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REVIEW

Position and structure of the Subtropical/Azores Front region from combined Lagrangian and remote sensing (IR/altimeter/SeaWiFS) measurements

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The position and structure of the North Atlantic Subtropical Front is studied using Lagrangian flow tracks and remote sensing (AVHRR imagery: TOPEX/POSEIDON altimetry: SeaWiFS) in a broad region (~31° to ~36°N) of marked gradient of dynamic height (Azores Current) that extends from the Mid-Atlantic Ridge (MAR), near ~40°W, to the Eastern Boundary (~10°W). Drogued Argos buoy and ALACE tracks are superposed on infrared satellite images in the Subtropical Front region. Cold (cyclonic) structures, called '*Storms*', and warm (anticyclonic) structures of 100–300 km in size can be found on the south side of the Subtropical Front outcrop, which has a temperature contrast of about 1°C that can be followed for ~2500 km near 35°N. Warmer water adjacent to the outcrop is flowing eastward (Azores Current) but some warm water is returned westward about 300 km to the south (southern Counterflow). Estimates of horizontal diffusion in a *Storm* ($D = 2.2 \times 10^2\ m^2\ s^{-1}$) and in the Subtropical Front region near 200 m depth ($D_x = 1.3 \times 10^4\ m^2\ s^{-1}$, $D_y = 2.6 \times 10^3\ m^2\ s^{-1}$) are made from the Lagrangian tracks. Altimeter and *in situ* measurements show that *Storms* track westwards. *Storms* are separated by about 510 km and move westward at 2.7 km d^{-1}. Remote sensing reveals that some initial structures start evolving as far east as 23°W but are more organized near 29°W and therefore *Storms* are about 1 year old when they reach the MAR (having travelled a distance of 1000 km). Structure and seasonality in SeaWiFS data in the region is examined.

CONTENTS

1. INTRODUCTION

The deployment of 11 drogued buoys and five ALACE subsurface floats in a subtropical eddy called '*Storm 0*' has allowed us to follow the westward progress of this eddy from ~33°W to the Mid-Atlantic Ridge or MAR (~40°W) near 33°N over a period of ~300 days. Buoys leaving the eddy show the position of the Subtropical Front (STF) or Azores Current (AC). These Lagrangian observations can be used to interpret the sea surface structures observed by remote sensing. Earlier, Gould (1985) also tracked a single cyclonic eddy in the region for ~200 d using three drogued buoys. In Pingree & Sinha (1998), referred to subsequently as *PS*, it was shown using *in situ* direct measurements that *Storms* and associated anticyclones could exist as a *regular* train of eddies (~3 to 4 *Storms* when regularly formed) near 33°N, on the south side of the Subtropical Front. The eddies moved westward at 3 km/d with a mean separation of 520 km between successive low pressure regions in the west of the region (~27°W–40°W). Two *Storms* a year might pass a fixed point (e.g. Mooring 156) when regularly formed. It was also shown that these features were readily identified in altimeter data and that the surveyed *Storm*, called '*Storm 0*', had a sea level depression signature of 42 cm. Drogued buoy tracks were superposed on the altimeter sea surface elevation pattern to show alternate cyclonic and anticyclonic flow structure associated with low and high surface pressure cells near 33°N. The hydrographic structure showed the eddies to be deeply penetrating with typical isotherm (isopycnal) displacements of 200 m from near surface (~200 m) to the sea-floor (~3.8 km). The altimeter surface elevation pattern mapped or mirrored changes in the deep ocean structure which showed a 600 times magnification for the isotherm (isopycnal) displacements. Successive cyclonic eddies, *Storms 0*, *1* and *2* (referred to here as S_0, S_1 and S_2), were surveyed or measured by hydrography and each was associated with a marked sea surface altimeter signature. The major westward propagating structures observed by altimeter remote sensing near 33°N were therefore interpreted as eddies rather than *Rossby* waves, though the regularly spaced eddies clearly have wavelike properties (Pingree, 2000). The eddy energy in the Subtropical Front region seen by the altimeter will be dominated by variability near semi-annual and shorter periods.

Here, we study the Subtropical Front region using infrared satellite imagery (AVHRR) and altimeter data in a broad region (~31° to ~36°N) of marked gradient of dynamic height (Azores Current) that extends from the Mid-Atlantic Ridge (MAR), near ~40°W to the Eastern Boundary (~10°W). SeaWiFS data from January 1998 to February 1999 is appraised for structure and seasonality of surface chlorophyll *a* in the Subtropical Front region and for Storm signatures. No distinction is made between the Subtropical Front (STF) or the Azores Front either being considered as the redistribution of mass that results in a thermal wind or the eastward flowing Azores Current. We superpose Lagrangian tracks on infrared satellite images in the Subtropical Front region and show that the signatures of eddies, the Subtropical Front and associated structures (e.g. 400–500 km scale) can sometimes be observed in the infrared imagery. The sea surface temperature (SST) of the Subtropical Front and adjacent regions is derived over an annual cycle from buoy temperature sensors. The thermal imagery identifies the Subtropical Front over a zonal scale of ~3000 km and ~500 km wavelike structure is clearly evident on the outcrop of the STF. Although eddies are less conspicuous (and Lagrangian tracks or altimeter data are generally necessary to confirm interpretations), we have been able to present in addition to Subtropical Front structure, the

Table 1. *Number of days Argos buoy (with drogue depth in m) or ALACE float (at a mean pressure in dbar) remained in* Storm 0. *Rank (1) for buoy 25977 means that this was first buoy to leave the eddy.*

	Deployment year-day 1995	Drogue depth (m)	Days (rank) in *Storm 0*	Comment
Argos buoy no.				
3899	302	200	143 (10)	
5031	302	40	50 (2)	shallow drogue (base of the mixed layer)
5032	295	360	190 (12)	
25682	297	100	72 (4)	drogue loss
25683	297	100	88 (7)	
25684	295	100	134 (9)	
25685	292	100	73 (5)	deployed in region of maximum flow
25686	297	200	198 (13)	stopped transmitting for 157 days
25687	295	200	200 (14)	
25977	292	200	38 (1)	deployed in region of maximum flow
ALACE float no.		Pressure (dbar)		
25972	297	195	208 (15)	
25973	297	780	80 (6)	deepest Lagrangian measurement
25974	292	220	65 (3)	deployed in region of maximum flow
25975	297	475	110 (8)	
25976	302	760	176 (11)	
Argos buoy no.	Deployment year-day 1996	Drogue depth (m)		
1811	156	200	77	deployed from HMS 'Hecla' in June 1996

Table 2. *Summary of characteristics of the satellite data (date, overhead time, NOAA number, orbit and identification code at Dundee University) and Argos buoy and ALACE float (AL) data (with track period in year-days, identification code and depth (m) of the drogued buoys and mean pressure (dbar) for the ALACE) used in the Figures.*

Date	Time GMT	Satellite Data Number	Orbit	ID	Lagrangian Data Year-day 1995, 1996	Lagrangian Data Buoy (Drogue Depth, m) AL/ALACE (Pressure, dbar)
Figure 2 (continuation of Figure 10B)						
4.06.96	1434	NOAA-14	7367	1757/07		
Figure 5A						
8.12.95	1506	NOAA-14	4842	1663/10	336–349	25682 (100), 25683 (100), 25684 (100), 25685 (100), 25687 (200), 3899 (200), 5032 (360)
					320–365	25977 (200)
					336–11	5031 (40)
Figure 5B						
01.02.96	1514	NOAA-14	5618	1629/08	22–43	25682 (100), 25684 (100), 25687 (200), 3899 (200), 5032 (360)
Figure 6A						
09.03.96	1515	NOAA-14	6140	1711/09	58–79	25684 (100), 25687 (200), 3899 (200), 5032 (360)
Figure 6B						
05.04.96	1524	NOAA-14	6521	1726/07	86–107	25684 (100), 25687 (200), 5032 (360)
Figure 7						
25.10.92	1645	NOAA-11	21056	1226/11		
27.10.92	1620	NOAA-11	21084	1227/07		
Figure 10A						
01.02.96	1514	NOAA-14	5618	1692/08	365–50	25977 (200)
09.02.96	0351	NOAA-14	5724	1696/05	332-87	AL/25974 (215)
Figure 10B						
08.06.96	1533	NOAA-14	7424	1759/09	161–205	25686 (200)
09.06.96	0831	NOAA-12	26335	1759/1	132-183	25687 (200)
10.06.96	0810	NOAA-12	26349	1760/06	160-190	5030 (200)
					147-167	AL/25974 (190)
					140-172	AL/25975 (435)
					133-173	AL/25976 (750)
Figure 12						
04.02.97	0747	NOAA-12	29747	1899/06		
05.02.97	1510	NOAA-14	10838	1900/03		
10.02.97	0715	NOAA-12	29832	1902/14		
Figure 14						
22.11.96	0348	NOAA-14	9773	1853/03		
23.11.96	0338	NOAA-14	9787	1853/11		

thermal signatures of the initial structure of the next two *Storms* passing westward near 33°N, S_3 and S_4, in relation to the thermal Subtropical Front outcrop near 35°N and follow their westward progress using altimetry. The easterly thermal structures (i.e. S_4), seen in the infrared imagery, show that *Storms* can start forming, as plumes of cold water from the north, as far east as 23°W. The mean position and zonal extent of the Subtropical Front outcrop or Azores Current is not so readily derived from altimeter data (see Le Grand, 1998) since a reference state is removed to determine the sea level anomaly. However, the altimeter sea level anomalies identify individual eddies much more clearly and these are seen to be tracking westward in the warmer water south of the thermal STF outcrop (~35°N) identified in the infrared imagery. Some of these cyclonic eddies intensify as they travel westward near 33°N by merging with other eddies, others decay, elongate and split or are absorbed by other eddies or the AC and do not reach the MAR.

2. METHODS

In all, ten drogued Argos buoys and five ALACE floats tracked *Storm 0* for varying degrees of time (see Table 1) from the initial RRS 'Charles Darwin' survey position near 33°W in October 1995 to near the Mid-Atlantic Ridge (MAR). A further Argos buoy (1811) deployed, from HMS 'Hecla' continued tracking *Storm 0*, over the MAR, extending the *in situ* tracking period from October 1995 to August 1996 (~300 days). Lagrangian structures in the eddy and subsequently in the STF region are appraised in conjunction with remote sensing data. The satellite thermal infrared (IR) structure of the Subtropical Front region was examined using band 4 (11.5–12.5 μm) data from the Advanced Very High Resolution Radiometer (AVHRR) onboard the NOAA-12 and NOAA-14 satellites. The data were processed following standard AVHRR image analysis techniques (e.g. Holligan et al., 1989). The actual satellite data used are listed in Table 2 as a reference source as it has not been possible to show all features of interest with a single brightness contrast and relevant cloud free images have not be found with which to make a cloud free composite image. Because of this, it has been found necessary to draw the position of the thermal STF (or temperature contrast structures with cooler water to the north, appraised from the images listed in Table 2) on three of the figures for a clearer presentation of the STF position in relation to the distribution of subpolar and subtropical Mode Waters, the Lagrangian tracks in *Storm 0* and the oceanic tracks in the STF region. Tracks from 11 drogued Argos buoys and three ALACE floats (Davis et al., 1992) were superposed on the AVHRR imagery. Table 2 shows the track period (in year-days), the depth of the drogue for the ARGOS buoys and the mean pressure of the ALACE floats. The individual buoys and ALACEs are referenced by their identification numbers and these same numbers were used in related Lagrangian studies (e.g. Pingree et al., 1996). The droguing was careful (i.e. drogues had to stay attached for long periods, >1 year) and effective (Pingree, 1997). The drogue acceleration difference test of Pingree (1993) was applied to the data recorded for each of the 11 drogued Argos buoys to determine whether the drogue was still attached as drogue attachment sensors can be unreliable. The surface temperature sensors on the Argos buoys were calibrated on deployment against *in situ* sea surface temperature (SST) measurements. Temperature data were also used from buoys that lost their drogues in a few instances. Hydrographic data are taken from RRS 'Charles Darwin' CD66, CD83 and CD97 cruises in the region and a North Atlantic crossing near 33°N completed by HMS 'Hecla'. Cruise reports are listed in Pingree (1997). Altimeter data and products were received and used from AVISO (1996) and from the CLS website/ftpsite. Data processing procedures and displays for the latter are described in Le Traon et al. (1998).

3. OBSERVATIONS AND RESULTS

3.1. Background framework. Hydrographic structure of Subtropical Front and transport near 34°N

3.1.1. Mode Waters. The position of the Subtropical Front (STF) or Azores Current (AC) results (see New, 1997) from the production of a subtropical mode water (σ_o~26.45 kg m^{-3}, ~ Sargasso Sea Water properties) and a more northern mode water (σ_o~27.1 kg m^{-3}, ~Eastern North Atlantic Central Water (ENACW), Pollard et al., 1996). Remarkably, the maximum thickness for the winter Subtropical Mode Water (STMW) with $26.4<\sigma_o<26.6$ kg m^{-3} lies close to (and above) the region of minimum winter thickness for water in the $27.0<\sigma_o<27.2$ kg m^{-3} density band, near 55°W, 37°N (WOA94 data). The winter thickness of these two mode waters (Figure 1; Levitus, 1982) changes in the STF/AC region and this region (usually given as a subduction zone) was considered as a barrier to vented subduction from the north in Pingree et al. (1996) and Pingree (1997), with east-west flow near the subtropical boundary or recirculating flow rather than direct southward flow across the region. The maximum winter thickness of ENACW is near ~46°N 16°W (WOA94 data). The two mode waters lie alongside each other at the STF/AC boundary with the northern water at a depth near 500 m and the subtropical water, though partially modified by mixing, in the upper 200 m (see for example, Rios et al., 1992).

3.1.2. Dynamic height gradient. The distribution of Mode Waters (Figure 1) results in a region of marked gradient of dynamic height (a scalar, derived from both north and east components) at the sea surface (relative to 2000 dbar) that extends from the Mid-Atlantic Ridge (MAR) ~40°W to east of Madeira (~15°W) near a latitude of 34°N and identifies the mean position of the Subtropical Front (Figure 2; Levitus, 1982). The maximum dynamic height gradient relates to the maximum surface geostrophic current or surface AC. For simplicity, we have converted dynamic height into water height or sea surface height so that the dynamic height gradient is expressed as its equivalent sea surface slope without dimensions. Using the higher resolution WOA94 data (and the average of four seasons) increases the gradient values by about 40% in the region of maximum values near 34°N with maximum values just $>35\times10^{-8}$ near 32°W. Although the axis of the maximum dynamic height gradient is near zonal or aligned east/west, the dynamic height contours themselves slope at about 15° to a fixed latitude (~34°N), with the 1.70 dyn m contour passing near 30°W and 1.60 dyn m contour near 15°W. Satellite (AVHRR) infrared images are appraised for the position of Subtropical Front and structure in this region of maximum sea surface slope. The dynamic height gradient (using WOA94 historical data base, see for example, Levitus & Boyer (1994)) although marked shows little clear variation in position or intensity seasonally (Le Traon & De Mey, 1994).

3.1.3. Transport. Transport values (using WOA94 data) at a mid position (~30.5°W) for a meridional section across the Azores Current from 30.5°N–36.5°N were 7.1 Sv (reference level 1000 dbar and using the mean of the seasonal values) and 10.0 Sv (2000 dbar reference level; dynamic height difference 16 dyn cm). These values are comparable but rather smaller (5.5 Sv to 800 dbar) than previous values (e.g. ~8 Sv to 800 m, Klein & Siedler, 1989). At 24.5°W, the values were 5.1 Sv (reference level 800 dbar) and 11.0 Sv (reference level 2000 dbar); at 20.5°W, the values were 4.0 Sv (reference level 800 dbar) and 6.7 Sv (reference level 2000 dbar; dynamic height difference 12 dyn cm). The values become smaller in the east as the flow is turned south. The instantaneous Azores Current can have a significant transport (~26 Sv, Pingree, 1997; 16–18 Sv, Tychensky et al., 1998) in this region but the total transport across the region may be much reduced by the adjacent Counterflows that may be

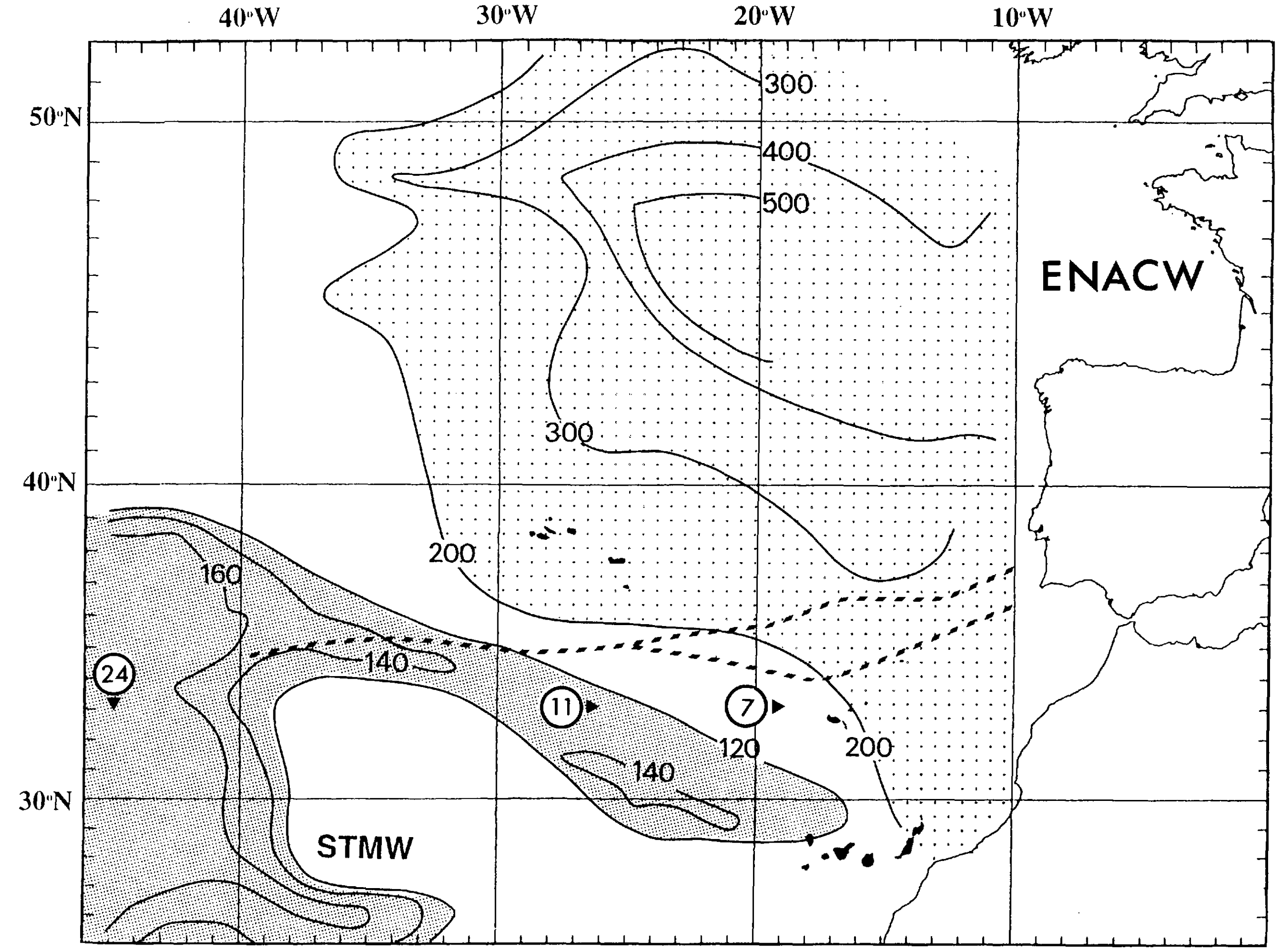

Figure 1. Winter thickness (m) of Eastern North Atlantic Central Water (ENACW) Mode Water with $27.0<\sigma_o<27.2$ kg m^{-3}, with maximum winter thickness near ~46°N 16°W (WOA94 data) and Subtropical Mode Water (STMW) with $26.4<\sigma_o<26.6$ kg m^{-3} (which contains Sargasso Sea Water (~18°C) with σ_o~26.45 kg m^{-3}). The STMW has a maximum winter thickness (240 m) in the Western Basin at ~36°N 52°W, near the position of minimum thickness (80 m) of water with $27.0<\sigma_o<27.2$ kg m^{-3}, located near 37°N, 55°W. The dashed lines represent mean positions of the Subtropical Front derived from the infrared imagery (see text for details). Ringed values are transport (in Sv, reference level 2000 dbar) associated with the STF (see text for details).

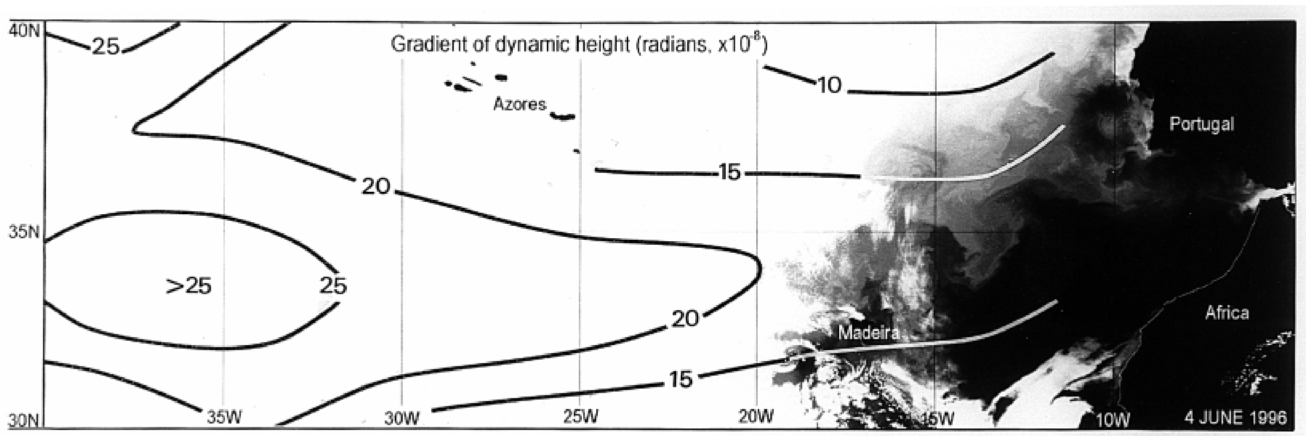

Figure 2. Distribution of gradient of dynamic height (expressed as equivalent sea surface slope$\times10^{-8}$; mean annual value relative to 2000 dbar) in the Eastern Basin of the North Atlantic. The satellite (AVHRR) infrared image of 4.6.96 is superposed in the east. Temperature calibrations (see Figure 8) give a change of about 1°C (the cooler being near 18.4°C) across the STF near 35°N, 14°W. Further June images covering the full region are illustrated in Figure 10b. The completely white features are clouds; dark regions show warm water. The sea level anomaly of the cyclonic structure near 14°W 35°N in the frontal region is evident in Figure 16.

present. No clear evidence was found for westward counterflows in the seasonal historical data (WOA94) at these sections (cf. Käse & Krauss, 1996, their figure 10.21a) but high-resolution ocean circulation models that resolve the AC show some evidence for the presence of adjacent counterflows (New et al., 2000). Neither was there clear evidence for the AC branches (see for example, Siedler & Onken (1996), their figure 11.6) based on annual averaged data. Buoy tracks do, however, tend to show a branch to the south near 20°W but this may be the eastward extension of the AC itself turning to the south.

For an overall baseline reference of the transport for the Azores Current or STF for the future monitoring of climate change we use the carefully calibrated CTD data from HMS 'Hecla'. With a reference level of 3000 dbar, the transport between CTD 7018 at 50.0°W, 32.5°N (1.6.96) and CTD 7025 at 20.0°W, 35.5°N (6.6.96) was 28 Sv. Transport values between CTDs were corrected for eddy transports by making a transport correction based on the altimeter sea level anomaly difference between stations (see *PS*). It turned out that the sea level anomaly difference between CTD 7018 and CTD 7025 was less than 2 cm and the correction in this case was less than 2 Sv. With a 2000 dbar reference level, the transport was 24 Sv and the dynamic height difference was 41 dyn cm. The transport values given (with a reference level of 2000 dbar) for the STF region are summarized in Figure 1.

3.1.4. Surface temperature. This study of the Subtropical Front and associated structure has focused on infrared images with structure in the region of maximum dynamic height gradient or just to the north since a near zonal region of mean maximum temperature contrast at a fixed latitude is not defined. For example, maps of mean sea surface (~50 m) temperature do not show an increased temperature gradient between 30°–40°N, even for the winter (March) period but at 200 m depth a temperature front near 33.5°N (20–30°W, with mean temperature 15.9°C) is evident. Seatruth can show a winter surface temperature contrast (17–18°C) in the region of interest near 34°–35°N (Fernández & Pingree, 1996). Single images show increased temperature contrasts, but over a wide range of latitudes (see monthly summary of thermal months for the period 1980–1988 in SATMER (1983 to 1988). The image of 10 March 1984 (SATMER, 1984; Kielmann & Käse, 1987) suggests a maximum temperature contrast near 38°–39°N (in the region east of the Azores) with further warm and cold features of interest between 35°–37°N. Some mean temperature gradients in the region based on sea surface temperature satellite data are given by Hernández-Guerra & Nykjaer (1997). A reference atlas of monthly (from May 1993 to April 1996) mean sea surface temperature of the north-east Atlantic derived from infrared remote sensing (AVHRR) has been given by Oliveira et al. (1996). The Subtropical Front studied here (near 34°N, or region of maximum dynamic height gradient) has a winter (March) temperature of ~18°C towards the west (~30°W) of the region and is ~17°C in the east (~10°W); the winter (March) salinity is near 36.5–36.7 psu. Cruise data shows that the σ_t=26.5 isopycnal in the Subtropical Front (STF) is fresh on the north side of the Azores Current and salty on the south side; the mean temperature on a central streamline of the Azores Current (AC) on this isopycnal is close to 17.4°C.

The mean surface position of the thermal STF based on the three infrared images studied here is drawn on Figure 1. A further line (overlapping in the west) but to the north in the east shows a mean position based on three images in March (1984, 1992, 1997). The overall position for the remote sensing sea surface thermal boundary lies close to the region of maximum gradient of dynamic height showing that the position and structure of the infrared frontal region examined in this paper relates to the dynamic STF boundary or AC. In fact, the mean frontal position based on the selected images lies just to the north of 34°N, reflecting the surface outcrop of the Subtropical Front structure in the region. The dynamic height gradient is an integrated property and so also reflects the inclination of the structure or outcrop at depth. Thus the maximum dynamic height gradient will lie to the south of the STF outcrop. Since the AC is typically about 100 km wide, cyclonic eddies travelling west near 33°N will be moving through surface water of subtropical origin.

3.2. Eddy structure

3.2.1. Storm 0 structure. The eddy, *Storm 0*, was characterized as a near-surface cold-core anomaly (Pingree et al., 1996) but there was no clear sea surface temperature anomaly in October 1995 when the initial hydrographic survey (RRS 'Charles Darwin' Cruise, CD97) was undertaken near 32.5°N 33°W. The initial shape of the eddy from the buoy data was elliptical with a central ratio of minor to major axes of ~0.7. The central orbits were cyclonic with period ~13 days. The ellipse itself also rotated cyclonically at a rate of ~1° per day. Of the ten Argos buoys and five ALACE deployed initially in October, two buoys (buoy 25687 drogued at 200 m depth and buoy 5032 drogued at 360 m depth) gave continuous tracks and two ALACE (ALACE 25972 (195 dbar) and ALACE 25976 (760 dbar)) gave positions within the eddy until 5 April (i.e. remained with the eddy for more than 160 days). The fact that ALACE 25976 at a mean pressure of ~760 dbar (mean temperature ~9.3°C) moved westward in the eddy shows that the structure penetrates to depth. Indeed, the 9.3°C isotherm is found at a mean pressure (depth) of ~960 dbar (950 m) in the region (*PS*, HMS 'Hecla' data) so the ALACE float was in a cold anomaly where the isotherms were raised by about 200 m. Over the same period, the mean temperature of ALACE 25972, at the shallower level (~195 dbar), was 15.2°C. This isotherm was at a mean pressure of 430 dbar so the shallower float also moved in a region where the isotherms were raised by a similar amount ~230 m. Buoys 25687 and 5032 travelled with the eddy for ~200 d and 190 d respectively moving ~500 km westwards near a latitude of ~32.5°N at a mean speed of ~2.5 km d^{-1}. ALACE 25972 also remained in the eddy for 200 days. The drogued buoy tracks in the eddy showing the general coverage of data in the region are summarized in Figure 3. The initial rotation of the elliptical structure is clearly evident in the position data. The magnitude of the associated Lagrangian velocities (with components u-east, v-north) is obtained by plotting

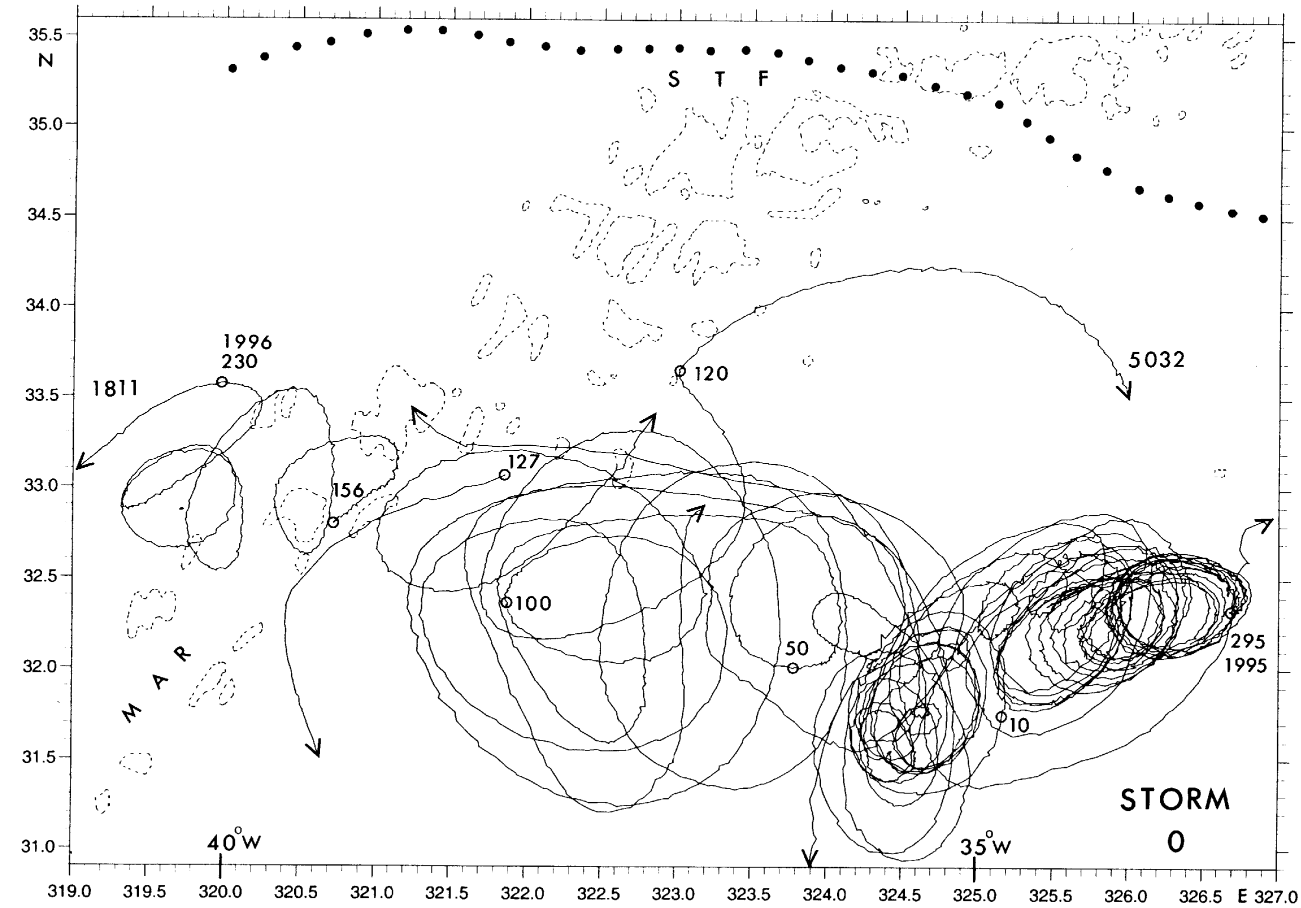

Figure 3. Tracks (raw data) of eight buoys deployed in the central region of *Storm 0* in October 1995 and further track of buoy 1811 (labelled) deployed from HMS 'Hecla' in June 1996 (year-day 156). The tracks extend from year-day 295 (1995) to year-day 233 (1996). Some annotated year-days (marked with circles) are given. Overall, the tracks cover 303 days and extend over a distance of 700 km. Tracks leaving the eddy are shown with an arrow. One track (buoy 5032, labelled) is extended for a further 15 days to show the position of the south part of the eastward Azores Current near year-days 120–135 (1996). The STF (dotted) is an approximate averaged position for the Subtropical Front based on contrast structures seen in infrared images covering the period December 1995 to June 1996 (see Table 2). The MAR is depicted by 2000 m depth contour.

all the buoy velocities in the u–v plane (Figure 4). The distribution of swirl velocity against radius is given in *PS* (their figure 7). The orbital velocities increase from near zero in the eddy centre to about 40 cm s^{-1} at a radius of about 80 km but some maximum speeds reach ~70 cm s^{-1}. For the near central region, consecutive 15 day plots in the velocity plane (not shown) confirmed a mean rotation of structure of one degree a day.

3.2.2. Warm and cold eddy structures. The movement of the Argos buoys in the eddy with respect to the thermal imagery is shown in Figures 5 & 6 for the period from December (1995) to April (1996). The Figures show most of the available (cloud free) satellite imagery during the 200 day period the Argos buoys were tracking the eddy. The temperature sensors on the buoys showed that the subtropical water to the south tends to be ~0.7°C warmer than the eddy surface temperature (see later section 3.3.). If this warmer water is drawn around or alongside the eddy, then exterior structure may be highlighted.

In early December 1995, the Subtropical Front is near 36°N in the west and near 34°N in the east passing 35°N at a longitude of 35°W (Figure 5A). The surface expression of the subtropical eddy (*Storm 0*, or S_0) is an elliptical cool patch with a slightly warmer central region (~35°W) near the innermost buoys which are moving cyclonically. Buoys leaving this region reach the Subtropical Front (Azores Current) near 34°N but then tend to move clockwise around the warm water region (W) which is an anticyclonic region of negative vorticity (track of buoy 5031) separating *Storm 0* from *Storm 1* (developing near 29°W, altimeter data). Seven out of the ten drogued buoys deployed in the eddy left the eddy to the north or north-east and then moved eastward in the warm STF/AC flow or were turned anticyclonically in a warm water cell. This implies that some eastward flowing AC water passes south around the cyclonic eddy and that the exterior region of the eddy is within the influence of the STF or eastward moving water.

At the start of February 1996, the eddy signature is a cool region and the centre estimated from the drogued buoy tracks has moved to 35.5°W (Figure 5B). A warm water region (W) is still evident to the east of the cyclonic eddy. The Subtropical Front itself has developed a pattern of

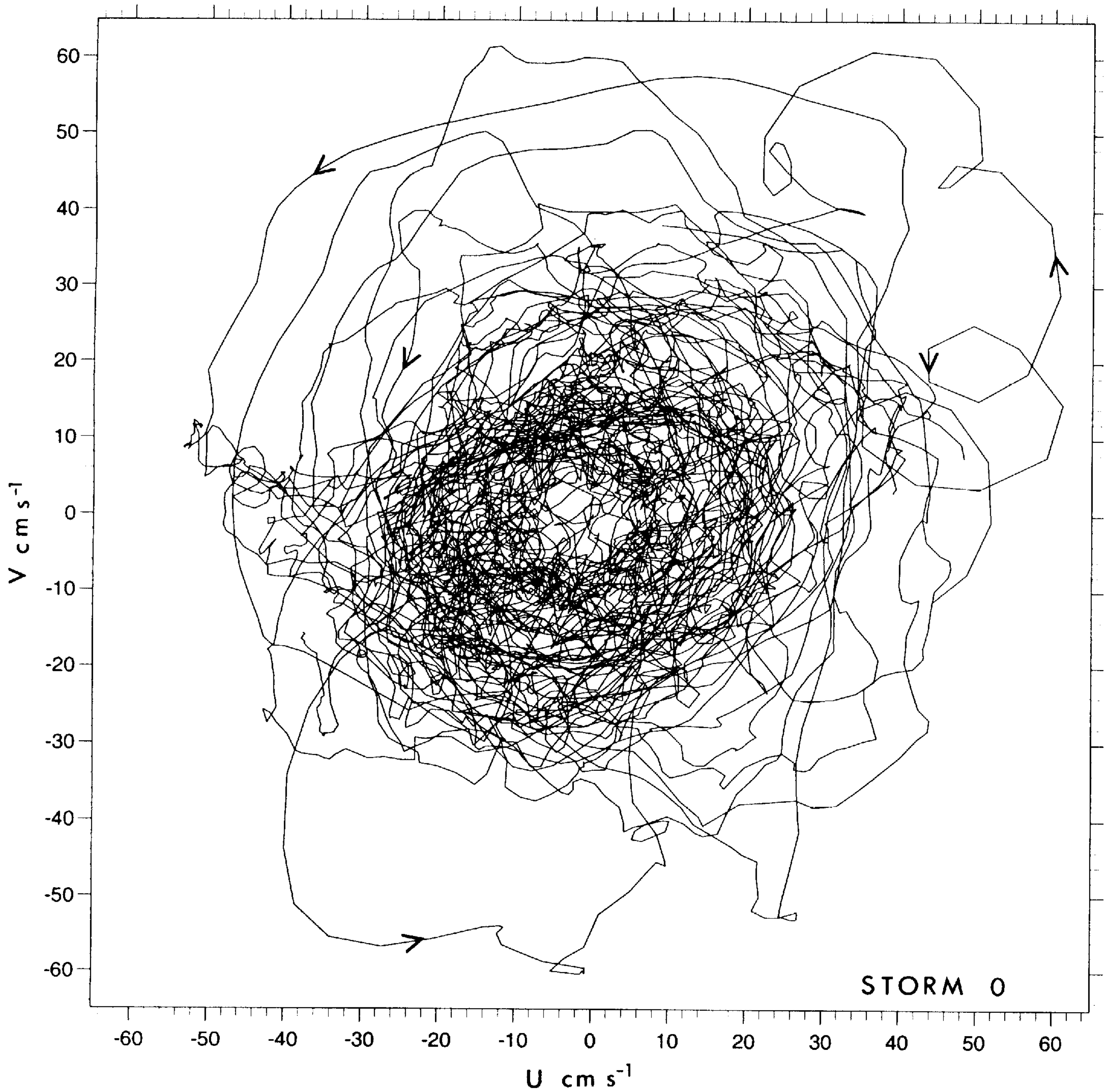

Figure 4. East and north components of velocity (derived from 12 h averaging of position data) of all buoys in *Storm 0* (representing 2.9 buoy-years of eddy velocity data). The apparent centre is displaced as buoys are moving westward with the eddy. Eddy rotation sense is clockwise and clockwise inertial motion is also evident.

alternate warm (W) and cold structures (C) near 34°–35°N and the inferred sense of surface water movement is indicated with curved broken arrows. The cool patch or cell protruding south from the STF near 34°W tends to merge with the cooler regions of the sea surface temperature of *Storm 0*, and this association with the STF can be a characteristic *Storm* signature. Altimeter structures show that *Storms* can split and an elongation of the structure to the north-east followed by a major splitting occurred in January 1996, though no drogued buoys were drawn into the associated cold water cell (or the altimeter low pressure cell) that was found near 34°W (34.5°N).

By early March 1996, the eddy has moved to 37°W and the buoy tracks define an inner cool water region (Figure 6A). Buoy 25684 leaves the eddy in a warmer water band. This buoy moves to a warm water region (W) where the track or flow curves anticyclonically. The Subtropical Front appears as a cooler boundary to the north near 35.5°N in the west.

By early April, *Storm 0* is against the eastern side of the MAR near 37.5°W (Figure 6B) without an apparent sea surface signature. A warm anticyclonic region (W) occurs in the north-east (buoy 5032 went clockwise around this region subsequently, see Figure 3 and later Figure 11). The Subtropical Front is evident near 35°N and buoy 25684 (now undrogued) moves eastward across the MAR in this cooler region giving a winter minimum sea surface temperature of 16.6°C for the cool side of the Subtropical Front. By the end of April/beginning of May, *Storm 0* is on the MAR near 38.5°W and the next *Storm*, *Storm 1*, has

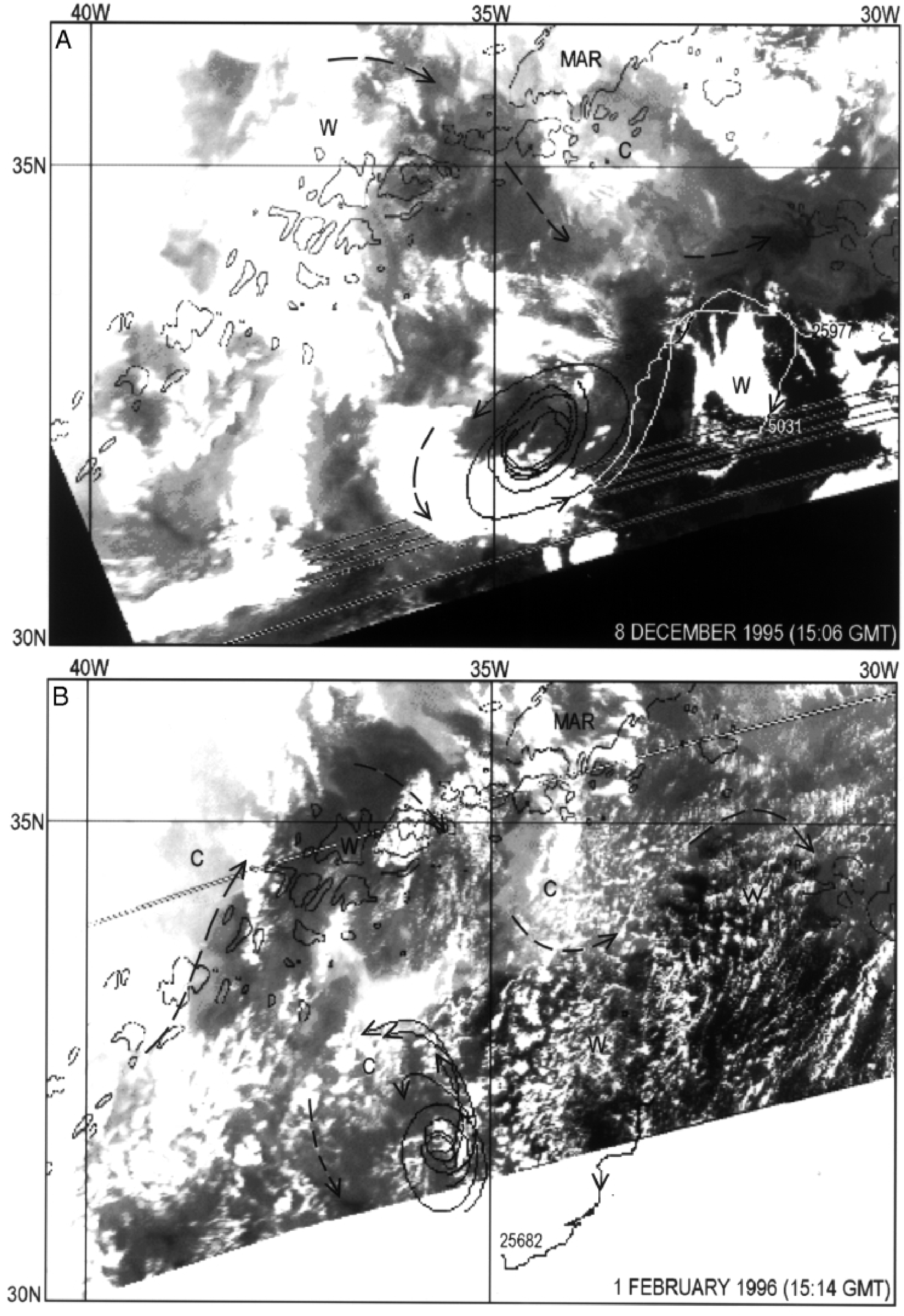

Figure 5. Combined Lagrangian and satellite infrared observations of the subtropical cyclonic eddy (*Storm 0*). (A) 8 December 1995. (B) 1 February 1996. The duration of the tracks, the identification code and depth of the drogue for the buoys are given in Table 2. Dashed arrows show known rotation sense for *Storm 0* and suggested flow based on temperature contrast structures, generally with cool water to the left of the direction of flow. 2000 m contour identifies the position of the MAR.

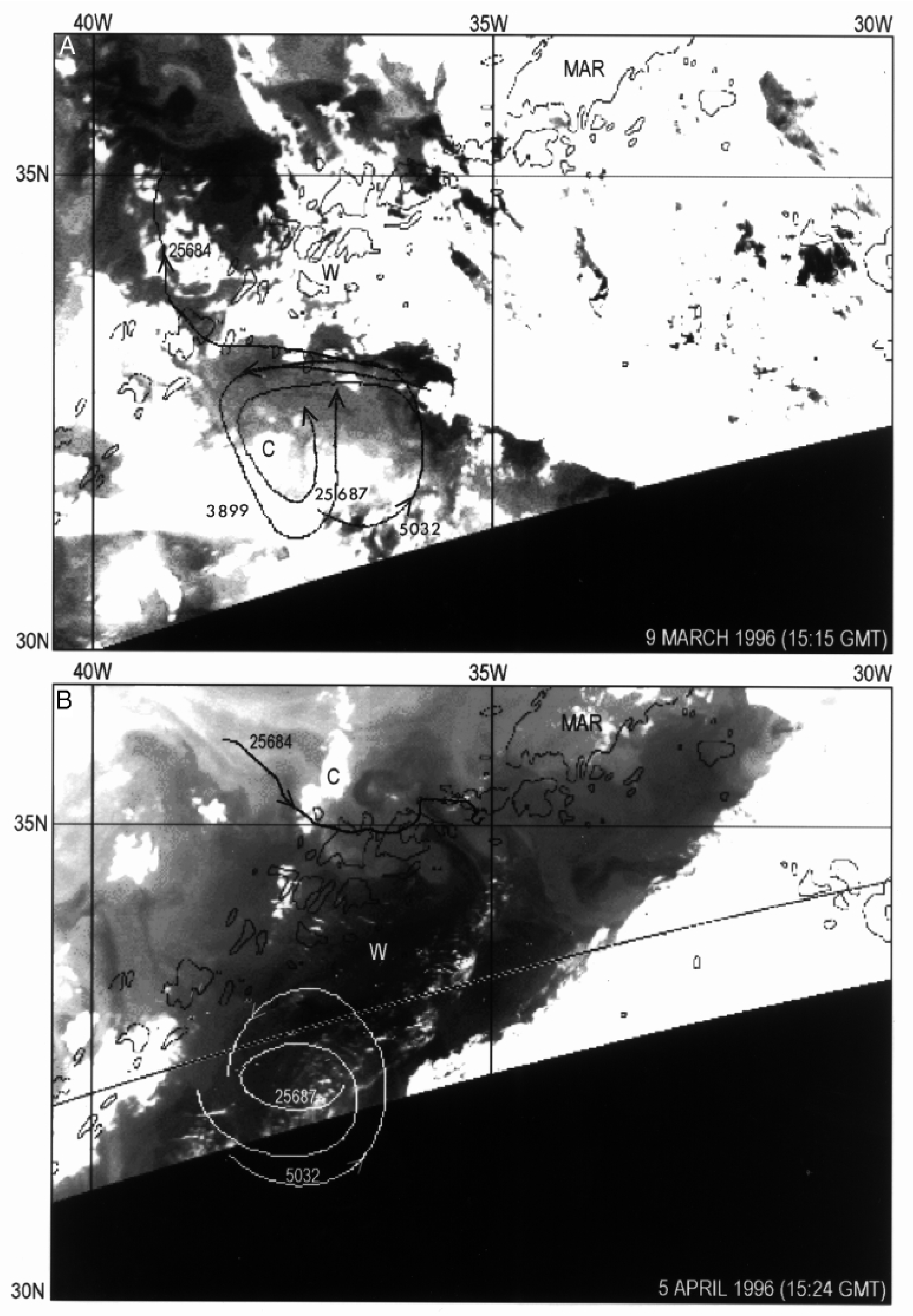

Figure 6. Combined Lagrangian and satellite infrared observations of the subtropical cyclonic eddy (*Storm 0*). (A) 9 March 1996. (B) 5 April 1996.

now reached the original CD97 October survey region with centre at 33°W (near Mooring 156). Later (6 June 1996), a North Atlantic section near 32.5°N by HMS 'Hecla' showed the centre of *Storm 1* near 33.7°W.

Storms, cyclonic eddies or their initial perturbations, are often first clearly apparent near 25°W (altimeter data). They generally develop in intensity as they move west near 33°N. Some reach the MAR, some decay, others appear to elongate and split and may be partially reabsorbed back into the AC. Generally, *Storms* do not have a clear SST signature but over simplifying and idealizing, four surface temperature signatures may indicate the presence of a *Storm*. (i) a cool oval region ~100–200 km scale may be present. An example is shown in Figure 7. Although this eddy might be about eight months old in October 1992 (based on its longitude, 32.6°W, with initial development stages near 25°W), it appeared to diminish in intensity in January 1993 and merge with other eddies or the AC in February 1993 near the MAR. The structure was about 100 km to the north of *Storm 0* near the same longitude (~ in October 1995) and was therefore perhaps less resolved from the AC. Further signatures are (ii) a 'doughnut' structure with warm centre surrounded by cooler region with a ~300 km external scale (Figure 5A); (iii) a cooler centre surrounded by a streak of warmer water at a ~200 km scale (Figure 6A); and (iv) as in (i) but 'sock-like' with cool region linked to the Subtropical Front (see later Figure 12). Structures like (i) are believed to reflect the upward displacement of the interior isotherm structure, whereas (iv) results from the movement or advection of surface water. Any of these structures may indicate the presence of the cyclonic eddy. Adjacent warm water regions of similar scale (~300 km) tend to be anticyclonic, particularly if to the north and partially surrounded by cold water features. Further eddy or meander structures exist on the Subtropical Front and these temperature features are also propagating westward (see Halliwell & Cornillon, 1989; Cipollini et al., 1997). The temperature structure giving the position of the Subtropical Front is examined in section 3.5. using individual satellite infrared images, but in conjunction with seatruth (Lagrangian tracks and *in situ* sea surface temperature measurements), which differentiates this work from other infrared remote sensing studies of the region.

3.3. Seasonal cycles of sea surface temperature in the subtropical region

Since the Argos buoys are each transmitting ~10 calibrated surface (~0.5 m depth) temperature measurements a day, seasonal temperature cycles are derived from *in situ* data rather than from remote sensing. Relevant calibrated temperatures for the infrared images presented are given in Figure 8A. The temperature contrast in the region is typically about 2°C from 31°N to 35°N with an '18°C Water' minimum in the Subtropical region in winter and a maximum summer temperature of ~26°C. The temperature sensors on the buoys showed that the subtropical water to the south tends to be only ~0.7°C warmer than the eddy surface temperature and so the eddy is unlikely to show a marked advective temperature signature. Any initial temperature contrast appears to be quickly lost. Although we do not envisage the formation process to be the same as Gulf Steam Rings, it is well known that cold core rings quickly lose their initial temperature contrast (Dewar, 1986). The surface temperature of the eddy cycles seasonally much the same as the other selected temperature characteristics (Figure 8A) so it would be quite wrong to suggest that the temperature of the eddy can be used to estimate the time of its formation.

The Subtropical Front itself tends to have about a 1°C temperature contrast. As a reference temperature for the Subtropical Front, we present an annual cycle derived from temperature sensors on two drogued buoys in the region. One (3916) remained drogued in the Azores Current for ~1 year; the other (3909) recirculated in the Azores Current and northern Counterflow for 606 days. The mean seasonal cycle (Figure 8B) is therefore a climate reference (for global change for example) for near the middle to northern side of the Azores Current or middle to cool side of the Subtropical Front, with the observations (1992/1993) centred near 20°W. The winter minimum, ~17°C, is cooler (~1°C) than the Subtropical Water minimum temperature showing that the STF/AC is the northern boundary for 18°C Water. The mean temperature is ~20°C (cf. Hernández-Guerra & Nykjaer, 1997) and the temperature range is 6.5°C.

3.4. Diffusion in Storms

Over a period of ~200 d, buoy and float tracks have spread over 1500 km in an east/west direction due to westward travel in the eddy and southern counterflow and relatively rapid eastward travel in the Azores Current. North/south spreading was about a half or a third. Diffusion in the eddy itself is considerably smaller and an estimate can be made from the rate of loss of buoys and floats (or particles) from the eddy (Table 1).

The loss against time of 15 particles deployed in *Storm 0* within a few days of each other is illustrated in Figure 9. From a practical point of view, it shows that for 15 particles deployed between 40 and 770 m depth only four remained in the eddy after 180 days. From a planning point of view, it would be necessary to deploy at least four buoys (carefully and effectively drogued) or floats to track the position of such an eddy for half a year. The gradient of the loss curve increases with time near 200 d so it will be difficult to track such an eddy for say 250 days. A further deployment near the eddy centre, as was attempted from HMS 'Hecla', is necessary to extend the tracking period (see Figure 3; Table 1).

For estimates of diffusion, we take the loss curve drawn through the larger dots. The smaller dots labelled 1 to 6 which are the first six particles to leave the eddy are not taken into account for the reasons given in Table 1. The mean radius, r, at which buoys cease to orbit the eddy centre was estimated at 97 km (not significantly different from 100 km). Account was taken for the fact the eddy and orbits were often elliptical by averaging semi-major (a) and semi-minor (b) axes; b/a was typically 0.8 in the outer region of the eddy. Three particles (labelled 1, 3, 5, Table 1) were deployed in the region of maximum azimuthal flow (near 95 km radius) so these particles were already nearly out of the eddy (though there is some probability that they

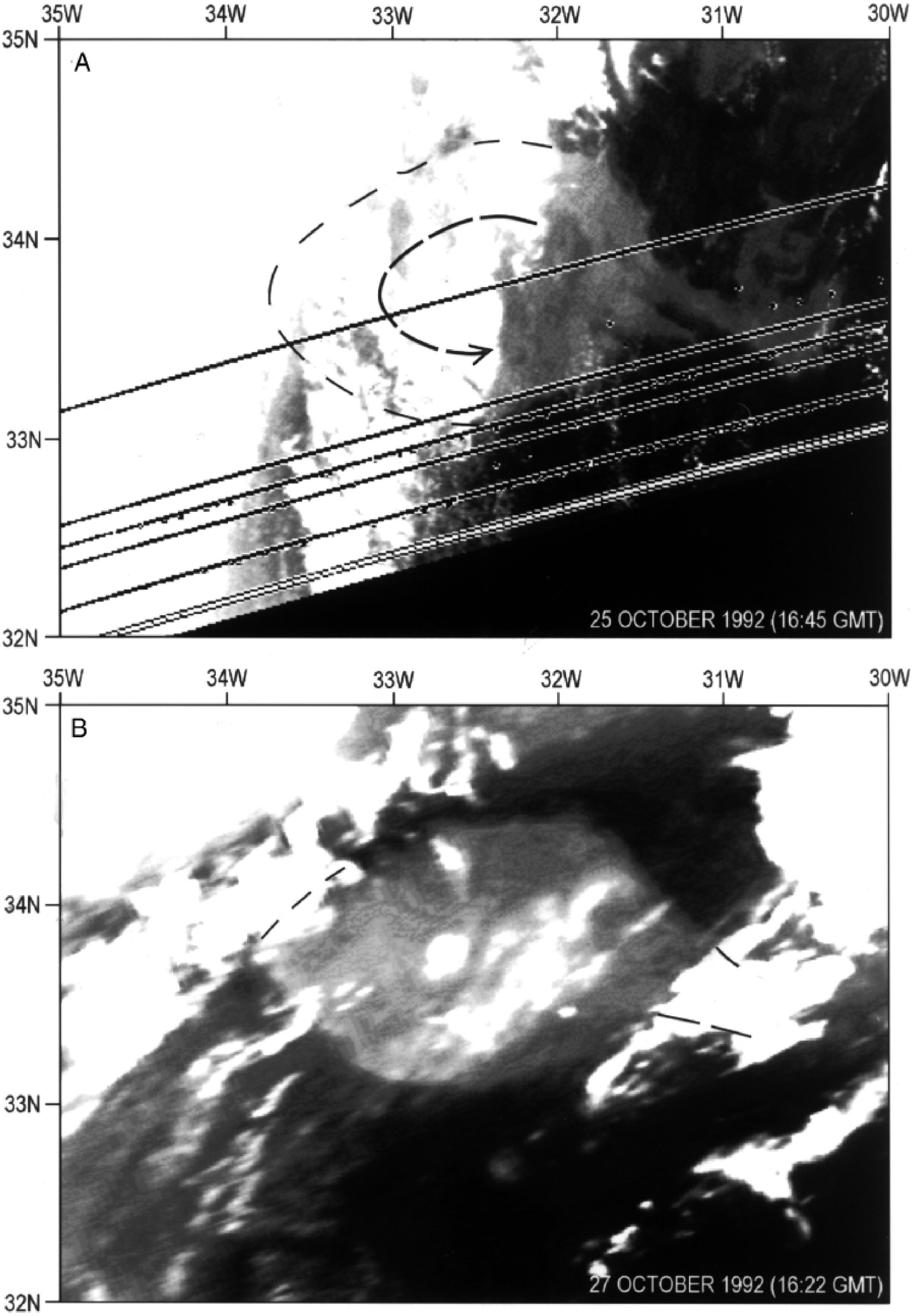

Figure 7. Infrared signature (image contrast enhanced) of a cyclonic eddy (broken arrow indicating rotation) showing cool oval region with major axis of ~200 km (A) 25.10.92 and (B) 27.10.92. Dashed lines show contrast features from the image not obscured by cloud.

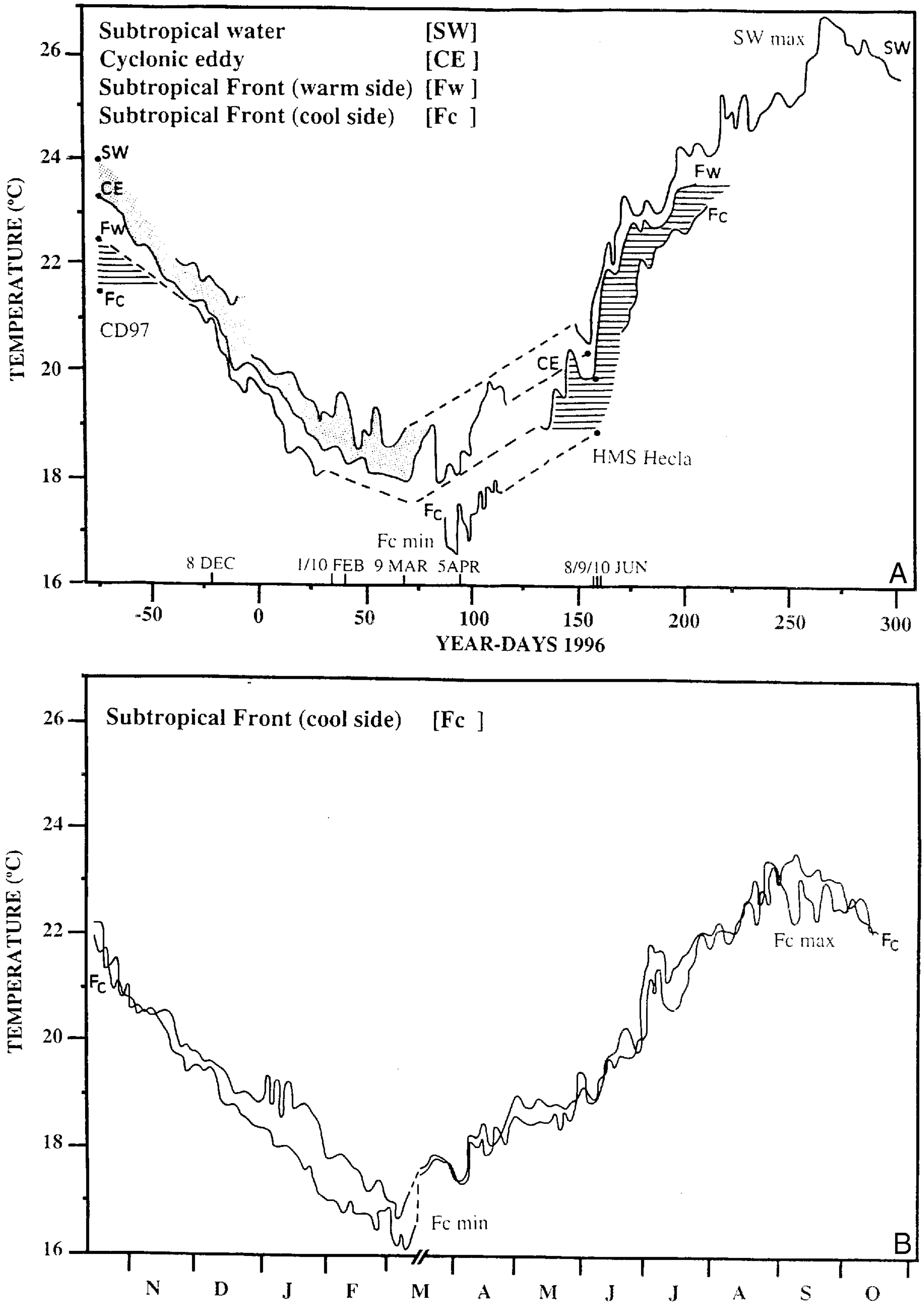

Figure 8. (A) *In situ* surface temperature from the calibrated temperature sensors on the buoys and from cruise data. The lines represent the cool (Fc) and warm (Fw) side of the Subtropical Front (~34–35°N), the Subtropical Water to the south (SW; ~30–31°N) and in the region of the cyclonic eddy (CE; ~31–33°N). The values were taken between 25–40°W. Discrete values in mid October and early June are taken from CD97 and HMS 'Hecla' sea surface data. The region shaded with dots highlights the potential contrast of the surface cool signature of the cyclonic eddy *Storm 0* (CE) with respect to warmer subtropical waters (SW); the region shaded with lines highlights the temperature difference across the Subtropical Front (Fw–Fc). Dates of infrared images with Lagrangian tracks are marked and the corresponding temperature values can be used to calibrate the relative thermal contrast of the images. (B) Annual cycle of temperature in the Subtropical Front region (from CD66 drogued buoy deployments; see text for details).

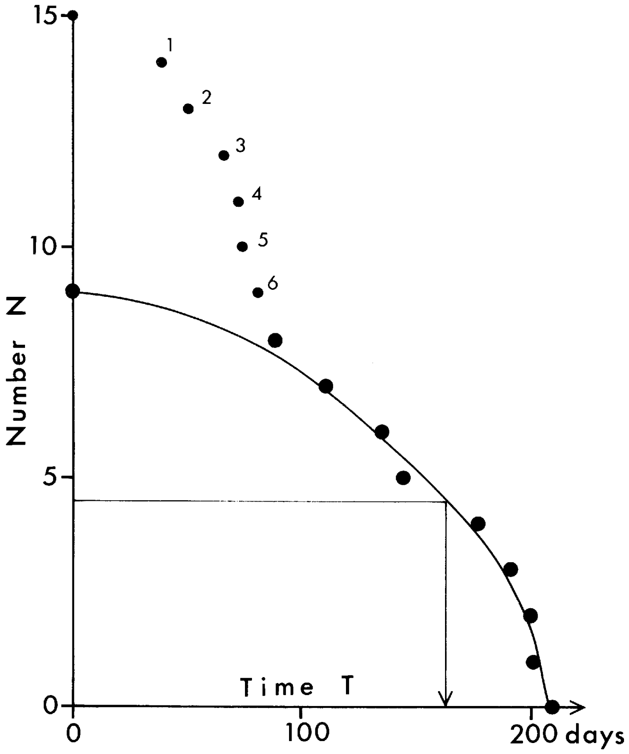

Figure 9. Attrition diagram or loss of particles (buoys and floats) from *Storm 0* (see text for details). N is the *number* of particles orbiting the eddy centre against *time* T in days.

may diffuse inwards) and are not included in the diffusion estimate. It is remarkable that particles do not remain in the eddy beyond a radius of ~100 km where the azimuthal currents are still in excess of the westward eddy speed (see Flierl, 1981). Perhaps diffusion increases markedly to oceanic values in this outer region or perhaps particles are removed by the eastward flow or AC.

Buoys with shallow drogues or buoys suffering drogue loss were not retained or strongly trapped by the eddy so points labelled 2 and 4 are discarded. This is consistent with a mixed layer with little temperature signature with respect to the surrounding water. Trapping will not occur at depth where the azimuthal currents are reduced. ALACE 25973 (point 6, 780 dbar) is not included in the loss curve of bolder points so that the results are more representative of shallower conditions. The remaining nine particles had initial orbits with a mean radius r=33 km. Hence for the depth range, d, where $100\,\text{m} < d < 750\,\text{m}$, with mean depth ~230 m, the mean increase in radius from 33 km to 100 km with time is ~430 m a day. We do not know if the rate depends on radius or even whether there is a radial component to the eddy flow. The drogued buoy in *Meddy Pinball* looped into the centre of the meddy after 16 orbits in the core (Pingree, 1995). The radial rate derived from the present study, although small compared with oceanic spreading, is considerably larger than the values found for the cores of anticyclonic Bay of Biscay eddies or Swoddies, which showed typical radial speeds of ~100 m a day (Pingree, 1994). These estimates were made within ~20 km of the eddy centre. The maximum azimuthal currents in these smaller anticyclonic eddies occur at a radius of about 30 km.

Now assume that the diffusion or radial spreading up to the radius of maximum swirl flow and just beyond with r~100 km can be parameterized by an apparent horizontal diffusion coefficient (or a Fickian diffusion coefficient if constant with time) D. Then, for a point release, the bounding radius containing half the particles after time, t, is given as

$$r^2 = 0.69 \times (4Dt) \quad (1)$$

Reference to Figure 9 shows that 4.5 particles are within r=100 km (or half are still retained by the eddy) at t=160 days, giving $D=2.6\times10^2\,\text{m}^2\,\text{s}^{-1}$, about 100 times larger than derived for Biscay Swoddy cores (Pingree & Le Cann, 1992). A small correction for the finite size (r~33 km) of the initial release can be estimated. For constant diffusion, the probable radius, r_p, or radius with maximum number of particles is given as

$$r_p = (2Dt)^{1/2} \quad (2)$$

Hence with $D=2.2\times10^2\,\text{m}^2\,\text{s}^{-1}$, it will take about 29 days for the maximum concentration of particle to move from the centre to a radius of 33 km and this value of D is consistent with (1) with $r = 100$ km if t is increased to t=189 days. The overall diffusion values are little changed (~10% increased, and not considered significant) if ALACE 25976 (at 760 dbar) ranked 11 is removed from the loss plot and buoy 5031 (drogue at 40 m), ranked 2, is included in the loss plot so that conditions now represent the upper ~500 m of the water column.

We now imagine that the eddy is uniformly covered with many particles and following Carslaw & Jaeger (1959) estimate the time, $t_{1/2}$, for the central concentration to fall to half its original concentration from

$$t_{1/2} = 0.2 \times r^2/D \quad (3)$$

The value, $t_{1/2}$ ~100 days, appears rather small in view of the fact that individual eddies can be followed for several hundred days (see later section 3.8.2.). Effective decay rates are likely to be faster as energy can be lost by elongation and splitting. We may have overestimated diffusion since buoys and floats are not true Lagrangian particles, representing conditions at a fixed depth (buoys) or related to a fixed pressure (subsurface floats) rather than at a fixed temperature or density. Alternatively, the estimate is realistic and the apparent long lifetime of some eddies results from merging with other nearby eddies or a wavelike transfer of energy between regularly spaced eddies with a clear wavelength or energy from wavelike meanders or eddies associated with the adjacent eastward Azores Current.

3.5. Subtropical Front position and structure

The winter 1996 (composite image of 1 and 9 February, Figure 10A) extends Figure 5B to the east (~20°W) showing further cold cells (C) or southern meanders of the Subtropical Front near 30°W and 24.5°W. The pattern extends from 25°W to 40°W and has a wavelength of 450 km. Buoy 25977 (drogued at 200 m depth;

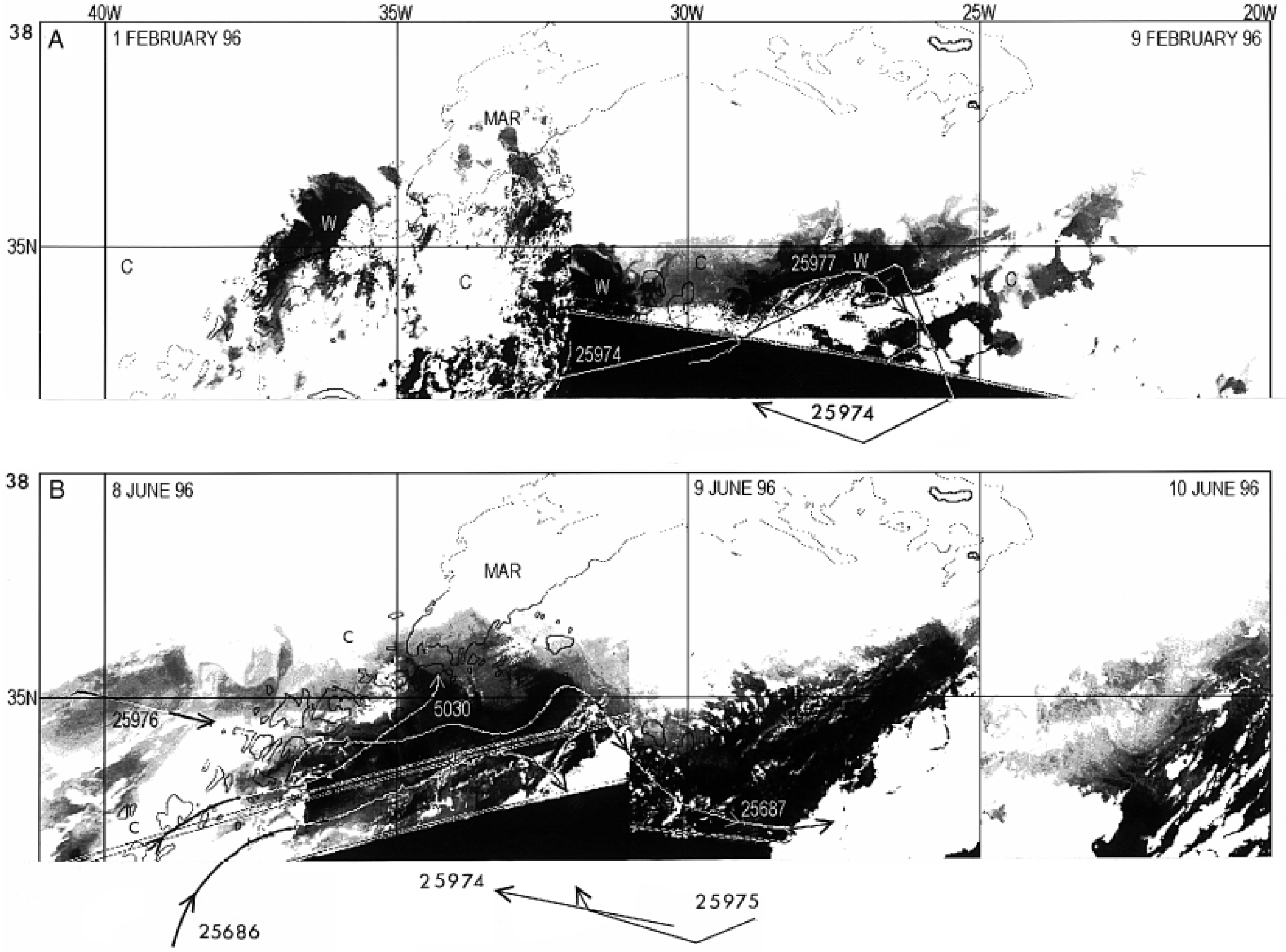

Figure 10. Combined Lagrangian and satellite infrared observations of the Subtropical Front (from 40°W to 20°W). (A) Winter 1996 (composite image of 1 and 9 February). W (warm) and C (cold) regions indicated. (B) Early summer 1996 (composite image of 8, 9 and 10 June). The duration of the tracks (of the Argos buoys and ALACE floats), the identification code and depth of the drogue for the buoys are summarized in Table 2. The remote sensing observations in (B) are continued to the east in Figure 2 (4 June 1996) which shows the Subtropical Front reaching 10°W. The 2000 m contour shows the Mid-Atlantic Ridge (MAR). Sea level anomaly of cool structure (cyclonic) near 33°N 23°W can be seen in Figure 16.

see Figure 5A) left the eddy at an early stage (~40 d after its release), found the eastward flow near 33.5°N 32.5°W and moved about 540 km to 26°W at a mean speed of ~12 cm s^{-1}. ALACE 25974 left the eddy 55 d after its deployment and followed buoy 25977 eastward in the Azores Current at a mean speed of ~20 cm s^{-1} to near 26°W. Some warm frontal water flowing east adjacent to cool regions subsequently flows south and then back to the west. This is shown by the track of ALACE 25974 (which was near a pressure of 210 dbar where the temperature was 17°C, in February 1996, when this subsurface float moved south) and buoy 25977 which left the Subtropical Front in a clockwise sense near the same position. The sea surface temperature of buoy 25977 was 17.8°C on 9 February in the warm water region where this buoy was turning anticyclonically south. ALACE 25974 found the region of flow reversal about two degrees to the south and moved westwards in late February and March at a mean speed of ~ 10 cm s^{-1}.

The early summer 1996 (composite image of 8, 9 and 10 June, Figure 10B) period was chosen as it corresponded to the North Atlantic crossing of HMS 'Hecla' near 32.5°N in the region. The satellite images show the Subtropical Front outcrop near 35°N. There is a cool extension stretching along the MAR which contains *Storm 0* near 39°W. *Storm 0* was first clearly evident in the altimeter structure in January 1995 (near 25°W) and so was about 1.5 years old when on the MAR. The cool region stretching along the MAR to the cool region of the STF represents a further elongation and splitting (as occurred in January, e.g. Figure 5B) of the structure and clearly evident in the altimeter data as a low pressure sea level anomaly. Drogued buoy (25686, 5030 and 25687) tracks identify the Azores Current (or Subtropical Front) clearly with water moving (ENE) along the eastern side of the MAR. From early June to July, the sea surface temperature contrast between buoy 5030 and buoy 25686 defining a 100 km wide Azores Current stream (with mean temperature near 21.5°C) was 1.3°C, with cooler surface water to the left of the flow direction. The mean speed of the flow in a direction along the MAR across a 100 km width of the stream was 25 cm s^{-1} (10 day average). We note that to a depth of only 200 m this represents a transport of 5 Sv. Argos buoy 25687 (drogued at

200 m depth), that tracked the eddy for the longest period, showed a ~1000 km route of the AC, as it moved eastward from 37°W to 26°W (see Figure 10B for partial track). The buoy moved first north-east along the eastern flank of the Mid-Atlantic Ridge (MAR) towards Oceanographer Fracture Zone (near 35°N), then along the western side of the chain of seamounts (Atlantis) extending south-east from the MAR and then eastward over Plato Seamount near 33°N at a speed of 28 cm s^{-1} (20 day mean). The warm water to the south of buoy 25687 (moving eastward in the Azores Current) is moving back westwards. This is shown by the tracks of ALACE 25974 (mean temperature ~16.9°C near 185 dbar) and ALACE 25975 (mean temperature ~13.8°C near 426 dbar) which went westward in June. These deeper ALACE show that the current structure is not confined to the warm surface water but can be deeply penetrating. ALACE 25976 (near 765 dbar, mean temperature now near 10°C) is moving eastward towards the MAR and crosses the MAR near 34°N in July. Buoy 25687 also moved south near 26°W (on year-day 200, 1996) and recirculated clockwise over the next 100 days.

The eastward track of both buoys (25977 and 25687) was ~1° south of the region of maximum thermal contrast or surface outcrop of the Subtropical Front (near 35°N) and the drogued buoys are measuring flow at 200 m depth (drogue depth). The flow above 200 m rides on the 200 m near-geostrophic flow, so the upper layer warm water above (evident in the imagery) will also be flowing east near the front as will the warm water to the north of the buoys. Buoys and ALACE show that the same warm water properties can flow back westwards in the south of the region (near 30°–32°N). Some subtropical flow is recirculating as both ALACE and buoys may then move north and rejoin the Azores Current where they move eastwards again (i.e. southern Subtropical Recirculation track). After about 300 days, ALACE 25974 recirculated back to the AC with east-west track extending for ~900 km (from ~25°W to ~35°W, see figure 5 in Pingree (1997)).

In summary, the IR imagery can identify the position of the STF outcrop as a temperature contrast in the region. The imagery shows that the drogued buoys and floats are mostly in the warm water adjacent to the cool STF outcrop and the superposed Lagrangian tracks show that this water is moving eastward (AC) although cells of warm water are turning anticyclonically. To the south some warm water is returned westward, some of which later recirculates back eastward in the warm AC. The STF position and structure can be seen in SeaWiFS images (see 3.9). The seasonally varying chlorophyll *a* SeaWiFS front matches the STF outcrop/IR structure in February and March. Signatures of *Storms* to the south are most evident in April (image composite for April 1998).

3.6. Ocean diffusion in the STF region

The ocean structure and westward moving eddies are spreading particles (drogued buoys and ALACE). Particles that were originally contained in the eddy are shown T~200 days after release (Figure 11). The eddy has moved from 33.6°W to near 39°W and the particles are spread across ~1500 km. An *apparent* horizontal diffusion D ($D_x = \sigma_x^2/2T$, $D_y = \sigma_y^2/2T$) based on the mean squared x-east (σ_x^2) and y-north (σ_y^2) separation or displacement from an initial release position (Okubo, 1971) is $D_x = 5.1\times10^3\ m^2\ s^{-1}$ and $D_y = 1.1\times10^3\ m^2\ s^{-1}$.

After 200 days, all the particles have left *Storm 0* and their subsequent positions are used to derive a *rms* displacement rate in the STF region. A displacement time interval of 40 days was chosen as it was the least common denominator (LCD) for the ALACE position sampling and sufficiently long not to be dominated by the displacements due to coherent eddy orbital motions. The oceanic diffusion values based on mean squared displacements (with respect to the centre of mass or corrected for overall displacements of the water in the sampling region) were $D_x = 1.3\times10^4\ m^2\ s^{-1}$ and $D_y = 3.9\times10^3\ m^2\ s^{-1}$ for the 40 day period. These estimates are even larger than before and again show preferential spreading in the east/west direction. The eddy, moving particles to the west and losing particles to the AC, does not spread them as fast as oceanic mixing in the region sampled. The apparent diffusion values for the same particles over the next 40 days were $D_x = 1.0\times10^4\ m^2\ s^{-1}$ and $D_y = 2.0\times10^3\ m^2\ s^{-1}$. Removing the two deeper ALACE tracks from the diffusion estimates so that conditions near 200 m depth are represented (mean depth 235 m) gives similar diffusion values of $D_x = 1.3\times10^4\ m^2\ s^{-1}$ and $D_y = 2.6\times10^3\ m^2\ s^{-1}$ (mean of both 40 day periods). The anisotropic diffusion is partially attributed to the tendency of particles to move eastwards in the AC and then return westward in the counterflow region to the south (see Figure 11). Over the 80 day period considered, the mean displacement (with means based on ~2 year averages or 8×80 day sampling) of the Subtropical Front region sampled was 1.2 km d^{-1} east and 0.6 km d^{-1} south. The oceanic diffusive values are one to two orders of magnitude greater than the eddy values. A diffusion velocity based on a *rms* separation gave 7 km d^{-1} for the east/west direction and 2 km d^{-1} for the north/south direction, over the 80 day period considered. The value of 7 km d^{-1} for the ocean can be compared with 0.43 km d^{-1} derived for the radial speed in the eddy. Although diffusion or radial spreading in *Storm 0* was large in comparison to other types of eddies found in the Eastern Basin, it was small in comparison to the apparent oceanic diffusion resulting from the overall effects operating in the STF region.

3.7. Selected composite image showing Subtropical Front, cold cyclonic and warm anticyclonic structures

The satellite infrared image for February 1997 (composite image of satellite passes on 4, 5 and 10 February; Figure 12) has been selected from an appraisal of all the available images between September 1995 to March 1997 as it most clearly characterizes the significant sea surface Subtropical Front thermal structure from 10°W–34°W (~2200 km), near 34°N. Cooler water is present north of 35°N and warmer water south of 35°N but the structure is convoluted with some order present. Cold water (or water columns with low dynamic height) displaced to the south (where the water columns have larger dynamic height) will develop cyclonic movement and these features represent or will develop into the regularly spaced cyclonic eddies or *Storms*. This dynamic effect will be augmented by the north-south displacement of planetary

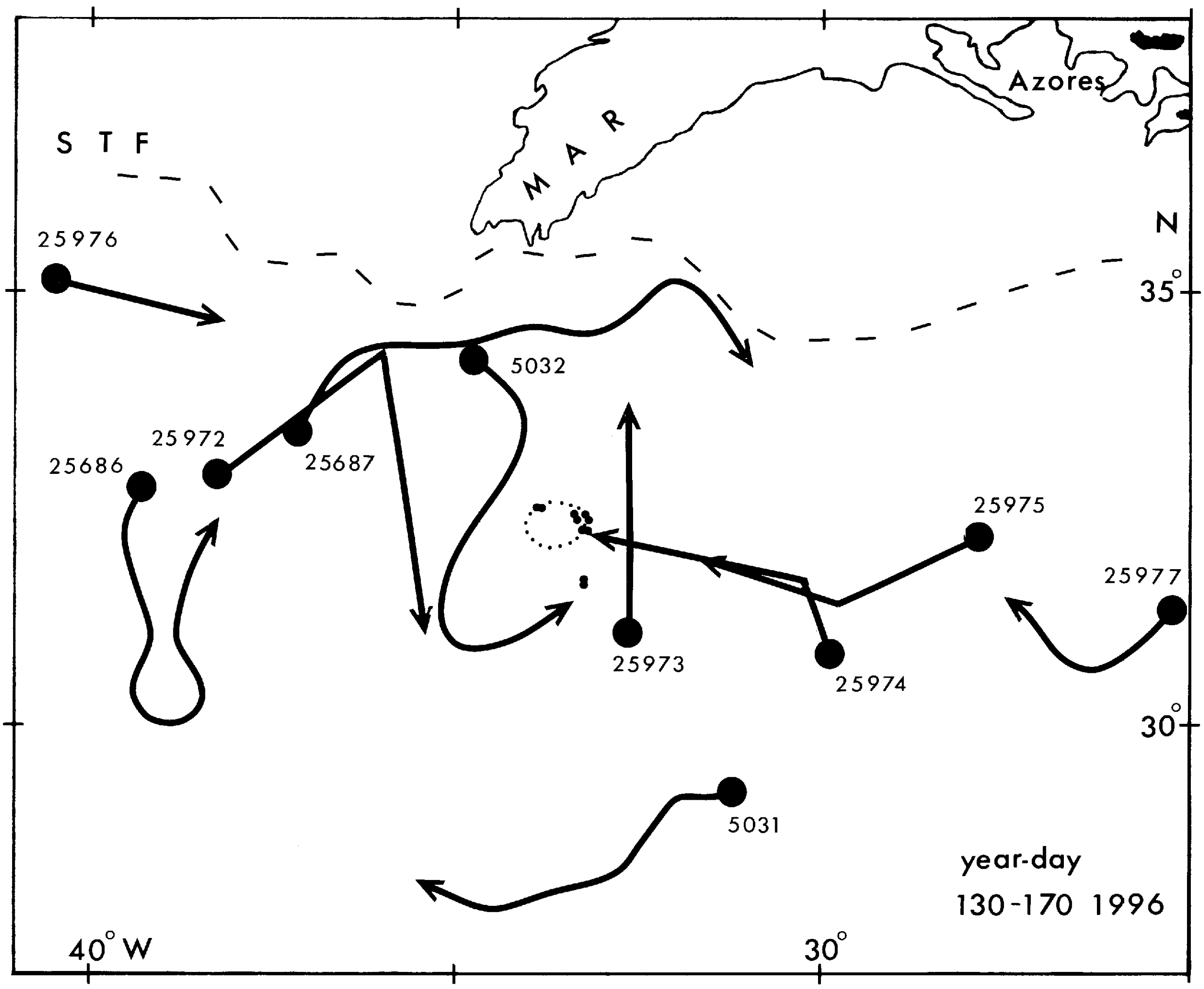

Figure 11. Buoy and ALACE tracks over a 40 day period (year-day 130 (large dot)—170 (arrow head), 1996) on the warm side of the STF outcrop (position of surface temperature contrast shown dashed is taken from Figure 10B; temperature can be appraised from Figure 8). Small dots are the release positions and the dotted region shows the initial eddy orbits in *Storm 0* (the previous year, October/November 1995), except for drogued buoy 25977 and ALACE 25974 which were deployed in the region of maximum azimuthal flow at a distance of 80 km from the eddy centre. Buoy 5032 is moving anticlockwise around the next *Storm*, *Storm 1*, passing westward through the region.

vorticity. The two features marked C near 32.5°N are surface cold water structures. These surface temperature structures will not in general reflect the movement of a water column but will rather show how surface water is drawn into patterns by the presence of the eddies. The two cold water structures can be seen clearly in altimeter data where they are confirmed as low pressure (cyclonic) anomalies (see Figure 13, with data extracted from CLS ftpsite (spike.cst.cnes.fr) for the nearest date corresponding to the western infrared image (4.2.97) that forms the composite of Figure 12). It has not been possible to quantify a relationship between temperature structure and sea level anomaly since the temperature reflects both structure and gradients (i.e. cooler water towards the north) whereas average gradients are largely removed (or hardly present if there are no mean surface currents) in determining the altimeter sea level anomaly from a reference state. We have called these two cold water low pressure *Storm* signatures, '*Storm 3*' and '*Storm 4*' (i.e. S_3 near 30.5°W and S_4 near 25.5°W with a separation of ~460 km). We note that the cool patch 'C' representing S_3 does not correspond quite with the centre of the altimeter structure and that cold and warm (to the south) surface water regions will be turned cyclonically by the eddy flow itself. *Storm 2* is ~500 km ahead (west) of S_3 and can be seen in the altimeter data, elongated near the MAR (Figure 13). *Storm 2* was also measured directly as it passed through the position of Mooring 156 (32.52°N 34.40°W) in December 1996, resulting in a 2°C drop in temperature near 800 m depth at this position, equivalent to a ~200 m uplift of isotherms (*PS*). Buoy 5032 (drogued at 360 m depth) failed on 3 February 1997 after 470 days, but moved anticyclonically (with a centre near 33.5°N 32.5°W) in the warm water region just (~130 km) to the north-west of the centre of S_3 near the end of January 1997. W (which extends to the west and south) is a warm water feature (with a water column of relatively larger dynamic height) which is displaced north or partially surrounded by cooler water and so the flow here is anticyclonic. The water movement will be eastward along the temperature front near 35°N (Azores Current) and then clockwise around the central structure or region of higher

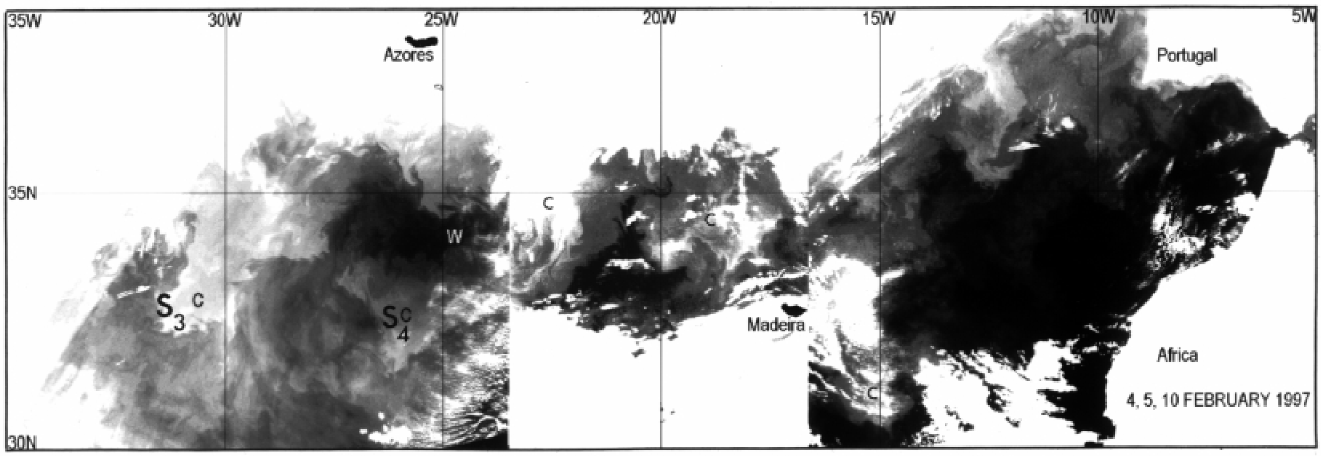

Figure 12. Satellite infrared image for February 1997 (composite image of satellite passes on 4, 5 and 10 February, from west to east). W (warm, anticyclonic) and C (cold, cyclonic) features indicated in relation to the STF outcrop near 34–35°N. Cold features near 31°W and 26W are infrared signatures of *Storms* S_3 and S_4 (labelled). Warm and cold features near 25°W are shown ~2.5 months earlier near 23°W in Figure 14. Azores (São Miguel), Madeira and coasts of Portugal and Africa labelled.

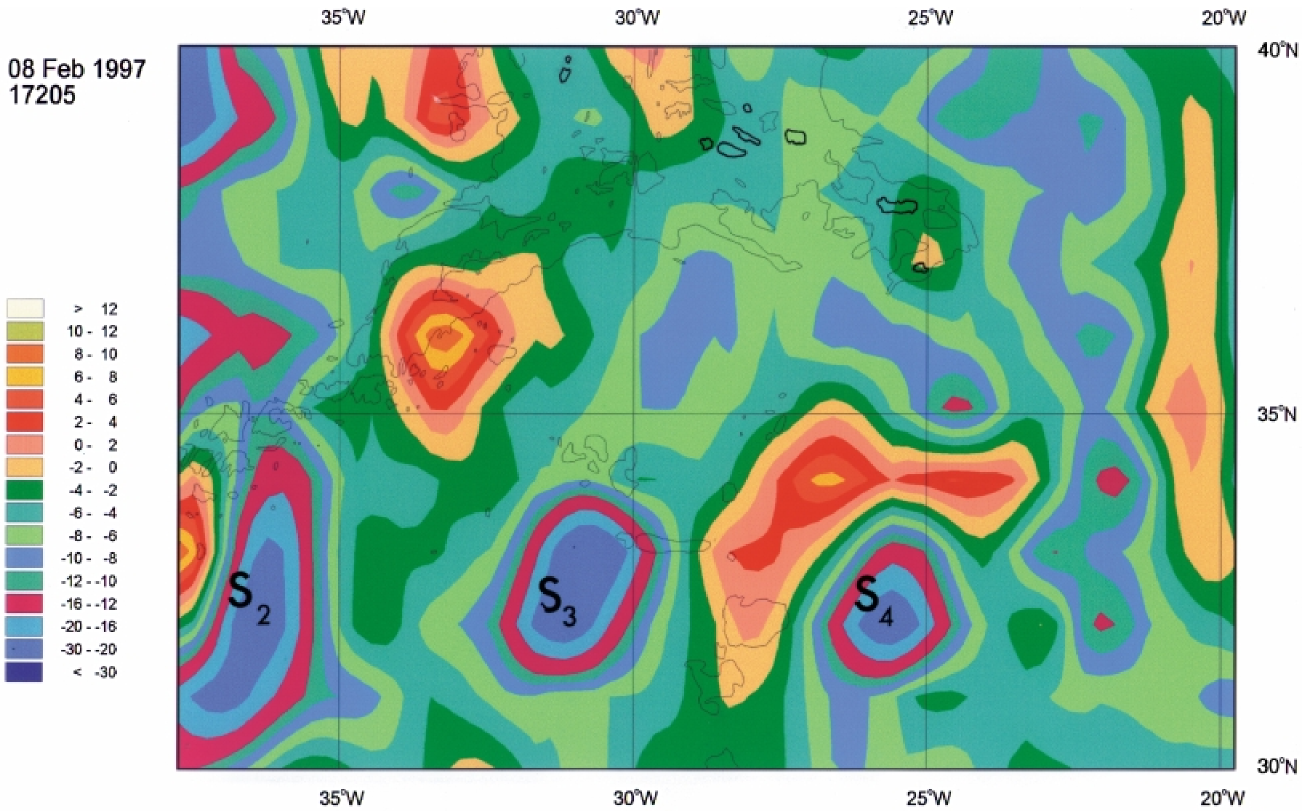

Figure 13. Altimeter sea level anomalies (cm scale in colour) corresponding to Figure 12. S_3 and S_4 (labelled) are evident near 31°W and 26°W (~32.5°N). Orange region to the north of S_4 matches the warm water region W in Figure 12 and blue meridional patch near 23°W corresponds to the cold streaks marked c.

sea surface elevation pressure. Just to the east of W (~23°W 35°N), the cold streaks also show a clockwise sheared pattern with implied cool flow from the north. Altimeter data confirm a region of high sea surface pressure (Figure 13) associated with the warm water structure (W) and ALACE 25974 turned clockwise around this warm region between December 1996 and March 1997, with mean temperature near 17.8°C (i.e. Subtropical Water with larger dynamic height) at 150 dbar. We note that ALACE 25974 has moved from a mean pressure of 220 dbar in *Storm 0* (where the mean temperature was ~15.7°C) to 150 dbar in the warmer region of the STF over a period of 450 days. ALACE move upwards in warmer water due to expansion (~50 dbar°C^{-1} at constant salinity) and with age

3.8. Westward movement of structure

3.8.1. Storm generation region. Although altimeter data is not affected by clouds and altimeter sea level anomalies show

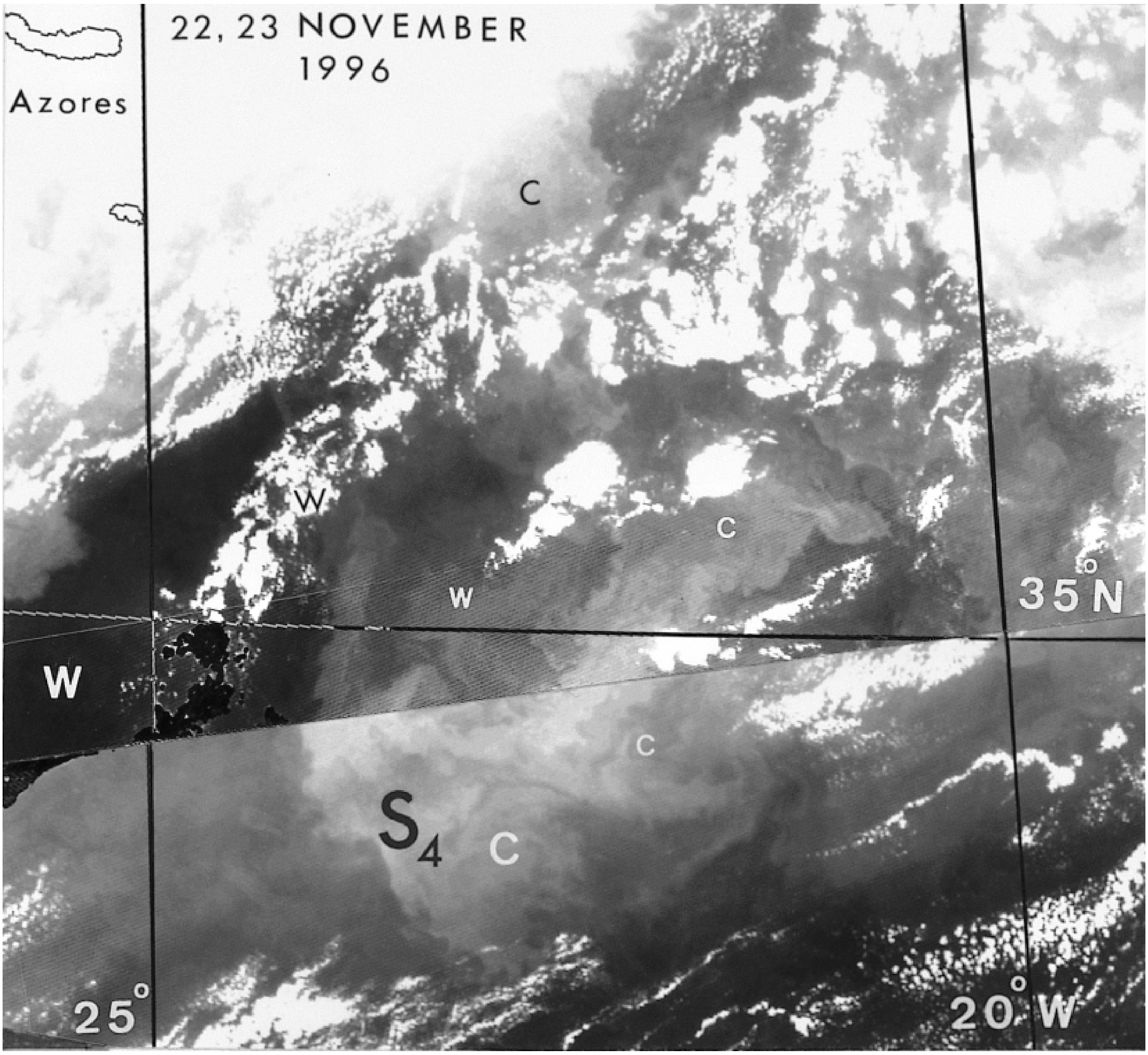

Figure 14. Satellite infrared image for November 1996 (composite image of satellite passes on 22 and 23 November) showing the early stages of S_4 (labelled). Cool jet across 35°N near 22°W (with a connecting irregular filament-like structure to the north) with W (warm, anticyclonic) and C (cold, cyclonic) structure forms a curved front near 24°W. Azores (São Miguel) shown. The structure is south of the STF outcrop near 36–37°N.

the eddy structures far more clearly, infrared images can give more detail of structure in the east of the region and may reveal some aspects of the *Storm* formation process. Infrared image sequences for the east of the region show westward moving thermal structure. The infrared image of 9.1.97 shows S_4 near 24.5°W (not shown) and the image of 13.3.97 (also not shown) indicates a position for S_4 near 26°W giving a westward movement of ~2.5 km day^{-1}. The warm water anticyclonic cell also moves westward (cf. Figures 12 & 14). The initial structures generally move westwards more slowly and so the separation scale is typically 460 km in the east. This infrared image sequence shows that S_4 is first evident as part of an anticyclonic/cyclonic dipole type of structure with cool stem extending from the north and directed across 35°N near 22°W in late November 1996 (Figure 14). The cool stem stretches to 38°N and is associated with a cyclonic low pressure sea level anomaly (altimeter data). This shows that *Storms* can start evolving as far east as 22.5°W. Eddy energy, or rather meridional motion, of this period is evident in long current meter records in the region near 22°W (Müller & Siedler, 1992) and westward moving cyclonic structures are already present near 18°W (33–34°N) (figure 4 of Pingree (1997)). Some early initial infrared signatures may even be observed east of Madeira ~12–13°W. For example, the AVHRR infrared image of 23 March 1992 (figure 11 of Pingree (1997)) shows warm (anticyclonic) cells separated by cool water extensions, filaments or plumes from the north, with a separation scale of ~370 km, which start near 10°W, but it is not known whether these most easterly regular features develop into *Storms*.

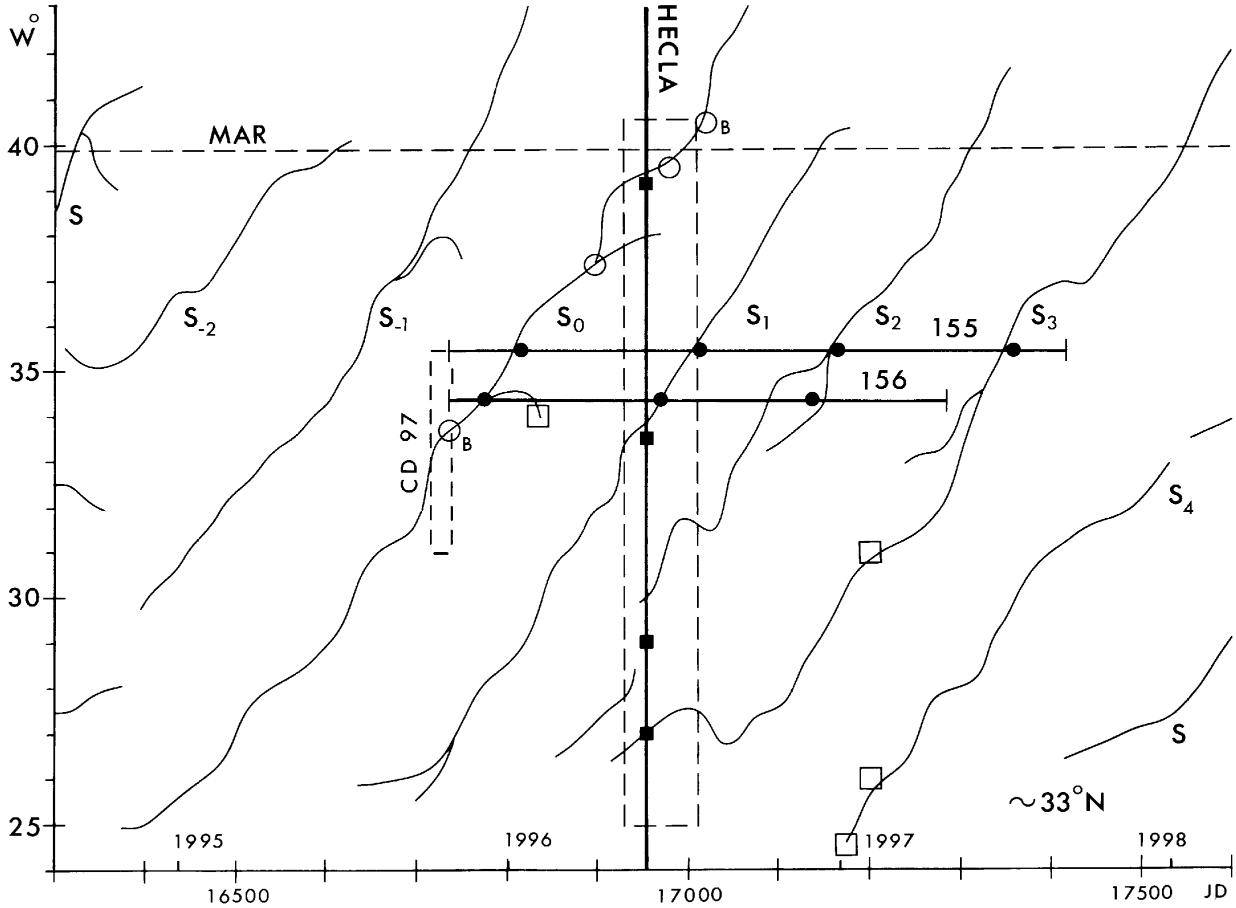

Figure 15. *Storm* travel curves summarizing conditions near 33°N, from 24°W to 43°W over a 3.6 year period (JD 16,300–17,600). *Storms* S_0, S_1, S_2, S_3 were identified by cooling at mooring 155 deployed at 35.5°W for two years and Mooring 156 at 34.4°W shown as dots. On an Atlantic crossing, HMS 'Hecla' identified upward doming of isotherms or cooling representing S_{-1}, S_0, S_1, S_2 (solid squares) near JD 16,957. Drogued buoy tracks (see Figure 3) are used to estimate the eddy centre of S_0 (open circles labelled B) and track this eddy across the MAR shown near 39.9°W for 32.5°N. Tracks of eddy centres were then extended from the central region using altimeter data (thin) lines. The track lines are not always continuous and merging and splitting of eddy structure is shown by bifurcation. The open squares correspond to IR signatures (see for example Figure 12 showing S_3 and S_4). The larger dashed window covers the 80 d period for horizontal diffusion estimates in the STF region. The smaller dashed window represents the RRS 'Charles Darwin' Cruise CD97 (Plymouth Marine Laboratory, 1995) survey of *Storm 0* in October 1995 and the deployment of drogued buoys (see Figure 3) and Moorings 155 and 156.

Storm formation appears to result from excessive southward movement of more northern (from say ~35° or even 37°N) colder water resulting in an irregular filament-like structure (*PS*) which subsequently turns westward and confines warmer (anticyclonic) water to the north (see Figure 12). Scrutiny of the altimeter structures suggests that some smaller low pressure features may originate in the south (near the latitude of Madeira ~32.8°N). Coalescence of structures may occur. *Storms* may intensify further as they move west into a region of increasing dynamic height (i.e. Subtropical Water). The mean dynamic height increases from 1.66 to 1.78 dyn m from 20°W to 40°W along 33°N, with the most rapid increase occurring near 30°W (WOA94, reference level 2000 dbar and average of four seasons).

3.8.2. Summary of Storm *positions 1994–1998 near 33°N.* Travel curves summarizing positions of *Storms* near 33°N from 1994 to 1998 are shown in Figure 15. Positions for *Storms* S_0, S_1 and S_2 were given in *PS* and further *Storms*, S_3, S_4, are identified here in IR imagery (Figure 12). S_3 was also measured 150 days later as it passed Mooring 155 (Pingree, 2000). Buoy tracks extending over 300 days showed some continuity of *Storm 0* from 33°W to 41°W, just across the MAR. Further continuity of structure was derived using altimeter sea level anomalies (from CLS ftpsite) in the region.

A number of general remarks can be made with respect to the travel curves. Eddies travel westward from the Eastern Boundary in the Eastern Basin with further generation of structures in the Western Basin moving westward from the MAR. Although individual patterns (low pressure structures) can be followed for enormous distances, for example S_0 from 25°W to 50°W over a period of ~900 days, merging and splitting or exchange of eddy structures occurs, so we cannot say that an individual eddy has followed the complete travel curves. In this sense, the structures have wavelike properties. S_{-1} (Figure 15) appeared to reach Bermuda (to the north) with inputs of energy from other structures which had

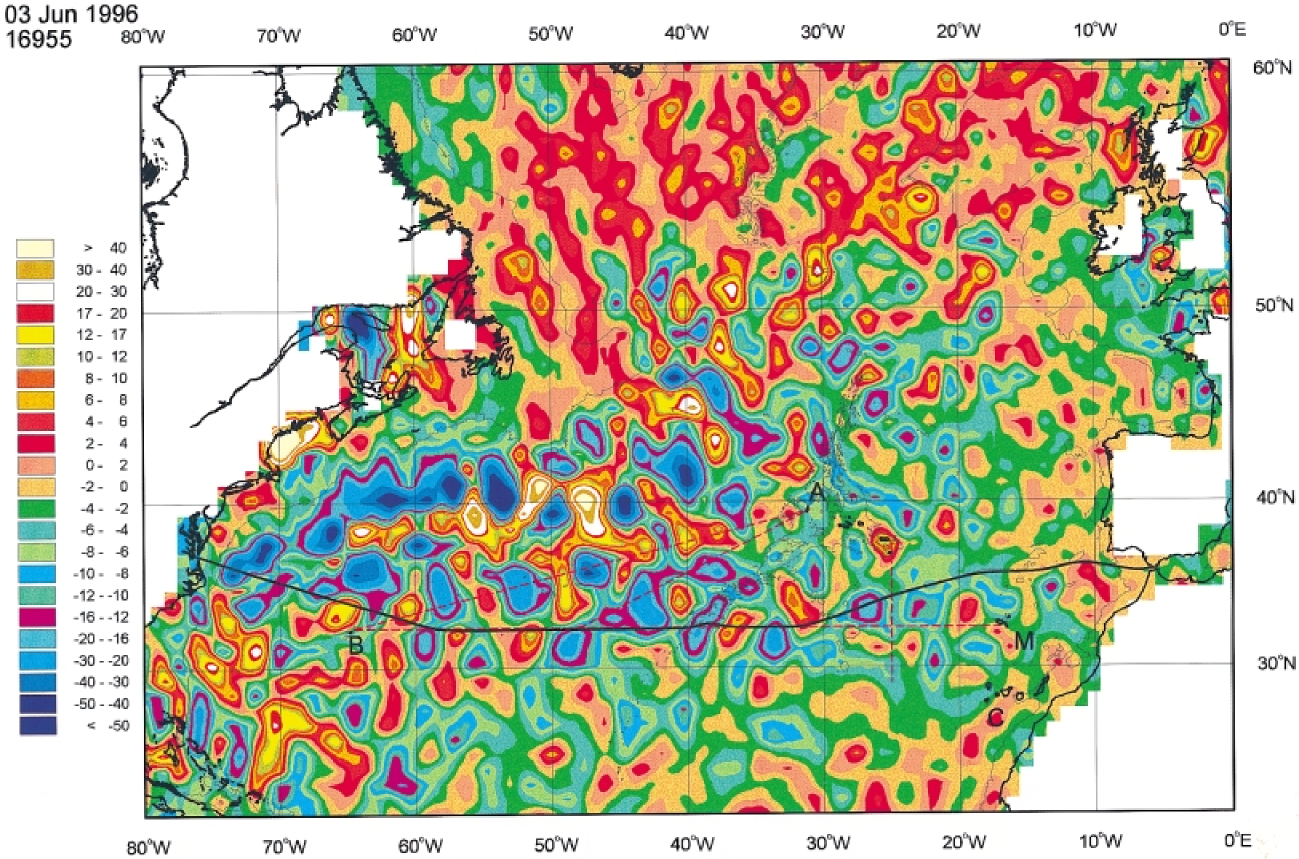

Figure 16. Altimeter sea level anomalies (cm scale in colour) for the North Atlantic (3 June 1996) corresponding to the North Atlantic crossing of HMS 'Hecla' from Norfolk, Virginia (28 May 1996) to Gibraltar (10 June 1996) with track superposed. On 3 June 1996, HMS 'Hecla' was on the MAR near 40°W. Buoy 1811 was deployed on 4 June 1996 (year-day 156, see Figure 3). A, Azores; B, Bermuda; C, Canary Islands; M, Madeira. Elongated purple/blue feature cut by ship's track across the MAR (near 40°W) contains *Storm 0* and cool IR signature is evident in Figure 10B. A more circular purple/blue feature cut near 33.5°W is *Storm 1*.

their origin in the Western Basin. S_{-1} was intersected on its north flank by HMS 'Hecla' near 49°W in the Western Basin (Figure 16) and could be tracked back to 29°W in the Eastern Basin. HMS 'Hecla' cut the southern flank of a further cyclonic structure in the Western Basin that was evident in the altimeter data near 43°W that did not have a travel curve in the Eastern Basin. *Storm 0* is on the MAR (elongated NE/SW near 39°W), S_1 is near 34°W and S_3 near 27°W. The structures are clearly not always aligned on 32.5°N. Figure 16 also shows the marked increased eddy energy in the Western Basin compared to the Eastern Basin which has relatively stagnant regions north and south of 30–35°N in the east of the region. The Gulf Steam signature is clearly evident in the west and the Stream or structure splits into two branches near 38°N, 50°W, in the Western Basin. One branch is the Gulf Stream and structure continuing to the north and then to the north-east, the other branch to the south-east becomes the Azores Current in the Eastern Basin. Similar altimeter sea level anomaly maps show that there is a tendency for *Storms* to elongate (Figure 13) in the direction of the MAR axis (~NE/SW) and split before crossing the MAR (see S_{-1} and S_0 near 38°W, Figure 15) and some decay before crossing the Ridge. S_1 and S_{-2} decayed or disappeared or were absorbed by transfer of energy before crossing the MAR.

In the central region ~35°W, the structures have a more obvious wavelength ~510 km and period ~190 days or westward speed of 2.7 km d^{-1} (~3 cm s^{-1}) but progress is not necessarily steady with S_0, for example, showing a half period (or ~100 day) wobble. Westwards speeds in the Western Basin are larger ~×1.5. Eddies do not increase their spatial scale zonally in the Western Basin as their speeds increase as further eddies are generated in the Western Basin. East of ~30°W, the structures are less organized, smaller or less intense and relatively more stationary for longer periods giving an overall reduced westward speed.

3.9. Seasonal cycle of surface chlorophyll a *and SeaWiFS data in the Subtropical Front region*

Storms and the STF have been studied by direct *in situ* measurements (Pingree et al., 1996), hydrography and altimeter data (*PS*) and using infrared satellite imagery (this paper). A natural extension is to examine the STF/AC system for signatures in the visual band (e.g. using, CZCS, SeaWiFS, MERIS data). In October 1995, no clear detectable surface chlorophyll *a* structure or signature was found for *Storm 0* (CD97 data) with chlorophyll *a* values of typically 0.1 mg m^{-3}. The seasonal cycle of surface chlorophyll *a* (based on cruise data near 34°N in

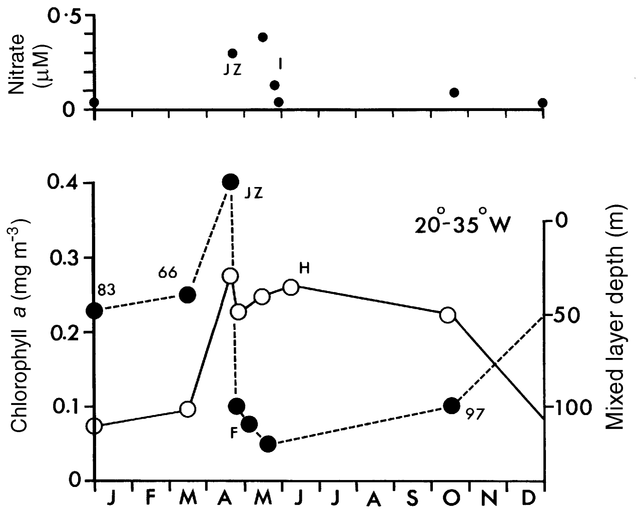

Figure 17. Seasonal cycle (month shown by letter) of surface chlorophyll *a* ($mg\,m^{-3}$, dots), the base of the mixed layer or depth of upper seasonal thermocline (m, circles) and inorganic nitrate values (top, dots) in the Subtropical Front region (~33–34°N) from cruise data–CD66; CD83; CD97; H, HMS 'Hecla'; F, from Fasham et al. (1980); I, from Irwin et al. (1983); JZ, from Jochem & Zeitzschel (1993), nitrate value near 20 m.

the Eastern Basin, Figure 17) gives a guide to the background levels for the Subtropical Front region. Surface values are low in the summer ($<0.1\,mg\,m^{-3}$) but increase in the cooling period (see Figure 8) reaching values of $0.3\,mg\,m^{-3}$ in late March (Fernández & Pingree, 1996) when maximum values are associated with the warm side of the STF outcrop. Surface values increase in the winter (January) when deeper mixing entrains inorganic nutrients (e.g. nitrate) into the photic zone although values $>0.3\,\mu M$ have not been observed at the sea surface. The general increase in chlorophyll *a* values in winter need not match the low nitrate concentration maximum as light is not limiting in the winter mixing season. The seasonal chlorophyll *a* values are comparable to those given by Longhurst (1995) for the North Atlantic Subtropical Gyre (West) region (or NAST(W) province) derived from the *Westerlies Domain: Model 3.* Future chlorophyll *a* values in *Storms* and associated anticyclonic structures will be appraised for significance against these baseline values. Early summer SeaWiFS images show zonal structure associated with the northward progression of the spring bloom. The SeaWiFS structures will tend to relate to surface temperature which also has a marked north/south gradient. The 500 km structure in the May SeaWiFS image (Figure 18) can be identified along the STF near ~33°N (with green protrusions near 31°W and 37°W). These two structures could be related to altimeter sea level anomalies which propagate westward at $\sim 2.7\,km\,d^{-1}$.

Monthly composite SeaWiFS images show a seasonal migration of the surface chlorophyll *a* signal or levels in the region (25°W–50°W, 20°N–50°N, excluding the effects of upwelling off west Africa) with a maximum southward displacement of the chlorophyll *a* levels in February south of ~35°N. In March, significant increases in chlorophyll *a* gradients occur near the Subtropical Front outcrop at ~34°N with a spatial maximum in levels to the north ~38°N. South of ~40°N, the temporal or seasonal maximum chlorophyll *a* levels occur in the January to April period (cf. Figure 17) but the winter maximum signal does not extend south to the region 20°N–28°N, and >35°W where the surface levels remain uniformly low (spatially and temporally) in the subtropical water. The seasonal migration (in the meridional direction) of the near zonal chlorophyll *a* levels ($\sim 0.3\,mg\,m^{-3}$) or the chlorophyll *a* front ranges from about 32°N February/March to 45°N August and in May the chlorophyll *a* front is near 40°N (Figure 18) with bloom conditions in the Bay of Biscay (Garcia-Soto & Pingree, 1998). Since the chlorophyll *a* front and thermal front are similarly positioned in the winter, *Storms* or excursion of cooler surface water to the south show elevated sea surface chlorophyll *a* values from January to May, though the overall levels will be higher to the north. The *Storm* SeaWiFS signatures were most conspicuous in April but structures related to cold water features and altimeter low sea level anomalies were evident later in the year.

In the *Storm 0* survey in October 1995, a Seasoar section showed increased levels of oxygen concentration ($5.5\,ml\,l^{-1}$) at the thermocline depth ~85 m in the central region of the eddy where the deeper thermocline was domed upwards (cf. $5.1\,ml\,l^{-1}$ in the exterior regions of the eddy at the same depth) but chlorophyll *a* or fluorescence values although increased with a subsurface maximum (typically $0.25\,mg\,chl\,a\,m^{-3}$, or at winter maximum levels) at the same depth were not elevated with respect to exterior values in October.

4. CONCLUSIONS AND SUMMARY

In the Eastern Basin of the North Atlantic Ocean, subpolar and subtropical mode waters lie alongside each other near the Subtropical Front (STF) and ~18°C water outcrops at the sea surface in late winter (March). The distribution of mass (STF) results in a region of maximum dynamic height gradient which defines the position for strongest eastward surface flow for the Azores Current (AC). The eastward geostrophic transport for the region is about 10 Sv across 30.5°N–36.5°N near 25°W–30°W but the total southward transport across 20°W–50°W was measured as 28 Sv. Effectively drogued Argos buoy and ALACE float tracks are examined in conjunction with infrared satellite images and altimeter structures in the region for the structure and flow associated with the STF/AC system and the position of the STF over a period from October 1995 to March 1997. A cyclonic eddy, or *Storm 0*, is followed from 33°W to over the Mid-Atlantic Ridge (to ~41°W) near a latitude of 33°N over a ~300 day period. Lagrangian tracks have been superposed on selected infrared images of the region for the period when the buoys were in the eddy and when they subsequently left the eddy and showed flow and structure in the STF region. Temperature sensors on the buoys define the seasonal surface temperature for the region and can be used to calibrate the imagery. Overall, the thermal imagery gives the position of the STF, whereas the altimeter shows more clearly the eddy structure. The Lagrangian data alone allows estimates of horizontal diffusion in *Storm 0* and in

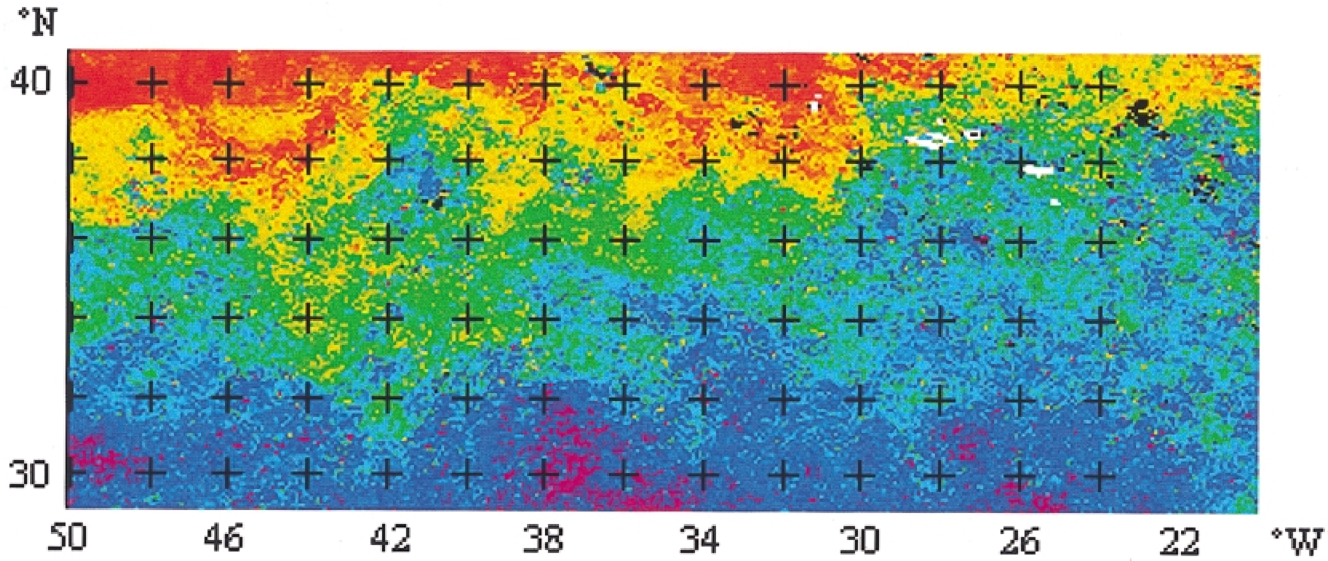

Figure 18. Composite SeaWiFS image for May 1998 with a relative chorophyll *a* colour scale (approximately 0.04 (blue/purple near ~30°N) to 0.8 (red, >40°N) mg m^{-3}, see for example, Seabass.gsfc.nasa.gov/~seabam/bioopt_workshop/).

the general STF region itself. Diffusion in *Storm 0* was about ×60 smaller than in the STF region. The infrared imagery shows an occasional cool thermal signature for *Storms* south of the Subtropical Front, which has a temperature contrast near 35°N. Warm structures adjacent to the cyclonic eddy, or to the north (near 34°N), are also evident just south of the STF outcrop and these are shown to be turning anticyclonically. Warm water adjacent to the STF outcrop is moving eastward (i.e. AC) but this water can turn south and flow back westward and some is recirculating. The outcrop of the STF near 35°N has a temperature contrast of ~1°C which can sometimes be followed for ~3000 km. An image is selected that shows the meandering variable structure of the STF over a zonal distance of 2000 km near 35°N, the positions of two cold water features or *Storms* near 33°N, separated by about 5° of longitude (~460 km) and still linked to the STF, and an anticyclonic warm water structure contained within the region between, near 34°N. The most easterly cool *Storm* signature found near 25.5°W can be traced back to a generation position near 22.5°W. Overall, the infrared imagery shows that the eddies are located in the warmer water south of the STF outcrop. The actual eddies themselves are far more readily resolved and followed using altimeter data and some *Storms* can have altimeter travel curves exceeding 1500 km over a ~600 day period. Altimeter structure shows that early structures may coalesce and start to group more regularly near 28°W. In the region near 32.5°N 35°W, current meter moorings and altimeter signatures (see Figure 15) show that regular *Storms* are separated by 510 km and that two *Storms* a year passed a fixed point over a two year interval. From 28°W, *Storms* will have travelled 1000 km and be about one year old when they reach the MAR (near 33°N). Surface measurements showing the seasonal cycle of chlorophyll *a* in the STF region are summarized and structure, seasonality and *Storm* signatures in SeaWiFS data are examined.

An extensive archive of AVHRR enhanced images was kindly supplied by the Satellite Receiving Station at University of Dundee. Image processing of selected AVHRR and SeaWiFS data was undertaken at the Remote Sensing Unit at the Plymouth Marine Laboratory. Altimeter data and products were received from AVISO, CLS and European Space Agency (grant A02.UK121). Part of this study was carried with the support of CANIGO (MAST-III Programme), a UK WOCE capital grant and the Procurement Executive, Ministry of Defence.

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