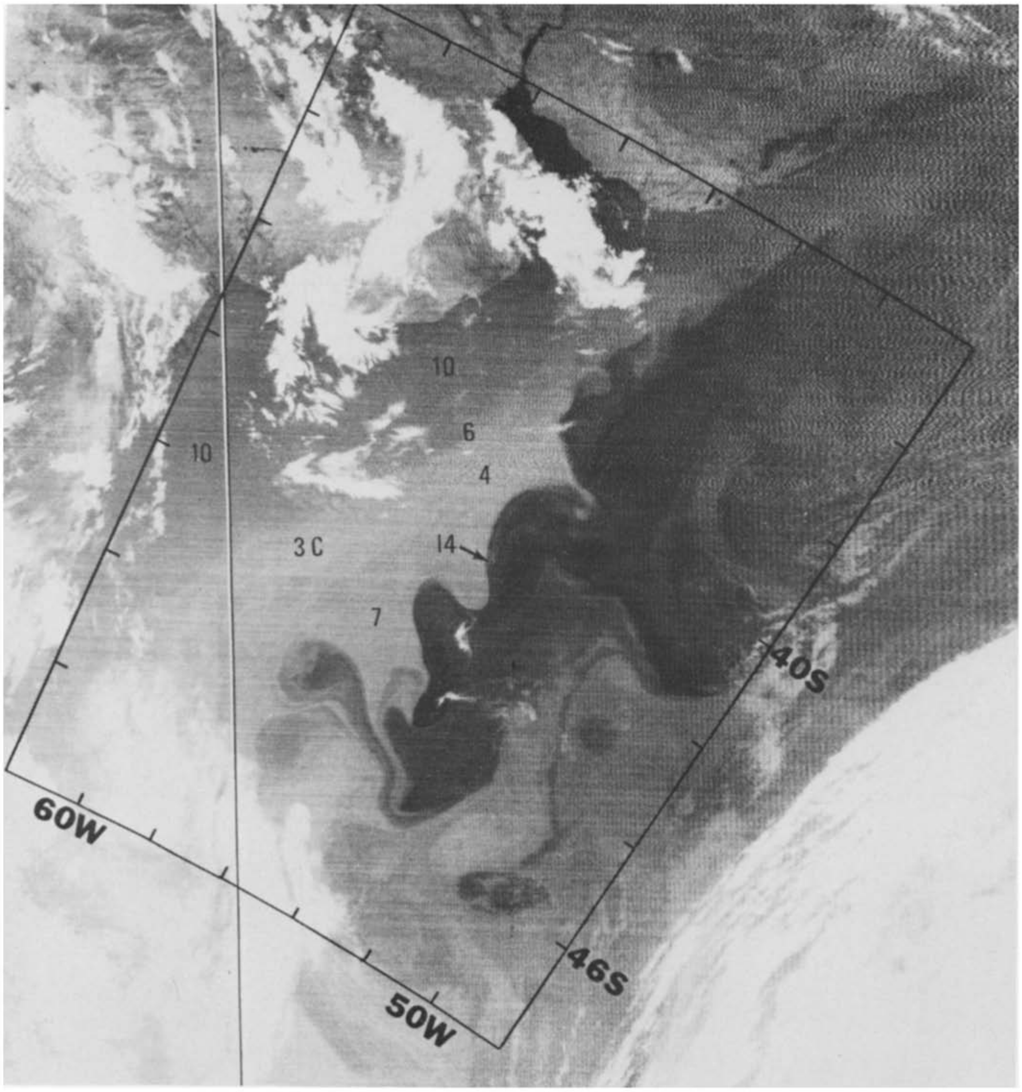

Fig. 1. The VHRR i.r. image was recorded on orbit 4200 by NOAA-4 on 17 October 1975. The darker shades of gray represent the warmer water. Wave-like meanders associated with the Brazil Current appear along the western SST boundary. Temperatures recorded at the satellite are shown. The temperature of the cold water associated with the Falkland Current increases northward from 3 to 4 C.

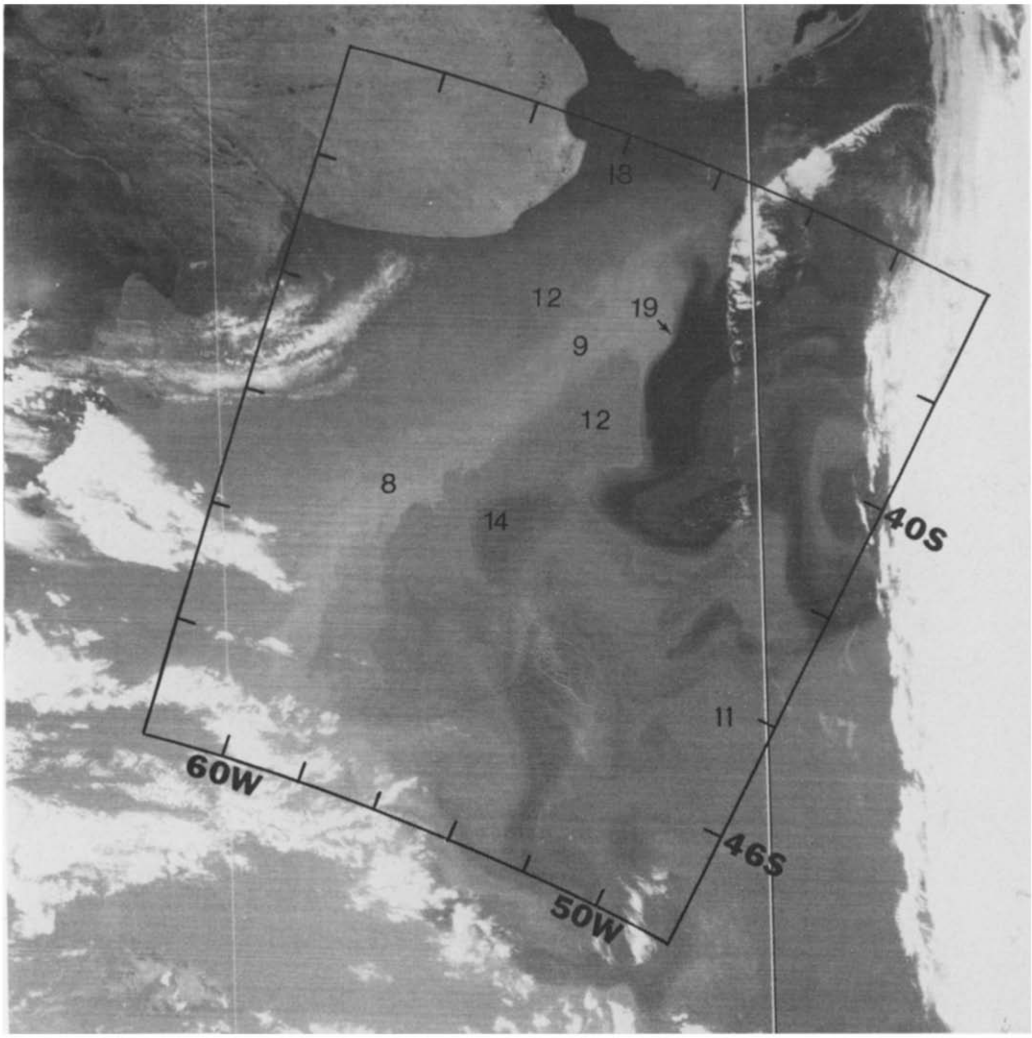

Fig. 2. The VHRR i.r. image was recorded on orbit 5001 by NOAA-4 on 20 December 1975. The darker shades of gray represent the warmer water. The warm water associated with the Brazil Current reaches 42 S before meandering eastward. At least three warm core eddies appear south of the Brazil Current (Fig. 15). Selected temperatures recorded at the satellite are shown. The temperature of the cold water associated with the Falkland Current increases northward from 8 to 9 C.

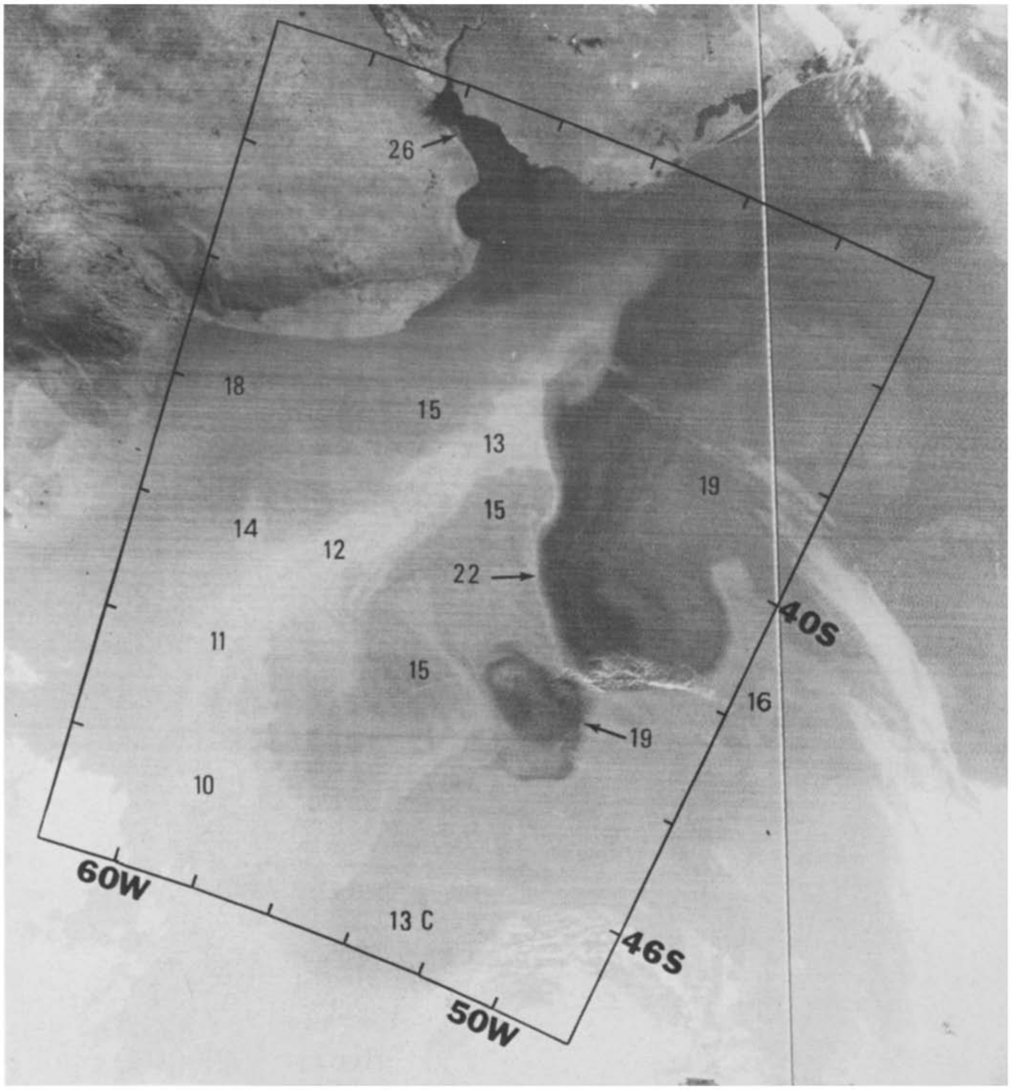

Fig. 3. The VHRR i.r. image was recorded on orbit 5339 by NOAA-4 on 16 January 1976. The darker shades of gray represent the warmer water. Selected temperatures recorded at the satellite are shown. The colder water associated with the Falkland Current increases northward in temperature from 10 to 13 °C. Wave-like meanders appear along the western SST boundary associated with the Brazil Current. A recently formed warm core eddy appears at 43 °S and 52 °W.

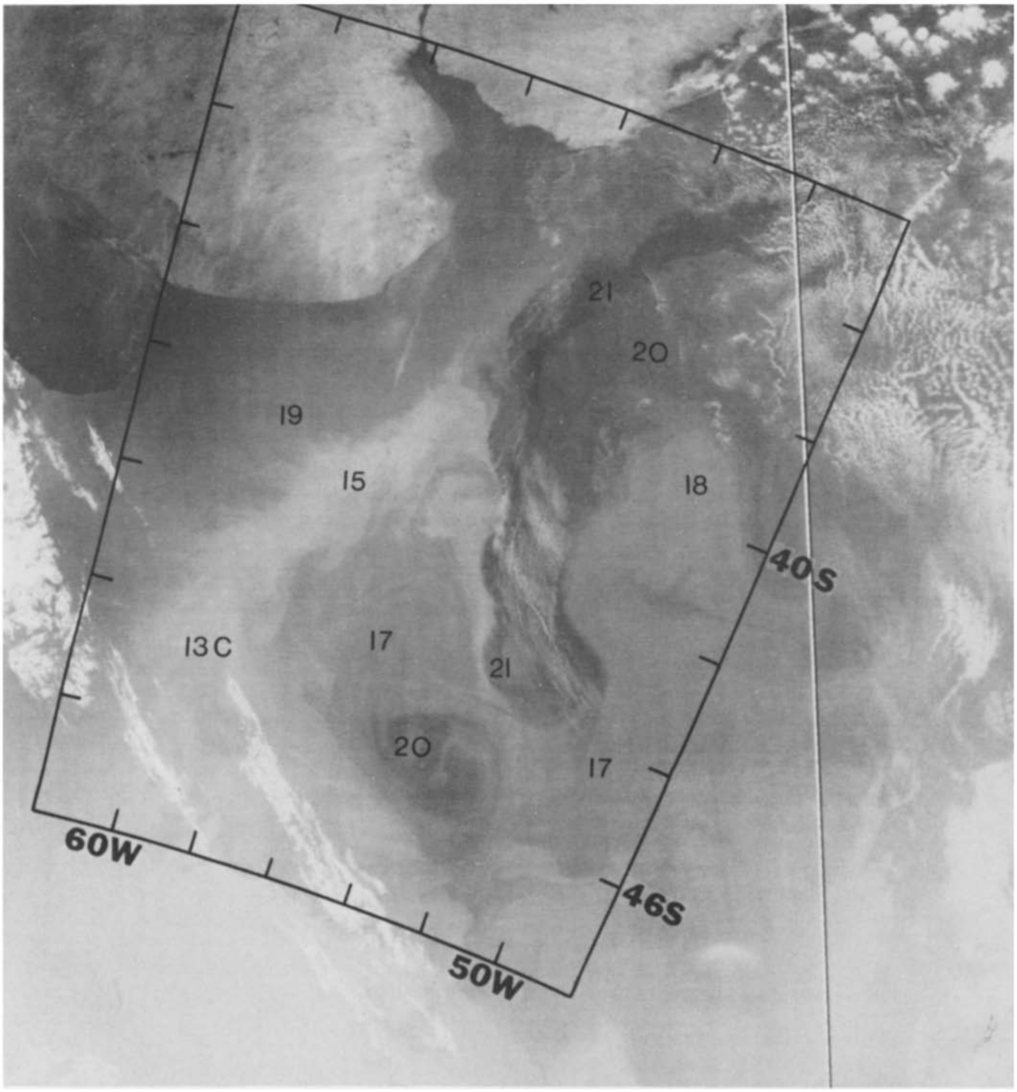

Fig. 4. The VHRR i.r. image was recorded on orbit 7283 by NOAA-5 on 10 March 1978. The darker shades of gray represent the warmer water. Selected temperatures recorded at the satellite are shown. The colder water associated with the Falkland Current warms northward from 13 to 15 C. Wave-like meanders are evident along the western SST boundary associated with the Brazil Current. A recently formed warm core eddy appears at 45 S and 53 W (Fig. 10).

200-m isobath and is bounded by the continental shelf waters. The northern SST boundary of the cold water is bounded by warm water associated with the Brazil Current. The eastern SST boundary of the cold water lies adjacent to warmer waters that are mixed periodically by meanders and warm core eddies associated with the Brazil Current. Based on the satellite observations listed in Table 1 between September 1975 and April 1976, the mean and the maximum deviation from the mean of the SST boundaries of the cold water are shown in Fig. 5 within a measurement uncertainty of 10 km. The mean position of the cold water in Fig. 5 coincides with the location of the northward flowing Falkland Current as described from the geopotential anomaly at the sea surface with respect to 1000 dbars by REID *et al.* (1977).

The position of the SST boundaries of the cold water associated with the Falkland Current is not always readily recognizable in the satellite i.r. images. For the images listed in Tables 1 and 2, the SST boundaries of the cold water were not recognizable from May to October, as shown in the i.r. image in Fig. 1, but became more distinct from November to April, as shown in Figs 2 to 4. Therefore, the optimum period for locating the SST boundaries of the cold water associated with the Falkland Current is during the austral spring and summer. One possible explanation for the seasonal occurrence of the SST fronts associated with the Falkland Current is that the mixed layer temperatures in the western South Atlantic increase during the austral spring and summer, while colder water continues to be carried northward by the Falkland Current. During the austral fall and winter, the

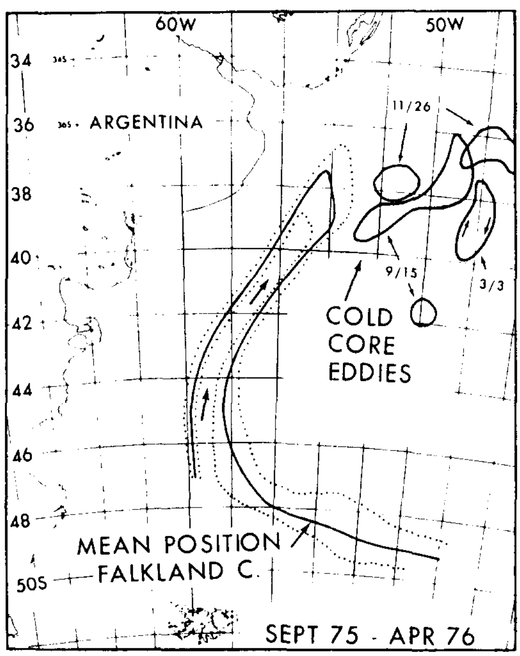

Fig. 5. The mean position of the boundaries of the cold water associated with the Falkland Current was determined from the sea surface temperature fronts apparent in the i.r. images from September 1975 to April 1976 (Table 1). The maximum deviation of the SST fronts from the mean is indicated by the dots. The shapes of the cold core eddies indicated in Table 1 are also illustrated.

mixed layer temperatures decrease due to convective overturning and wind mixing, and the SST gradients become less distinct.

There are distinct differences in the magnitude of SST gradients at the boundaries of the cold water associated with the Falkland Current. Representative values of the SST gradients observed during the austral summer were obtained on 22 February 1978. The satellite radiometer temperatures for orbit 7085 were averaged in 2-km squares for analysis. The cold water appeared as a 70-km wide ribbon of water of nearly uniform temperature. The along-stream temperature increased gradually from 11 to 12 C between 43 and 40 S, over 300 km. The eastern and western SST boundaries of the cold water were identified by the location of a cross-stream SST gradient of 1 C(2 km)$^{-1}$. Adjacent to the SST boundaries there was an additional increase of 1 C in a distance of 10 to 20 km while the waters surrounding the cross-stream gradients appeared well mixed. The largest temperature changes observed on 22 February 1978 occurred at the northern boundary of the cold water where the SST gradient was 5 C(2 km)$^{-1}$. The magnitude of SST gradients at the northern boundary can be appreciably higher. For example, JOHNSON and NORRIS (1977) reported temperature changes of 1 C in a distance of 67 m based on i.r. measurements made from SKYLAB.

The most significant excursions of the SST boundary of the colder water from the mean position (Fig. 5) occur at the northern and southeastern sections. Otherwise the boundary appears nearly stationary within our measurement uncertainty of 10 km. The translation of the northern SST boundary between 37 and 39 S can be attributed to the confluence of the Brazil and Falkland currents. REID *et al.* (1977) showed that the mean location of the confluence occurs near 39 S. BOLTOVSKOY (1970) used biological tracers, collected over a 16-year period, to establish the northern limit of the cold water associated with the Falkland Current at 36 S. The SST patterns observed in the satellite images suggest that the excursions of the northern SST boundary between 37 and 39 S, over 200 km, are due to the time-dependent motions of the warm water associated with the Brazil Current to be described later. The reason for the deviations of the southeastern SST boundary from its mean position (Fig. 5) is not clear. However, it will be shown that the warm core eddies that separate from the Brazil Current and subsequently drift southward are bounded by the eastern SST boundary of the cold water associated with the Falkland Current. It is possible that the deviations of the boundary of the cold water from the mean position shown in Fig. 5 may be due to its interaction with the warm core eddies.

Several SST patterns observed in the satellite images at the boundary of the cold water associated with the Falkland Current suggest time-dependent circulation changes. For example, on 22 February 1978 the cross-stream width of the cold water was about 70 km between 40 and 43 S. By 10 March, the width of the cold water had increased to over 100 km. On 22 February the eastern and western SST boundaries were nearly parallel, while on 10 March the SST patterns at the eastern boundary (Fig. 4) appeared irregular and wave-like, suggesting a shear instability. As this is the only example of such an event in our data set, it is not possible to describe its evolution or frequency. Occasionally the eastern SST boundary is distorted by the appearance of a series of cusp-like features about 50 km long. Examples of this pattern appear in the images for orbits 4951, 5965, and 6616 (Table 1). This SST pattern may be associated with shear edge disturbances, but the lack of data prevented an analysis of their time dependence. Recently, MOLLO-CHRISTENSEN, CORNILLON and DA MASCARENHA (1981) suggested that similar SST patterns observed by satellite over the Gulf Stream could be used to estimate the speed of ocean currents.

An SST pattern that appears more often in the i.r. images is the intermittent entrainment of the cold water associated with the Falkland Current along the western SST boundary of the warm water associated with the Brazil Current. The entrained cold water originates at the confluence of the two distinct water masses and extends southward in continuous streams for up to 400 km (Figs 3, 4). The entrained water varies from 5 to 40 km wide. Similar events were observed in images for orbits 4875, 5001, and 6353 (Table 1) and orbits 6825, 7283, and 7518 (Table 2).

BRAZIL CURRENT

In the satellite i.r. images, the SST patterns in the western South Atlantic south of 32°S are dominated by the warm water associated with the Brazil Current and warm core eddies. Based on the satellite images (Tables 1, 2) and the examples in Figs 1 to 4, the SST patterns associated with the Brazil Current will be described.

The western SST boundary associated with the Brazil Current is nearly parallel to the edge of the continental shelf between 32 and 38°S. South of 38°S, the western SST boundary separates from the shelf edge and turns southeastward towards deeper water. The confluence of the warm water associated with the Brazil Current and the cold water associated with the Falkland Current occurs between 37 and 39°S (Figs 1 to 4). REID *et al.* (1977) show that the mean position of this confluence in the surface circulation occurs near 39°S. It will be shown later that the changes in the location of the confluence, judging from satellite observations, appear to arise from the time-dependent fluctuations of the western SST boundary associated with the Brazil Current.

After the western SST boundary separates from the edge of the continental shelf, the southern limit of the warm water associated with the Brazil Current fluctuates between 38 and 46°S, a distance of nearly 900 km. The meridional displacements of the warm water are accompanied by the intermittent formation of warm core eddies. It will be shown later that in some cases the eddies appear to form after prolonged southward displacements of the warm water associated with the Brazil Current. The eddies are usually south of the southern limit of the warm water as shown in Figs 1 to 4. Occasionally warm core eddies are also observed west and east of the warm water (Fig. 1).

At the southern limit of the warm water associated with the Brazil Current, the SST patterns suggest a reversal of flow. In effect, the warm water that flows southward along the western SST boundary turns counter-clockwise and then flows equatorward. Associated with this flow reversal, there is a distinct eastern SST boundary that sometimes extends to 38°S. Temperature changes of up to 3°C in a distance of 2 km have been observed at the eastern SST boundary (Figs 1 to 4) in the satellite data. REID *et al.* (1977) demonstrated that a reversal of the surface circulation of the Brazil Current occurs between 40 and 46 S and that the equatorward return flow is just seaward of the poleward flow of the Brazil Current. In the satellite images, the western and eastern SST boundaries of the warm water associated with these two opposing flow components are separated by 150 to 300 km. Similar reversals of a western boundary current have been described by HARRIS, LEGECKIS and VAN FOREEST (1978) for the Agulhas Current.

Another SST pattern that appears in the satellite images is a zonally oriented meander along 40°S. The meander pattern is usually observed as the extension of the eastern SST boundary associated with the equatorward return flow of the Brazil Current (Figs 1 to 4) near 50°W. Judging from the satellite (Tables 1, 2), typical meanders have a zonal wavelength of 200 to 400 km and longitudinal amplitudes of 100 to 300 km. The surface circulation patterns illustrated by REID *et al.* (1977) show a similar zonal meander pattern east of the Brazil Current. This may be a recurrent flow pattern, although it was not possible to establish its temporal behavior from the satellite observations.

In the satellite images, there often appears a band of warmer water on the seaward side of the western SST boundary associated with the Brazil Current. The band is 30 to 100 km wide, and it is suggested that it represents the core of the Brazil Current. The eastern boundary of the warmer water is usually difficult to recognize because the water east of it is also relatively warm (Fig. 3) near 40°S, 52°W. In Fig. 3, the band of warmer water appears only to about 42°S, and it does not appear to turn poleward along the eastern SST boundary near 49°W. In some cases the band of warmer water appears to separate into a southward and southeastward component as in Fig. 1 near 40°S. On rare occasions (Fig. 2) bands of warmer water are interleaved continuously along the western and the eastern SST boundaries for hundreds of kilometers. This suggests that horizontal mixing is not strong enough to dissipate the interleaved waters on short time scales.

TIME DEPENDENT CROSS-STREAM FLUCTUATIONS OF THE BRAZIL CURRENT

The position of the western SST boundary associated with the Brazil Current moves in the cross-stream direction with time. There were insufficient satellite data to allow a time series of these movements to be constructed without aliasing. To estimate the range of the motion, a composite of the positions of the western SST boundary associated with the

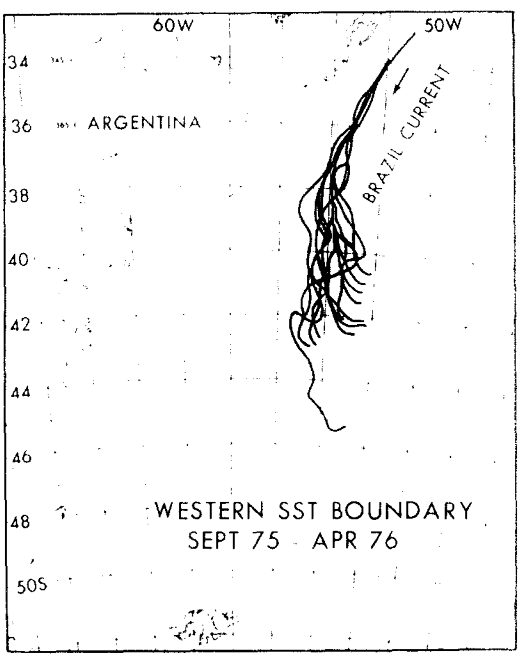

Fig. 6. The composite shows the positions of the western SST boundary associated with the Brazil Current from September 1975 to April 1976 as seen in the i.r. images tabulated in Table 1. The east west displacement of the position of the boundary increases rapidly south of 36°S.

Brazil Current was made from September 1975 to April 1976 using the i.r. images listed in Table 1 (Fig. 6). It is evident that the cross-stream displacements of the western SST boundary increase substantially south of 36°S. For example, between 36 and 40°S the peak-to-peak range of the fluctuations increases from 50 to over 200 km. This is the approximate area of the confluence of the Brazil and Falkland currents as described by REID *et al.* (1977). It is suggested that the meridional changes in the position of the northern SST boundary of the cold water associated with the Falkland Current (Fig. 5) can be attributed to the time-dependent cross-stream displacements of the western SST boundary associated with the Brazil Current (Fig. 6).

The cross-stream time-dependent fluctuations of the western SST boundary occur at several spacial and temporal scales. For example, between 22 February and 10 March (Fig. 7), the western SST boundary moved about 50 km westward north of 40°S and a comparable distance eastward south of 40°S. The meridional scale of the motion is on the order of 1000 km. Concurrently with the large-scale displacements, time-dependent wave-like disturbances with shorter length scales occur intermittently. The latter disturbances appear like a succession of crests and troughs of varying amplitude along the western SST boundary (Figs 1 to 4). The separation between adjacent wave crests can be used to estimate their wavelength. Based on the satellite observations (Tables 1, 2), 12 measurements yielded an average wavelength of 200 km and a range of 100 to 250 km. The average cross-stream wave amplitude was 50 km and the range was 20 to 100 km, measured peak to peak.

Only one pair of satellite observations allowed an estimate of the wave phase speed and direction. The wave train observed on 17 October 1975 (Fig. 1) was displaced about 150 km downstream by 23 October, suggesting a wave phase speed of 25 km day^{-1} with the waves travelling in the same direction as the Brazil Current. To a stationary observer, the waves would appear to have a period of 8 to 10 days. By 31 October, the warm water associated with the Brazil Current south of 41°S was breaking up into several warm core eddies, and the wave-like disturbances could no longer be recognized. Therefore, significant displacements of the western SST boundary associated with the Brazil Current can occur on time scales of about one week or longer and along-stream spatial scales of 200 km. Similar length and time scales have been measured from satellite observations of waves along the western SST boundaries of the Gulf Stream by LEGECKIS (1978) and of the Agulhas Current by HARRIS *et al.* (1978).

BRAZIL CURRENT—MERIDIONAL FLUCTUATIONS—JANUARY TO JULY 1978

The Brazil Current and associated warm core eddies and zonally oriented meanders dominate the SST patterns in the satellite images. Most unusual are the meridional fluctuations of the current; the warm water associated with the Brazil Current moves southward and, after reaching a southern limit, its southern part breaks up into one or more warm core eddies so that the southern limit of the warm water appears further north. The fluctuations occur between 50 and 55°W and 38 and 46°S with a time scale of about two months.

Three examples of the positions of the SST boundaries of the warm water associated with the Brazil Current are illustrated in Fig. 7 for 22 February and 10 and 18 March 1978. It is apparent that the meridional displacements of the SST boundaries of the warm water are accompanied by zonal displacements and by changes in the width of the zonal cross-

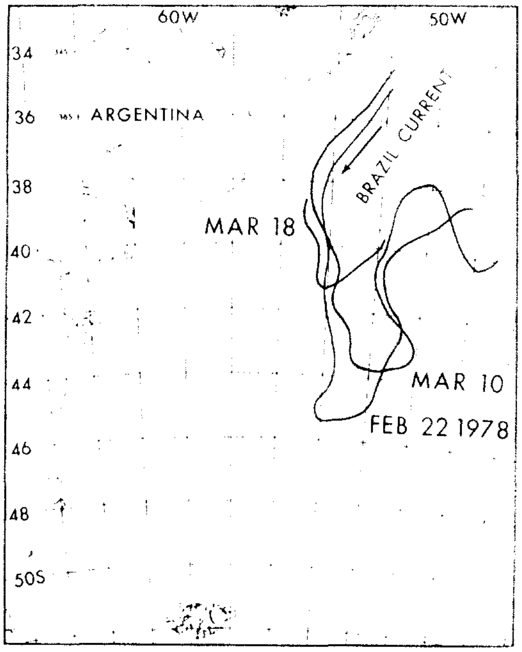

Fig. 7. The three positions of the boundaries of the warm water associated with the Brazil Current suggest an apparent northward displacement of the southern limit of the warm water between 22 February and 18 March 1978. During this interval two warm core eddies separated from the Brazil Current (Figs 10, 11).

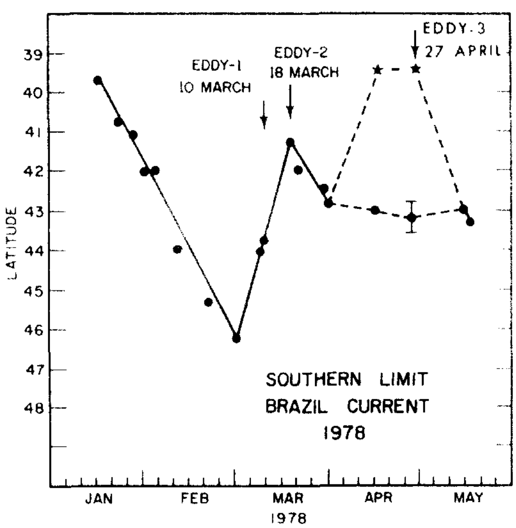

Fig. 8. A time series of the southern limit of the relatively warm water associated with the SST boundary of the Brazil Current from January to May 1978. The first two eddies formed after the southward displacement of the warm water during January and February. The dashed lines indicate the ambiguous interpretation of the southern limit due to cloud cover. EDDY 3 was observed only on 27 April. The measurement uncertainty in estimating the southern limit is indicated.

section. A time series of the southern limit of the warm water associated with the Brazil Current during the first half of 1978 is shown in Fig. 8. From mid-January to the end of February, the warm water moved southward at a steady rate of 17 km day^{-1} (20 cm s^{-1}). The speed of a western boundary current is on the order of 100 cm s^{-1}, so we suggest that the poleward flow of the warm water associated with the Brazil Current along the western SST boundary is being recirculated northward along the eastern SST boundary. This reversal appears in the surface maps described by Reid *et al.* (1977).

An example of the position of the warm water associated with the Brazil Current for 1 February 1978 (Fig. 9) shows no apparent warm core eddies south of 42°S during February. After reaching its extreme southward position at 46.3°S at the end of February, the southern limit of the warm water was at 43.8°S on 10 March and at 41°S on 18 March (Fig. 7). During the interim, two warm core eddies were formed south of the Brazil Current. The first, EDDY 1, was observed on 10 March (Fig. 10) and in the corresponding i.r. image (Fig. 4) EDDY 2 appeared on 18 March (Fig. 11). Between 10 and 18 March, while the second eddy was forming, EDDY 1 remained in nearly the same position although its shape was not well defined because of partial cloud cover on 18 March.

After 18 March, the warm water associated with the Brazil Current was moving southward again as indicated by the time series (Fig. 8). By 29 March, the warm water had reached 42.5°S (Fig. 12). Comparing Figs 11 and 12, it is evident that the two eddies had

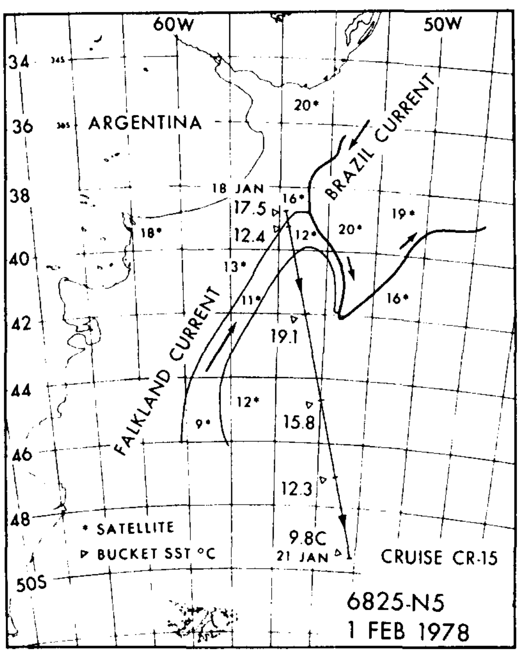

Fig. 9. The SST boundaries associated with the Brazil and Falkland currents on 1 February 1978 are shown based on the VHRR i.r. image from orbit 6825 on NOAA-5. The entrainment of the cold water associated with the Falkland Current along the western boundary of the Brazil Current is evident. The southward track for cruise IO-15 of the ARA *Islas Orcadas* is shown from 18 to 21 January. Selected temperatures recorded at the satellite and surface bucket measurements are also included.

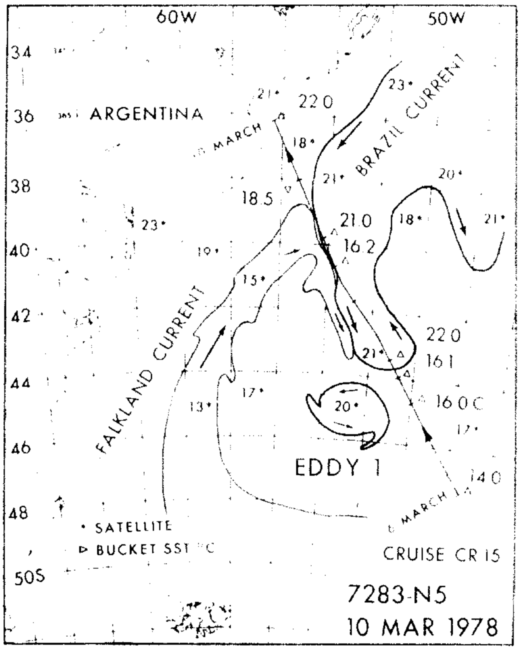

Fig. 10. The SST boundaries associated with the Falkland Current, the Brazil Current, and a warm core eddy are shown on 10 March 1978 on the VHRR i.r. image from orbit 7283 on NOAA-5. The track for cruise IO-15 of the ARA *Islas Orcadas* extends northward from 6 to 10 March 1978. Selected temperatures recorded at the satellite and surface bucket measurements are also shown.

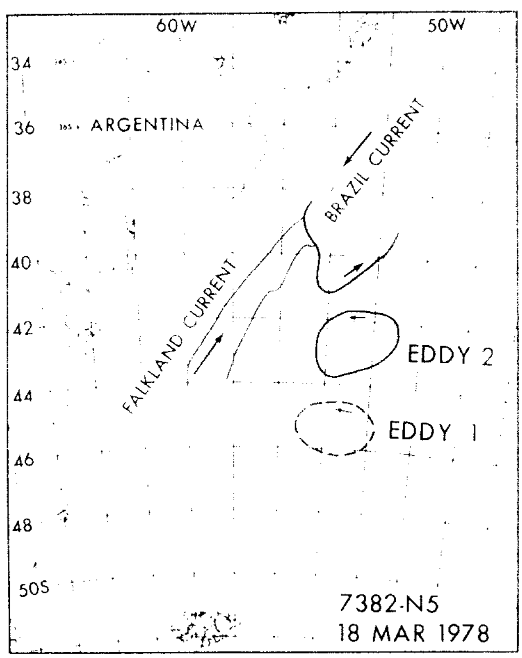

Fig. 11. The SST boundaries associated with the Falkland Current, the Brazil Current, and two warm core eddies are shown on 18 March 1978 based on VHRR i.r. image from orbit 7382 on NOAA-5. EDDY 1 was partially cloud covered and its position is approximate.

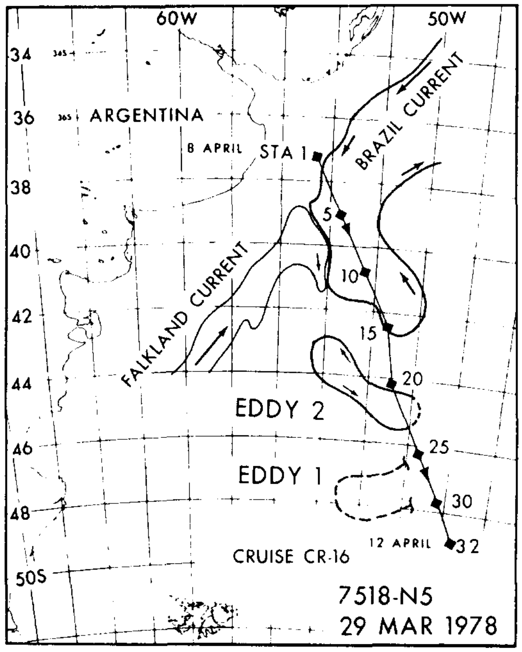

Fig. 12. The SST boundaries associated with the Falkland Current, the Brazil Current, and two warm eddies are shown on 29 March 1978 based on the VHRR i.r. image from orbit 7518 on NOAA-5. EDDY 1 was partially cloud covered and its position is approximate. The southward track for cruise IO-16 of the ARA *Islas Orcadas* is shown from 8 to 12 April. The locations of XBT Sta 1 to 32 are indicated and the corresponding surface temperatures and mixed layer depth are shown in Fig. 18.

been displaced southward between 18 and 29 March and that EDDY 2 had been deformed and elongated, possibly due to the influence of the southward motion of the warm water associated with the Brazil Current. Unfortunately, the eddies were not observed again and their subsequent evolution was not established. Nevertheless, the sequence of satellite observations between January and March 1978 illustrates the events that lead to the formation of the warm core eddies observed south of the Brazil Current.

From April to July, the satellite observations were limited and there was some ambiguity about the position of the southern limit of the warm water associated with the Brazil Current (Fig. 8). For example, on 27 April (Fig. 13) the warm water associated with the Brazil Current appeared to be bisected by a lens of colder water from the Falkland Current, resulting in the formation of a large warm area of water, EDDY 3, south of 40°S. It is unknown to what depth this gap developed but the short ($\sim$ 75 km) waves at the western boundary of EDDY 3 may indicate an abrupt change in the horizontal shear of the current. There was some evidence that the warm water associated with the Brazil Current was moving southward by mid-May although the fate of EDDY 3 is not known.

WARM CORE EDDIES—SEPTEMBER 1975 TO APRIL 1976

Between September 1975 and April 1976, 40 warm core eddies were identified in the i.r. images listed in Table 1. At least 20 were unique while the remaining 20 were either repeated observations of the same eddy or not sufficiently well defined to be classified as

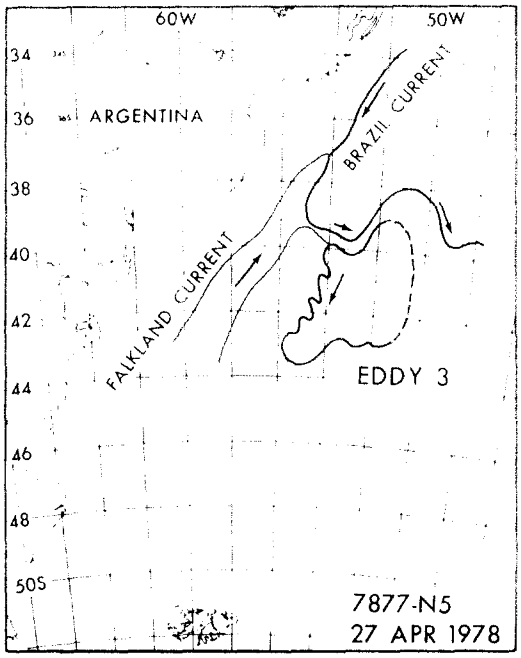

Fig. 13. The SST boundaries associated with the Falkland Current, the Brazil Current, and a large area of warm water, called EDDY 3, on 27 April 1978 are shown based on the VHRR i.r. image from orbit 7877 on NOAA-5. The eddy and the warm water associated with the Brazil Current appeared to be separated by a narrow filament of cold water associated with the Falkland Current.

unique observations (Figs 14 to 16). The mean position of the SST boundaries of the cold water associated with the Falkland Current is shown for reference.

All of the warm core eddies appear south of 38°S and east of the cold water associated with the Falkland Current. The eddies are usually elliptical with a mean major axis of 180 km and a mean minor axis of 120 km. The eddy dimensions vary from 70 to 350 km for the major axis and 60 to 230 km for the minor axis. The shapes suggest low-frequency wave motions associated with the warm core eddies similar to the motion associated with cold core Gulf Stream rings described by SPENCE and LEGECKIS (1981). Satellite observations were insufficient to demonstrate this low-frequency motion in our study. A statistical analysis by LUTJEHARMS and BAKER (1980) shows an upper limit of 150 to 250 km for the mesoscale turbulence in most parts of the Southern Ocean. In our study, only one eddy reached a dimension of 350 km while all others had an upper limit of 280 km.

After they are formed, the centers of the warm core eddies appear to move southward with speeds from 4 to 35 km day^{-1}. For example, a nearly circular eddy with a diameter of 70 km (Fig. 14) was displaced southward along 50°W between 17 October and 2 November at a speed of 9 ± 1.2 km day^{-1}. A large elliptical eddy with a major axis of 170 km was displaced southward along 50°W between 31 October and 2 November at a speed of 35 ± 10 km day^{-1}. Both eddies appear to have changed shape during the transition. Of three additional eddy tracks (Fig. 15) one moved southward along 53°W from 16 November to 24 November at a speed of 20 ± 2.5 km day^{-1} and from 24 November to 20 December at 12 ± 1 km day^{-1}. Another large elliptical eddy, first

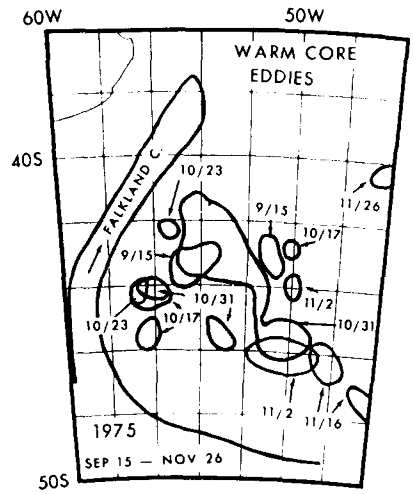

Fig. 14. The mean SST boundary associated with the Falkland Current and the position of the warm core eddies are shown between 15 September and 26 November 1975. Two eddies moved southward along 50°W from 17 October to 2 November and from 31 October to 2 November. Most of the other eddies are unique observations and their displacement was not established.

observed on 24 November at 40°S, moved southeastward at a speed of 20±3 km day^{-1}. Finally, the eddy first observed on 16 December at 43°S, moved southwestward along 55°W at a speed of 15±5 km day^{-1}.

During 1976, the available observations of the warm core eddies (Fig. 16) were less frequent and it was more difficult to establish the eddy displacements with time. If we assume that the two eddies observed on 16 March and 15 April (Fig. 16) were the same,

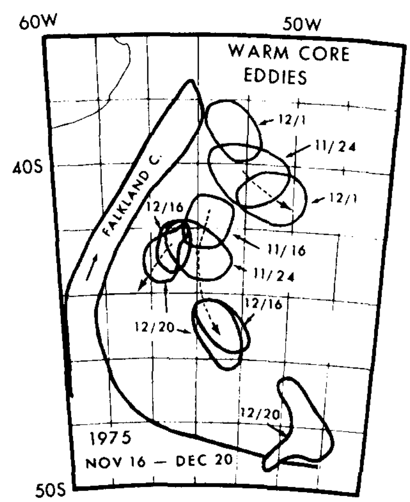

Fig. 15. The mean SST boundary associated with the Falkland Current and the position of the warm core eddies are shown between 16 November and 20 December 1975. Three of the eddies were displaced southward as indicated by the dashed lines. The eddies observed on 20 December also appear in the i.r. image in Fig. 2.

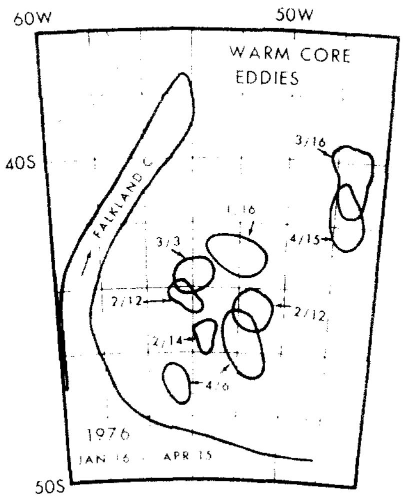

Fig. 16. The mean SST boundary associated with the Falkland Current and the position of the warm core eddies between 16 January and 15 April 1976 are shown. The eddy observed along 48°W on 16 March and 15 April may be the same eddy as well as the eddy observed on 16 January and 6 April along 52°W. The rest of the eddies appear to be unique.

then it moved southward along 48° W at a speed of 4.7 ± 0.6 km day^{-1}, half the eddy speeds measured over shorter time scales during 1975. As this eddy was further east than those shown in Figs 14 and 15, its speed may not be atypical for the region. It is also possible that the eddies observed on 16 January and 6 April along 52° W were the same. The former was recently formed (Fig. 3) while the latter appeared to be an older, less well-defined eddy of similar size. If this is correct, the speed of the eddy was 4.0 ± 0.25 km day^{-1}, also less than the slowest eddy speeds measured several months earlier.

There is some evidence that the southward displacement of the warm core eddies slows down with time. For example, the eddy that moved along 53° W between 16 November and 20 December (Fig. 15), slowed from 20 to 12 km day^{-1}. In general, the higher speeds (15 to 35 km day^{-1}) were measured for more recently formed eddies. Therefore, the lower speeds (~ 4 km day^{-1}) measured from January to April 1976 along 48 and 52° W may indicate the nominal speeds of older eddies if the identifications of the eddies are correct. RICHARDSON (1980) showed that warm core eddies that spin off north of the Gulf Stream move southwestward at 3 to 7 km day^{-1}. While the Gulf Stream eddies carry heat and momentum westward or counter to the flow of the stream, the Brazil Current eddies carry these quantities poleward.

From our satellite observations, there appear to be three ways that warm core eddies are formed in the vicinity of the Brazil Current. The first is similar to that described by SAUNDERS (1971) for the formation of warm core eddies from northward meanders of the Gulf Stream. In our case, the warm core eddies pinch off from wave-like meanders observed along the western SST boundary associated with the Brazil Current. An example of such an eddy, with a diameter of 140 km (Fig. 1) was on 17 October at 44°S and 56° W. The trailing tongue of warm water indicates that the Brazil Current continued to move southward after the eddy pinched off. Another circular eddy with a radius of 70 km was pinched off on

23 October at 42°S and 55°W (Fig. 14). The dimensions of these eddies and the fact that the continuity of the warm water associated with the Brazil Current is not disrupted after eddy separation makes them appear similar to the warm core eddies described by SAUNDERS (1971) north of the Gulf Stream.

A second way that warm core eddies are formed in the western South Atlantic appears to be the pinching off of the southern end of the warm water associated with the Brazil Current. Examples that may have formed this way appear in Figs 2 to 4. According to REID *et al.* (1977), the Brazil Current reverses direction after reaching a southern limit and flows equatorward just east of its poleward flow. The horizontal shear created by the reversal of the current may make it more susceptible to instabilities that may lead to eddy formation. The eddies (Figs 14 to 16) tend to be large (150 to 350 km) and are usually elliptical.

A third way that warm core eddies are formed in the western South Atlantic appears to be the result of a wave instability observed along the western SST boundary associated with the Brazil Current. Some of the wave characteristics were described above. During wave instability, large volumes of warm water break off or a series of large warm core eddies form over a time scale of about one week. The result is that the southern limit of the warm water associated with the Brazil Current is found progressively further north (Fig. 17) in a time series between September 1975 and April 1976. The interval between October and December 1975 (Fig. 17) suggests a time scale of about two months for the completion of one cycle of the meridional displacements. After a prolonged southward displacement of the warm water during October, at least four warm core eddies appeared on 31 October; Fig. 14 shows that the two larger eddies were still attached by a tongue of warm water. This event was preceeded by the increase in the amplitude of the wave-like meanders along the western SST boundary (Fig. 1) on 17 October.

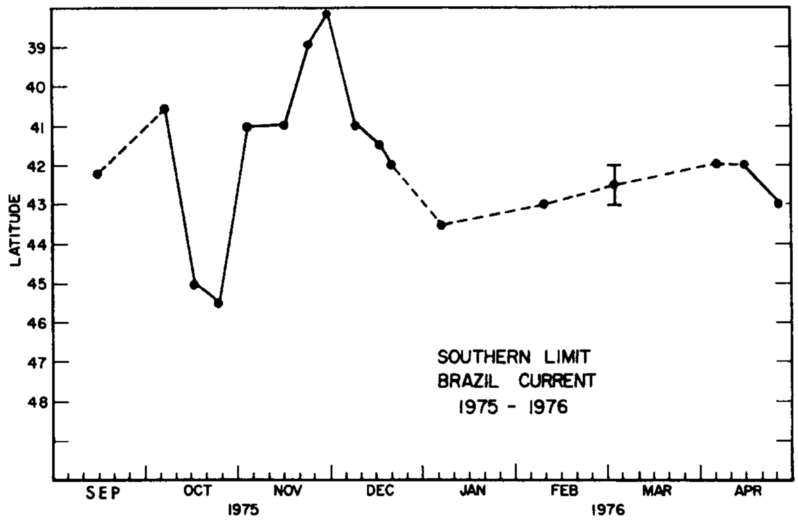

Fig. 17. The time series of the southern limit of the relatively warm water associated with the SST boundary of the Brazil Current from September 1975 to April 1976. At least six large warm core eddies formed south of the Brazil Current during October and November (Figs 14, 15). The measurement uncertainty in estimating the southern limit is indicated. The dashed line is used where sufficient observations were not available to resolve the fluctuations of the southern limit.

Between 31 October and 2 November (Fig. 14) the eddy initially at 45.5°S was displaced about 70 km southward along 50°W. The large warm eddy centered at 53°W changed shape somewhat during this time, but a uniform displacement was not evident and the subsequent fate of the eddy was not determined. Between 16 November and 1 December there was a continued northward displacement of the southern limit of the warm water (Fig. 17). During this interval, at least three large elliptical warm core eddies appeared (Fig. 15). The eddy first observed on 16 November at 42°S moved southward along 53°W until 20 December. A second eddy first observed at 40°S moved southeastward between 24 November and 1 December. The last eddy appeared at 39°S on 1 December, but its movement was not established. Subsequently, the warm water associated with the Brazil Current appeared to move southward again and there is some evidence that by 10 December it reabsorbed the eddy formed on 1 December at 39°S. The series of large eddies formed during November and December 1975 may be an example of wave-like instabilities that result in the break-up of the poleward flow and the adjacent return flow of the warm water associated with the Brazil Current.

Although the warm core eddies move southward after separation from the Brazil Current, most of them do not appear to be reabsorbed by the current as is the case in the North Atlantic, where warm core eddies re-enter the Gulf Stream (RICHARDSON, 1980). GORDON (1981) observed a series of thick and relatively warm, saline intrusions in the mid-thermocline depths (300 to 600 m) along 38°S. He interpreted the features as being derived from winter cooled warm core eddies. It is possible that the warm core eddies, after being cooled, lose their surface signature and eventually sink and spread northward to re-enter the South Atlantic subtropical gyre at the mid-depth region of the thermocline. Thus, the separation from the main body of the subtropical gyre is long enough to force the re-absorption to occur below the surface water layer.

COLD CORE EDDIES

There were only a few cold core eddies observed in the satellite images during the 1975 to 1976 interval and none was observed in the images during 1978 (Table 1). The eddies tend to be elliptical with a major axis between 100 and 300 km (Fig. 5). The large area of cold water that appeared on 15 September (Fig. 5) with a dimension of nearly 500 km may have been in the process of pinching off into two smaller eddies. There was no opportunity to study the evolution of these eddies because each was observed only once. However, changes in the zonally oriented meander pattern often observed near 40°S, 50°W may lead to the formation of the cold core eddies illustrated in Fig. 5, as they are usually found north of the meander. For example, the meander pattern that appeared on 20 December 1975 (Fig. 2) may have been in the process of enclosing relatively colder water at 39°S, 50°W.

COMPARISON OF SATELLITE AND *IN SITU* MEASUREMENTS

Between January and May 1978, two hydrographic surveys were made in the western South Atlantic with the ARA *Islas Orcadas* (GORDON, 1978). The SST fronts observed by satellite correspond to a deep-reaching subsurface temperature structure and the mixed layer depth correlates with the surface temperature patterns of the Brazil Current and two warm core eddies.

The southward leg of cruise IO–15 from 18 to 21 January 1978 is shown in Fig. 9 relative to the satellite-derived SST boundaries of the currents on 1 February. Although the satellite observation was not concurrent with the ship track, the image is representative of the SST patterns observed during January. For example, according to the time sequence (Fig. 8), the warm water associated with the Brazil Current was moving southward from 40 to 42°S during the latter half of January. It is evident that the ship traversed the Falkland Current boundaries between 40 and 41°S but did not intercept the Brazil Current. Only bucket surface temperatures were obtained during this leg (Fig. 19). For example, there was a 5°C drop in bucket temperatures at 39°S on 19 January. Representative values of satellite radiometer temperatures, averaged in 10-km squares, show a 4°C temperature drop on 1 February (Fig. 9) near the intersection of the cruise track with the northern SST boundary of the cold water associated with the Falkland Current.

The northward leg of cruise IO–15 from 6 to 10 March 1978 is shown in Fig. 10 relative to the SST boundaries on 10 March derived from the i.r. image (Fig. 4). Representative

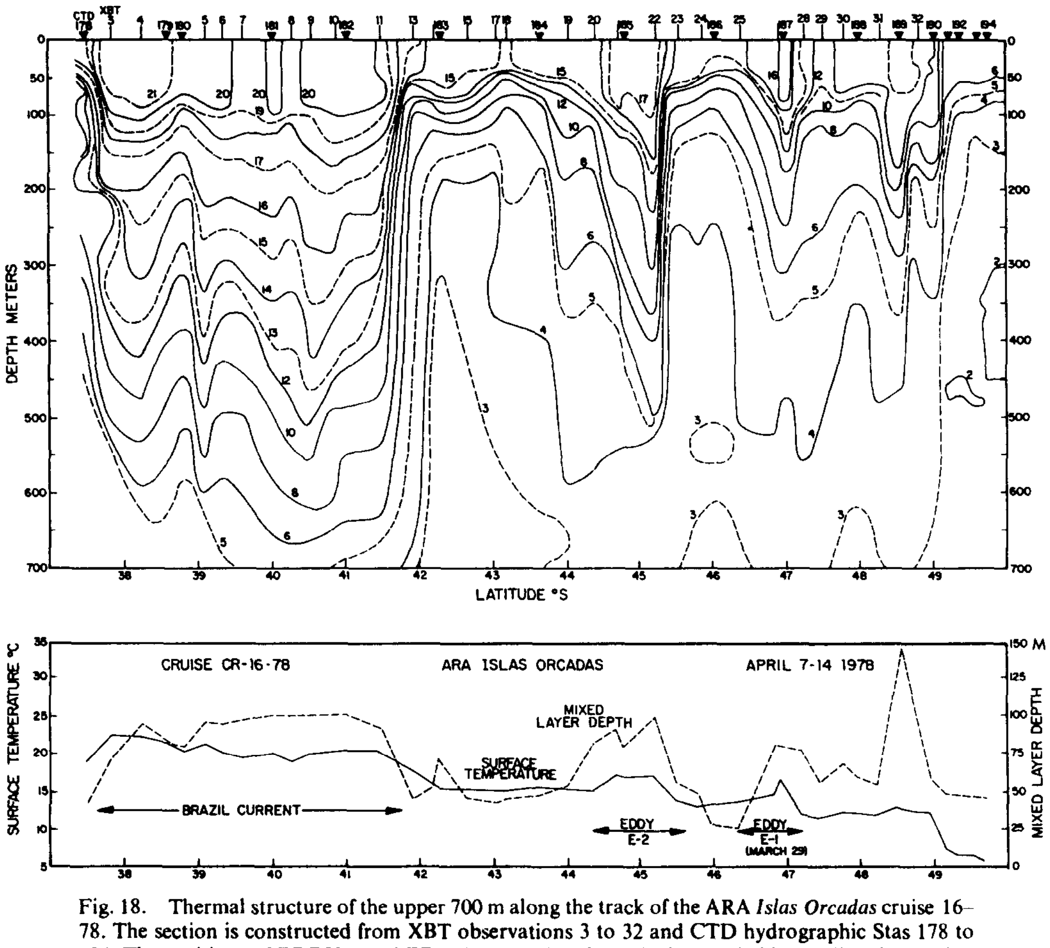

Fig. 18. Thermal structure of the upper 700 m along the track of the ARA *Islas Orcadas* cruise 16–78. The section is constructed from XBT observations 3 to 32 and CTD hydrographic Stas 178 to 194. The positions of EDDY 1 and EDDY 2 are taken from the last available satellite observation on 29 March 1978 (Fig. 12).

values of surface bucket temperatures and satellite radiometer temperatures are shown in Fig. 10. The cruise track traversed the southern limit of the Brazil Current at 43.7°S, where the bucket measurements indicate a 6°C temperature change. The averaged radiometer temperatures indicate only a 3 to 4°C temperature change at this boundary on 10 March. The smaller gradient may be attributed to atmospheric absorption of the i.r. radiation, to the partial cloud cover evident in Fig. 4, or to changes in temperature of the surface layers during the 3 days separating the satellite and *in situ* measurements. The surface bucket temperatures of the warm water associated with the Brazil Current were relatively constant at 21 to 22°C over a considerable distance while the radiometer temperatures were about 1°C lower. The decrease in the bucket temperature to 16.2°C at 40.7°S was due to mixing of the Brazil and Falkland waters.

The southward leg of cruise IO–16 from 8 to 12 April 1978 is shown in Fig. 12 relative to the satellite-derived SST boundaries of the eddies and current on 29 March. Although the eddies were not observed after 29 March, the hydrographic observations during cruise IO–16 revealed their subsurface structure about two weeks later. The *in situ* measurements are reconstructed from XBT Stations 3 to 32 and CTD Stations 178 to 194 (Fig. 18).

The hydrographic sections (Fig. 18) reveal that the surface temperature patterns observed from satellite are associated with significant subsurface thermal structure. The lower thermocline level, as identified by the 10°C water, has a relief of about 400 m between the Brazil Current at 40°S and the waters at 42 to 44°S. The surface signature of EDDY 2 appears between XBT Stas 20 and 23 at 44.5°S. This suggests there was little southward translation of EDDY 2 from its position on 29 March in Fig. 12. The 10°C water for this eddy reaches 370 m at 45.3°S.

There is some ambiguity in establishing the position of EDDY 1 from the hydrographic sections (Fig. 18). The problem is compounded by the fact that the satellite-derived position of the eddy on 29 March in Fig. 12 was based on a partially cloud-covered warm area at 47.5°S. If we assume that the eddy did not move after 29 March for about 10 days, then the mixed layer depth of 80 m at 47°S probably represents the location of EDDY 1. The second warm water feature at 48.5°S with a mixed layer depth of 150 m may be an eddy previously formed but not detected in the satellite data. An alternate interpretation is that EDDY 1 split into two warm core eddies.

Another interesting feature in the hydrographic sections (Fig. 18) is the relatively stronger subsurface gradients on the poleward side of the warm core features. This is apparent at the Brazil Current at 41.5 to 42°S, at EDDY 2 at 45.2 to 45.4°S, and at the warm water feature at 49°S. It is also apparent (Fig. 18) that the mixed layer depth at latitude 48.5°S is greater than at the Brazil Current. This may be due to the convection induced by atmospheric cooling effects as the eddies are displaced to higher latitudes.

CONCLUSIONS

The satellite i.r. observations of the surface thermal patterns in the western South Atlantic show that the time-dependent motions are dominated by the meridional fluctuations of the warm water associated with the Brazil Current. The southern limit of the warm water fluctuates between 38 and 46°S with a time scale of about two months (Figs 8, 17). After a prolonged southward displacement of the warm water associated with the Brazil Current one or more large anticyclonic warm core eddies form south of the warm water at intervals of about one week. The eddies are usually elliptical with a major axis range from 70 to 350 km. The eddies drift southward at speeds of 4 to 35 km day^{-1}. RICHARDSON (1980) showed that anticyclonic eddies in the western North Atlantic drift westward at 3 to 7 km day^{-1} and tend to be reabsorbed by the Gulf Stream. The fate of the Brazil warm core eddies is not known. They may eventually sink as they cool and then re-enter the subtropical gyre at subsurface depths.

There were at least 20 unique warm core eddies observed between September 1975 and April 1976 (Figs 14 to 16). It is proposed that there are three ways these eddies form south of the Brazil Current. The first is similar to the description given by SAUNDERS (1971) for the pinching off of eddies from meanders of the Gulf Stream. In these events, the warm water associated with the Brazil Current remains intact after eddy separation as shown in Fig. 1. Only a few eddies were observed to form in this way and their dimensions were between 70 and 140 km.

A second way that warm core eddies form is by pinching off of the southern end of the warm water associated with the Brazil Current. REID *et al.* (1977) showed that the poleward moving current reverses direction at its southern limit and flows equatorward. It is suggested that shear instabilities in the area of current reversal lead to this type of eddy formation. Examples of recently formed eddies south of the warm water associated with the Brazil Current are shown in Figs 2 to 4.

A third way that warm core eddies form may be a result of the instability of a series of wave-like meanders that appear along the western SST boundary associated with the Brazil Current. These features (Figs 1 to 4) vary in wavelength (100 to 250 km) and in peak-to-peak amplitude (20 to 100 km). For example, the relatively larger amplitude waves evident on 17 October 1975 (Fig. 1) preceded the formation of about six warm core eddies during November and December 1975 between 38 and 45°S. These eddies (Figs 14, 15) appeared at intervals of about one week. The result of such eddy formation is that the southern limit of the warm water associated with the Brazil Current is found farther north. These meridional fluctuations have periods about two months (Figs 8, 17).

We suggest that there is qualitative agreement between our observations and the numerical model described by BRYAN and COX (1968a, b). In the model, the outflow from the western boundary current contains eddies that separate spontaneously and move poleward. The cycle is similar to the meridional fluctuations of the warm water and eddies associated with the Brazil Current in the satellite images. Similar events may also occur in the East Australian and the Agulhas currents. Reversals of the Agulhas Current have been identified in satellite images by HARRIS *et al.* (1978). LUTJEHARMS (1981) described the formation of a large warm core eddy in the region of reversal of the Agulhas Current. NILSSON, ANDREWS and SCULLY-POWER (1977) described three warm core eddies south of the East Australian Current and suggested that the mechanism of their formation appears to be significantly different from warm core eddy formation at the Gulf Stream as described by SAUNDERS (1971).

GODFREY (1973) suggested that the BRYAN and COX (1968a, b) numerical model also applies qualitatively to the East Australian Current. However, GODFREY (1973) cautioned that there are significant differences between the model and the current that will prevent good agreement with observations. Among the differences are bottom topography, the seasonal variability of the current, and the method of parameterizing the frictional effects. Similar differences exist for the Brazil Current, but the qualitative agreement between our satellite observations and the model should inspire further model improvements.

The satellite i.r. observations were limited in their usefulness to identify the surface thermal expression of the eddies within several weeks after their formation. This was partly due to the air–sea exchange as the eddies moved to higher latitudes. The depth of the mixed layer deduced from the hydrographic surveys of the ARA *Islas Orcadas* during 1978 suggested strong convective motions to depths of 150 m. One could probably obtain a more continuous history of the eddy tracks if satellite altimetry and ocean colour measurements were also used in the survey. The altimeter could identify sea-level changes at the eddy in the presence of clouds and the ocean color differences could be used to locate eddies under cloud-free but isothermal surface conditions.

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