Two Years in the Life of a Mediterranean Salt Lens*

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ABSTRACT

A lens of Mediterranean water (Meddy) was tracked in the eastern North Atlantic for two years with SOFAR floats. The Meddy was first found between the Canary Islands and the Azores in October 1984. Its center moved in an irregular pattern, at speeds of a few cm s^{-1}, and translated 1100 km to the south in two years. This Meddy was surveyed four times by CTD and velocity profilers, and once with the microstructure profiler EPSONDE. When observed during the first two surveys the Meddy had a core that was stably and smoothly stratified in both salinity and temperature, nearly uniform in the horizontal, and was saltier than the surrounding ocean by 0.65 psu. The Meddy was eroded from its edges, top and bottom, and lost salt and heat with an e-folding time of about one year. The salinity at the center remained at its original value during the first year and decreased during the second year. Evidence was seen for mixing by lateral intrusions, double diffusion, and turbulence; the intrusions are thought to be the most important mode of mixing in terms of salt and heat loss.

Radial profiles of azimuthal velocity revealed a core in almost solid body rotation, with a period of 5–6 days corresponding to 0.35 times the local Coriolis parameter. During the October 1984 survey, the azimuthal speed had a maximum of 0.3 m s^{-1} at a radius of 24 km. Both the radius and magnitude of the velocity maximum decreased with time. The anticyclonic circulation attained a maximum at the radius of the salinity front. As the lens was eroded from the sides, the radius of maximum velocity and the maximum velocity both decreased, but the rotation rate of the core remained fairly steady.

1. Introduction

A new class of persistent, isolated eddies, called Meddies, discovered in oceanic observations are dynamically interesting for a variety of reasons. In particular they have a core that retains passive tracers for a long time, and indeed, their property anomalies were the clue to their discovery. McWilliams (1985) has reviewed the different types of isolated eddies found to date.

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* This was an informal collaborative experiment involving all the authors, whose contributions are shown in Table 1. The order of authors' names was assigned alphabetically. Armi initially proposed the experiment and was joined by others. Hebert was the scientist in charge of reduction and analysis of data from all four surveys.

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TABLE 1. List of participants and measurement made during the four surveys of the Mediterranean salt lens.

Survey	Date	Julian days[†]	Principal investigators	Objectives
I	Oct 84	259–277	Armi (Scripps Institution of Oceanography) Rossby (University of Rhode Island)	—find a Meddy —seed it with SOFAR floats and pop-up drifters —detailed CTD survey —PEGASUS velocity profiles
II	Jun 85	519–537	Oakey (Bedford Institute of Oceanography) Ruddick (Dalhousie University) Hebert (Dalhousie University)	—locate same Meddy —detailed CTD survey —nutrients & ^{3}H-He samples —velocity measurements (9 expendable current profilers and a current meter mooring) —EPSONDE microstructure measurements
III	Oct 85	662–668	Armi (Scripps Institution of Oceanography) Bower (University of Rhode Island)	—locate Meddy —detailed CTD survey —PEGASUS velocity profiles
IV	Oct 86	1013–1015	Richardson (Woods Hole Oceanographic Institution) Price (Woods Hole Oceanographic Institution)	—locate Meddy —XBT survey —CTD survey —XCP profiles

[†] Julian Day 1 is 1 January 1984.

The term Meddy, or Mediterranean salt lens was coined by McDowell and Rossby (1978), when they discovered a large anticyclonic subsurface eddy with a warm and salty core off the Bahamas. It had a diameter of approximately 100 km, occupied the depth range from 700–1300 m, and had a salinity anomaly of 0.25 psu. McDowell and Rossby concluded at the time that the eddy was composed partially of Mediterranean water, and that the Meddy must have taken several years to wander across the Atlantic. It seemed remarkable that the lens had held together without completely mixing with the surrounding waters, or breaking up due to self-generated instabilities or external forces (McWilliams 1985). [More recent consideration (T. Rossby) has raised other possibilities for the origin of that particular Meddy.] Armi and Stommel (1983) discovered another such lens among 150 stations in the β-triangle region. Its salinity anomaly was 0.65 psu, about 20 standard deviations from a fitted value at its location. In recent years, Meddies have been found to be relatively common in the Canary Basin. Armi and Zenk (1984) found and surveyed three others, and saw an indication of a fourth. Käse and Zenk (1987) found evidence of several more.

Because Meddies have such a strong salinity anomaly, typically 0.2–1.0 psu, and are relatively common, they may play an important role in the transport of salt in the northeast Atlantic (Armi and Stommel 1983; Armi and Zenk 1984; Hebert 1988a). A large fraction of the salt and heat transport could occur in these isolated eddies; but to know this, we have to learn how many are formed, where they go, and whether they tend to leak slowly or burst suddenly. The eventual dispersion of the heat and salt into the surrounding waters depends on the processes which cause the Meddy to decay, mix, or break up. It was, therefore, of interest to follow a Meddy for an extended period of time in order to discover which processes are important to its evolution.

In October 1984, two of us (L.A. and H.T.R.) began a long-term study of a Meddy. We found Meddy Sharon[1] in the Canary Basin, surveyed it with velocity and conductivity, temperature, depth (CTD) profilers, and seeded it with four SOFAR floats (Rossby et al. 1975). The floats were tracked acoustically from Autonomous Listening Stations, and could also be located with shipboard listening equipment. One of the floats remained in the Meddy for nearly two years, which allowed us to follow the movements of the Meddy, and to relocate and resurvey the same Meddy several times. In all, we obtained four surveys of Meddy Sharon spread over two years (October 1984, June 1985, October 1985 and October 1986); Table 1 gives a list of participants and measurements made for the four surveys. These data give a unique picture of the movements and evolution of a single Meddy over two years, a time long enough to observe significant changes in the structure of the Meddy. A preliminary note on some of the results of this experiment have already been pre-

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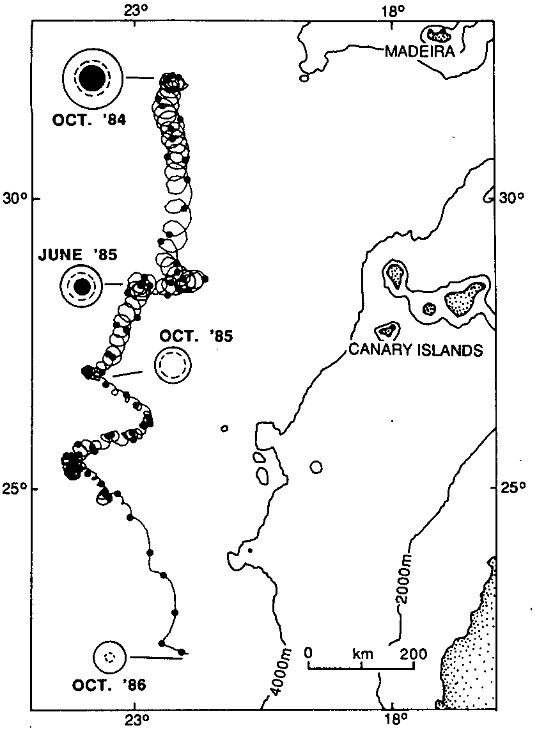
[1] The scientific party on the initial cruise held a pool in which the objective was to guess the hour of the day in which a suitable Meddy would be found. Sharon Yamasaki was the lucky winner of 2400 escudos and the Meddy was named in her honor.


23°
18°
MADEIRA
OCT. '84
30°
30°
JUNE '85
OCT. '85
CANARY ISLANDS
25°
25°
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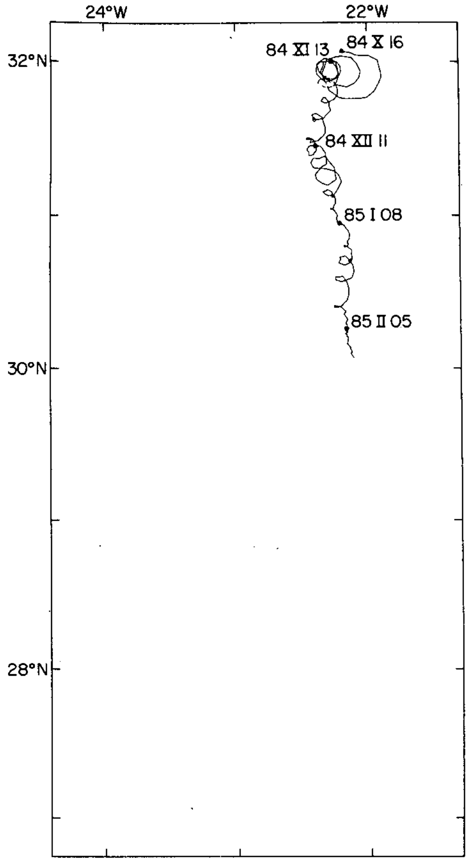
0 km 200
OCT. '86
23°
18°


24°W
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84 XII 11
85 I 08
85 II 05
30°N
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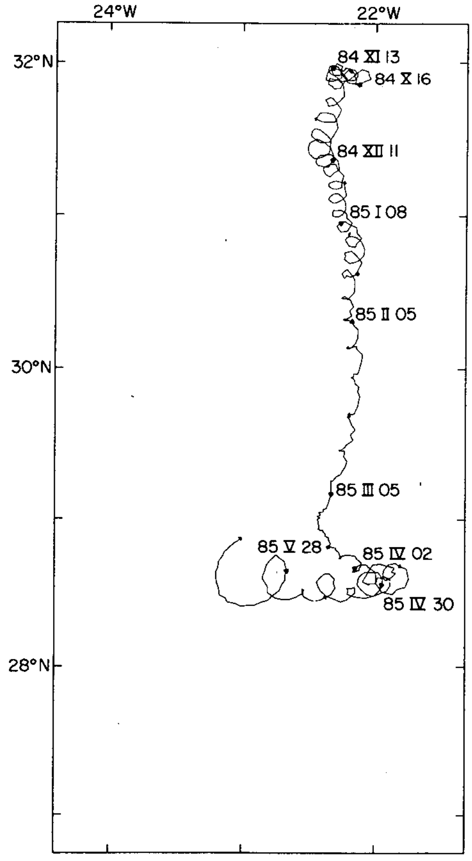
24°W
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85 II 05
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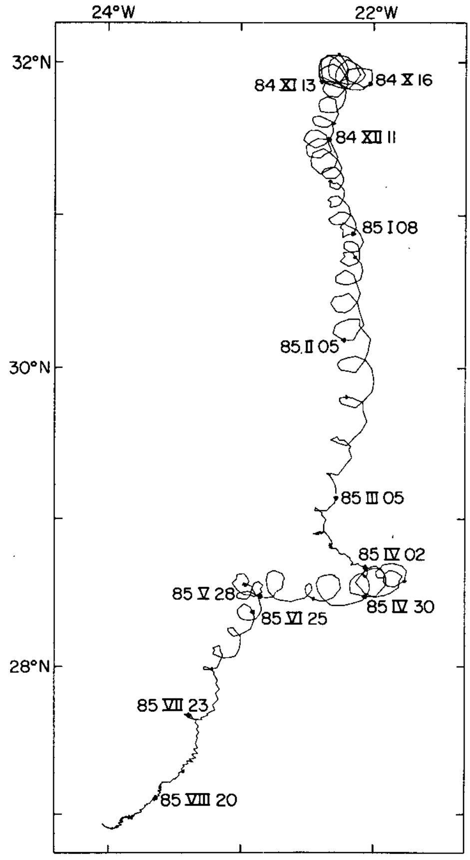
85 III 05
85 V 28
85 IV 02
85 IV 30
28°N


24°W
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84 XII 11
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85 II 05
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85 V 28
85 IV 30
85 VI 25
28°N
85 VII 23
85 VIII 20

sented by Armi et al. in a paper in *Nature* (1988). The current paper extends the description considerably.

The track of float 128, which stayed with the Meddy for two years, provides an overview of some of our observations, Fig. 1a. It shows an irregular southerly drift, due to the translation of the Meddy core, plus a looping motion due to anticyclonic rotation of the Meddy core. This irregular motion, with stops and starts and direction changes, is consistent with advection of the Meddy in a field of larger scale eddies. The Meddy was found to the south of the Azores front (Käse et al. 1985), and moved away from it with a net southerly drift of 1100 km in two years. Other floats released at similar depths (1100–1200 m) but one month later in the same area tended to move in an east–west direction (Price et al. 1986).

In the four surveys, we saw evidence for mixing by at least three processes: 1) lateral exchange of layers of water (thermohaline intrusions), 2) vertical mixing at the base of the Meddy core by salt fingers, and 3) mixing by turbulence. The gross effects of the first process on the Meddy are indicated in Fig. 1a by the circles which indicate the size and structure of the Meddy at each survey. The core of the Meddy is defined to be the region that contains anomalously warm and salty (>36.2 psu) water, and which is smoothly and stably stratified in the vertical in both temperature and salinity. We will call the water in this region Meddy Core Water. Its radial extent is shown as the filled circles in Fig. 1a. Surrounding the core was a region containing numerous temperature and salinity inversions, the result of lateral mixing processes. The water in this region, between the filled circles and the outer, solid circles, we call Meddy Mixed Water. The radius of maximum radial salinity gradient at each survey is shown in Fig. 1a as the dashed circles. During the year between October 1984 and October 1985, Meddy Core Water, initially 30 km in radius, was entirely supplanted by Meddy Mixed Water as lateral intrusions mixed into the center of the Meddy. During this time, the outer boundary of the intrusive region decreased in radius from 58 to 34 km. However, in the following year, when Meddy Mixed Water occupied the Meddy center, the outer boundary decreased in radius only from 34 to 31 km.

This paper is organized in the following manner. In section 2 the SOFAR float data are presented and decomposed into Meddy translation and looping components. Sections of salinity and density from each survey and dynamical calculations are presented in section 3. Direct observations of the velocity fields are shown in section 4. Thus, sections 2, 3, and 4 concentrate on the mesoscale structure of the lens at each of the survey times. In section 5, the finestructure at each survey is shown, and evidence for the various types of mixing that may be occurring is discussed. Some results from the microstructure measurements made during the second survey are also presented and discussed in the context of the other observations. In section 6, some of the bulk changes in Meddy properties are discussed, and in section 7 is a summary and overview discussion of the evolution of this Meddy.

2. SOFAR float observations

Float 128 was carried around the Meddy center by its anticyclonic azimuthal velocity, with a period of 5–8 days, and was advected with the Meddy as it translated erratically to the south. The tracks of the other floats are shown in Figs. 1b, c and d. Close comparison reveals that the floats moved around each other coherently, and that the radius of motion of each float changed slowly with time. There is some hint that the period of rotation was longer when the radius was larger.

The regular, coherent character of the float tracks suggests that the float movements were predominantly due to rotation of the Meddy core about its center, plus a translation of the Meddy center. In order to separate these velocities, a model of the form

$$\underline{x}(t) = \underline{x}_0 + \underline{u}t + \underline{R}e^{i\omega t}$$

was fitted, by linear least squares, to 20-day segments of the float positions spaced at 10 day intervals. The float positions, $\underline{x}$, Meddy center position, $\underline{x}_0$, Meddy translation velocity, $\underline{u}$, and radius and angular phase of the float track, $\underline{R}$, are complex numbers with the real and imaginary parts being the eastward and northward components, respectively. The radius of the fitted float track is $|\underline{R}|$. The angular frequency ω was varied until the residual error of the fit was a minimum. The fitted radius and angular velocity are shown in Figs. 2a and 2b, respectively. Also shown are the telemetered float temperature (Fig. 2c) and pressure (Fig. 2d), both averaged over 10-day blocks. The east and north components of translation velocity are shown in Figs. 2e and 2f. The residual error in float position from the fits was typically 2–4 km, and the positions indicated by the floats at the times of the surveys agreed well with the positions of the Meddy center estimated from the hydrographic data. Agreement was good also in fitted translation velocity and position of the Meddy center for the different floats within the Meddy.

The signal from float 140 was not heard by the listening stations after day 390 although a weak signal was heard aboard the ship during the June 1985 survey.

FIG. 1. (a) The trajectory of the Meddy over a two year period as shown by SOFAR float 128. The float track is marked each 10 days by a solid dot. Locations and size of the Meddy at each survey are shown to scale (solid circle: core, open circle: total size, dashed circle: salinity front). (b, c, d) Trajectories of floats 140, 141 and 143. The tracks are marked with open triangles each 15 days, and with closed triangles, labelled with the data, each 30 days.

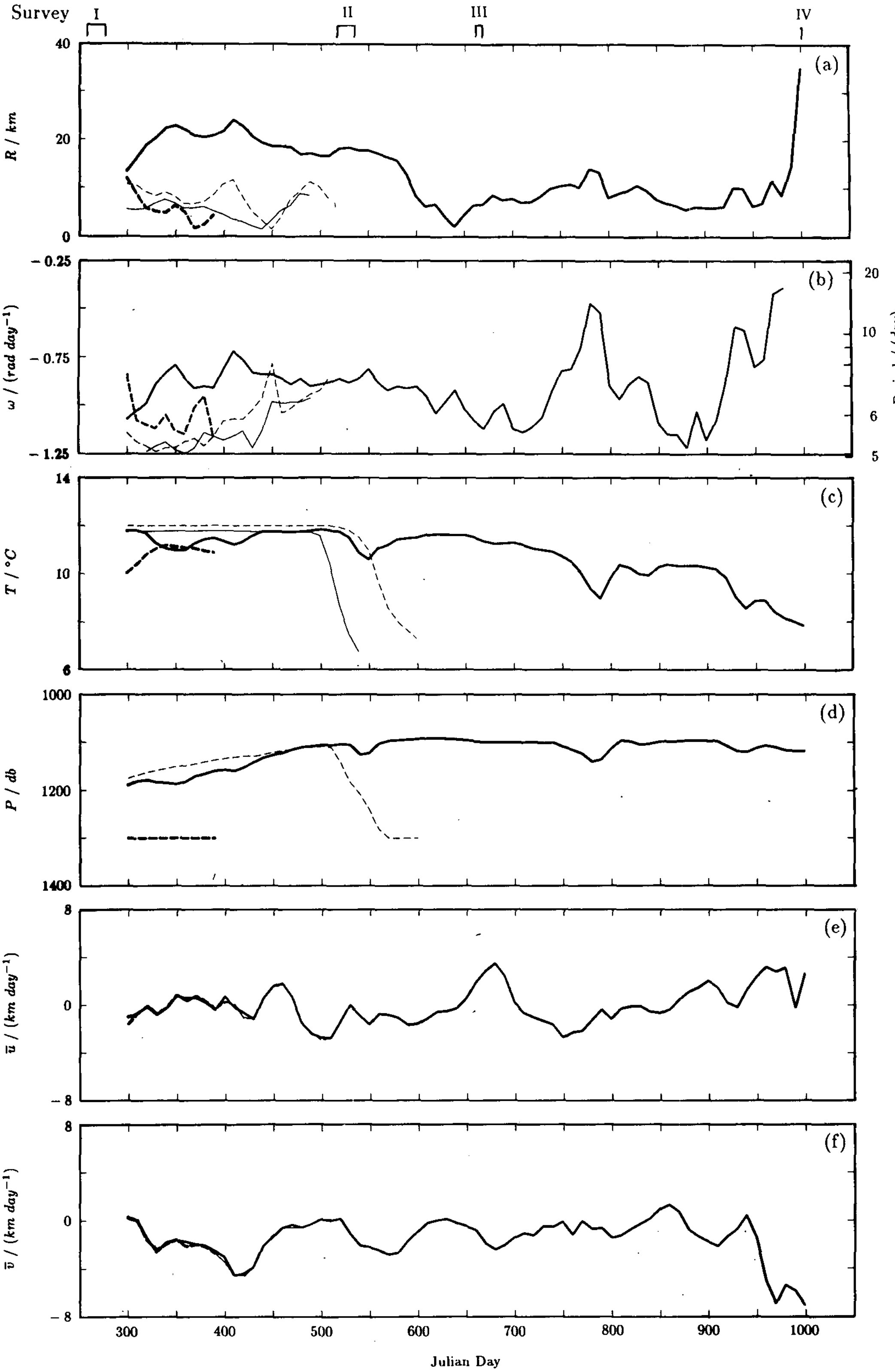


FIG. 2. (a) The radial distance of the float from the Meddy center, determined by the fit described by Eq. (1) in the text over 20 day intervals. (b) Fitted angular velocity of the float about the Meddy center. (c) Temperature and (d) pressure for the same period. The (e) east and (f) north velocity components of the center of the Meddy. Float number 128 (solid thick line), 140 (dashed thick line), 141 (solid thin line), and 143 (dashed thin line). The time of the surveys are shown at the top of the figure.

Floats 141 and 143 went offscale in temperature and pressure around day 540 and day 600, respectively. We believe that the floats sank at these times and further data from these floats were not used. Float 128 functioned perfectly, stayed well inside the Meddy until day 970 and left the Meddy by the time of the fourth survey. This float could have left the Meddy through the bottom (as the Meddy decayed vertically) or through the side. A detailed report of all floats deployed in the region for the first year of observations is contained in Price et al. (1986).

The angular frequency (Fig. 2b) was relatively uniform from float to float, at approximately $f/3$, where f is the local Coriolis parameter. However, two tendencies are apparent. Float 128, at a larger radius than the others near the beginning of the experiment, shows a slightly smaller rotation rate. At about day 600, it moves inward, and the rotation rate shows a corresponding increase. The floats sampled a range of radius over time, and so it was possible to construct radial velocity profiles corresponding broadly to the survey times. These are discussed later in section 4 (Fig. 9), along with the velocity profiler measurements.

3. Hydrographic surveys

a. Salinity sections

The most apparent change in the Meddy salinity structure is the decrease in diameter and thickness over the two years, as indicated by the gradient region surrounding the lens, Fig. 3. When considered volumetrically, the mixing at the sides had a much greater effect on the lens than did mixing at the top and bottom. The total salt content of the lens decreased with time, so that the mixed water must have been carried away from the lens. However, there is a central unadulterated core region (Meddy Core Water), indicated by the S = 36.2 psu contour, which retained its identity through surveys 1 and 2 (also see section 5). We believe this water has the characteristics of the formation water of the Meddy. In the third survey, intrusions have reached the central region of the Meddy (Fig. 11), but the central salinity anomaly is still large, and the maximum radial salinity gradient occurs at a radius of about 20 km. In the fourth survey, the central salinity is 35.8 psu. The irregular wiggles in contours, which become more apparent at the sides of the lens in the later surveys, are indicative of the finestructure discussed in section 5.

b. Density sections

The fields of potential density referenced to 1000 db (σ_1) which correspond to the four salinity sections shown above are shown in Figs. 4a–d. The Meddy signature was particularly large and strong in the first survey (a), when isopycnals were a factor of two further apart inside the lens than outside it. The isopycnal displacements are smaller in the subsequent surveys,

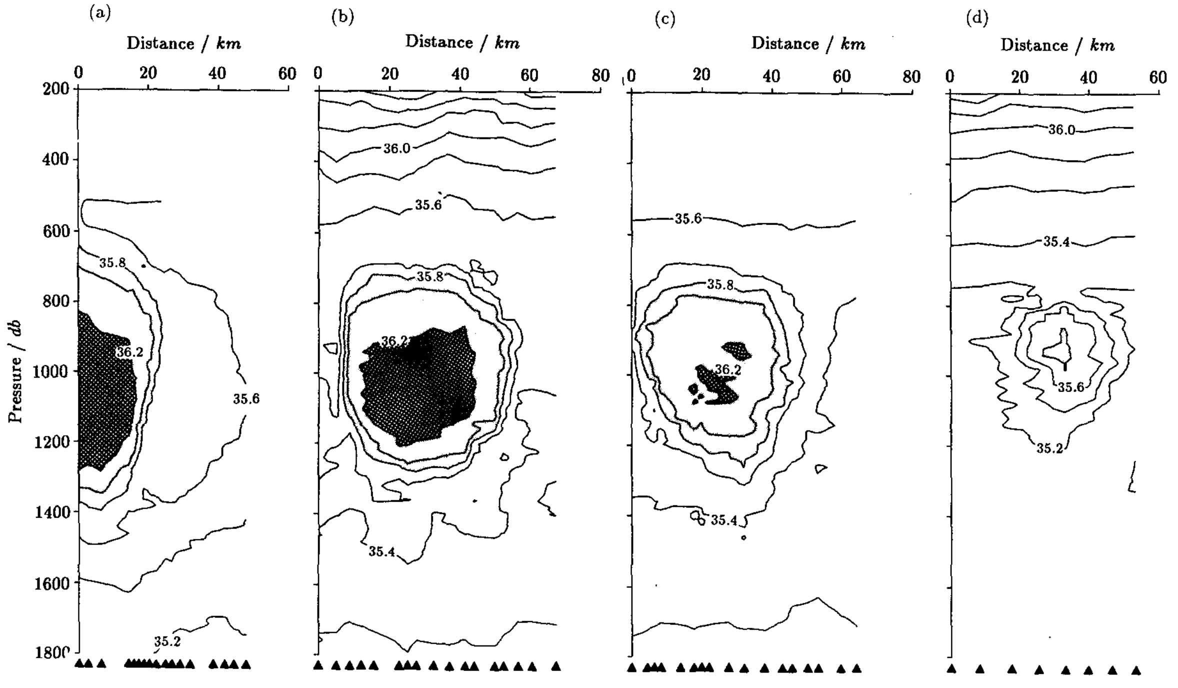


FIG. 3. Cross sections of salinity from each of the four surveys: (a) October 1984, (b) June 1985, (c) October 1985, (d) October 1986. The contour interval is 0.2 psu. The horizontal and vertical scales, and contour interval, are the same for each survey. The plot from the first survey starts near the lens center, while the others are from one side of the Meddy to the other side and pass nearly through the center. Triangles at bottom of figures indicate station positions.

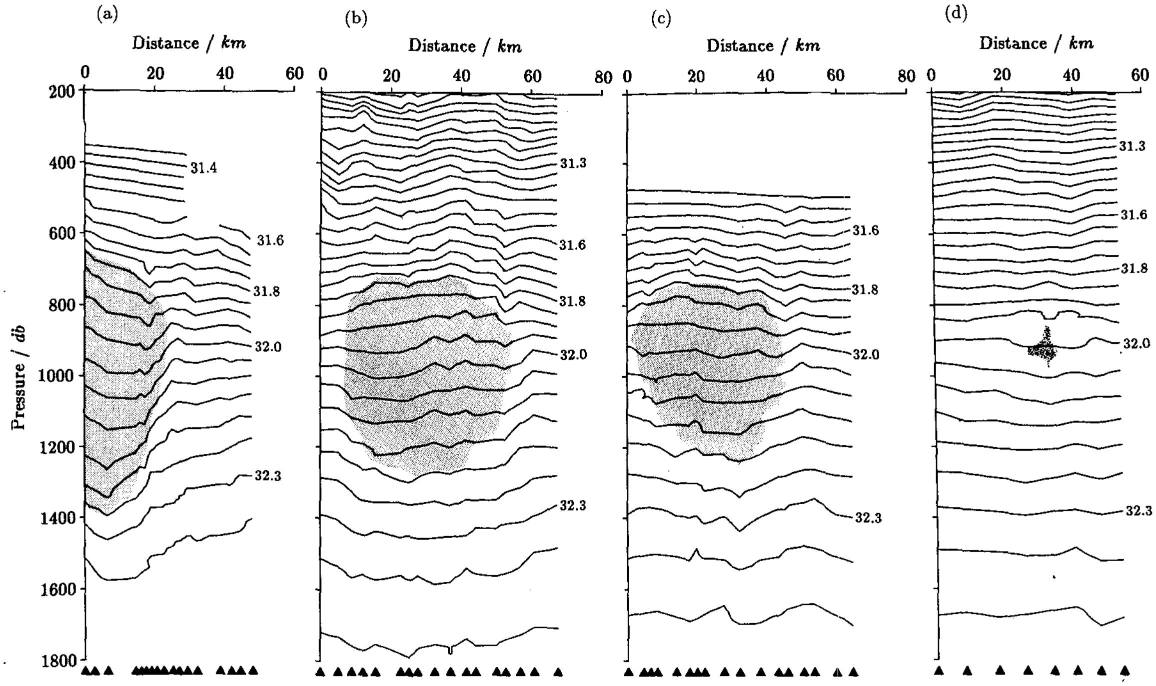


FIG. 4. Contours of density (σ_1) corresponding to each of the sections in Fig. 3. The $S > 35.8$ psu region for each survey is stippled. Contour interval is 0.05 kg m^{-3}.

which can easily be discerned when the salinity structure is used for guidance. Isopycnal slopes indicate a high pressure in the Meddy, and anticyclonic velocity relative to ambient water. The influence of the Meddy can be seen in terms of isopycnal displacements from about 300 db to below 1600 db, although the salinity structure only extends from 650 to 1400 db. Gill's (1981) model of a homogeneous intrusion in a stratified background showed a similar result. The intrusion displaced the background isopycnals both above and below so that the dynamic effect of the intrusion extends beyond the immediate layer occupied by the intrusion.

Vertical profiles of σ_1 through the Meddy center show a slight increase in density gradient near the lens top, and a decrease in the center, relative to an outside station, Fig. 5a. The difference of the two profiles (for all four surveys) or density anomaly, $\Delta\sigma_1$, clearly shows the decay of the density anomaly over time, Fig. 5b.

The positive peak in $\Delta\sigma_1$ at 600–800 db depth tends to correspond with the upper surface of the Meddy core as indicated by the salinity field (Fig. 3), and moves deeper as the lens becomes smaller and thinner. The negative peak in $\Delta\sigma_1$ at the lower edge of the core is weaker in all surveys, and covers a larger vertical extent. The density difference is small over the central few hundred meters, a result consistent with the observation of vertically uniform velocity in the Meddy core presented in section 4. The density difference seems to be closest to zero at 900 db.

The geopotential anomaly at 1000 db relative to 1900 db is shown in Fig. 6 as a function of radius for all stations from each survey (with successive surveys offset by 0.5 J kg^{-1} to separate the data). A few of the stations did not reach 1900 db and were extrapolated from the deepest pressure down to 1900 db for the geopotential anomaly computation. The largest interval of extrapolation was from 1800 to 1900 db. The geopotential anomaly observations are noisy, because of isopycnal displacements due to internal waves (Hebert 1988b) or internal tides (Rossby 1988). It is clear nevertheless that the central geopotential anomaly and the maximum geopotential anomaly gradient (velocity) both decrease with time, and that the velocity maximum moves toward the center. The noise in the geopotential anomaly is sufficient that a great deal of smoothing would be necessary to give meaningful estimates of geostrophic (or cyclostrophic) velocity. Hebert (1988b) explored the calculation of cyclogeostrophic velocity in detail for the Meddy survey II (to be described separately, manuscript in preparation). For this reason and because of the difficulty of providing a meaningful estimate of geostrophic velocity we concentrate here instead on direct velocity measurements.

4. Velocity observations

A diverse set of instruments was used to observe the velocity structure directly. In the first survey, 31 profiles were taken with the acoustically tracked dropsonde PEGASUS. In the second survey, a 2-week duration current meter mooring with six instruments, and nine

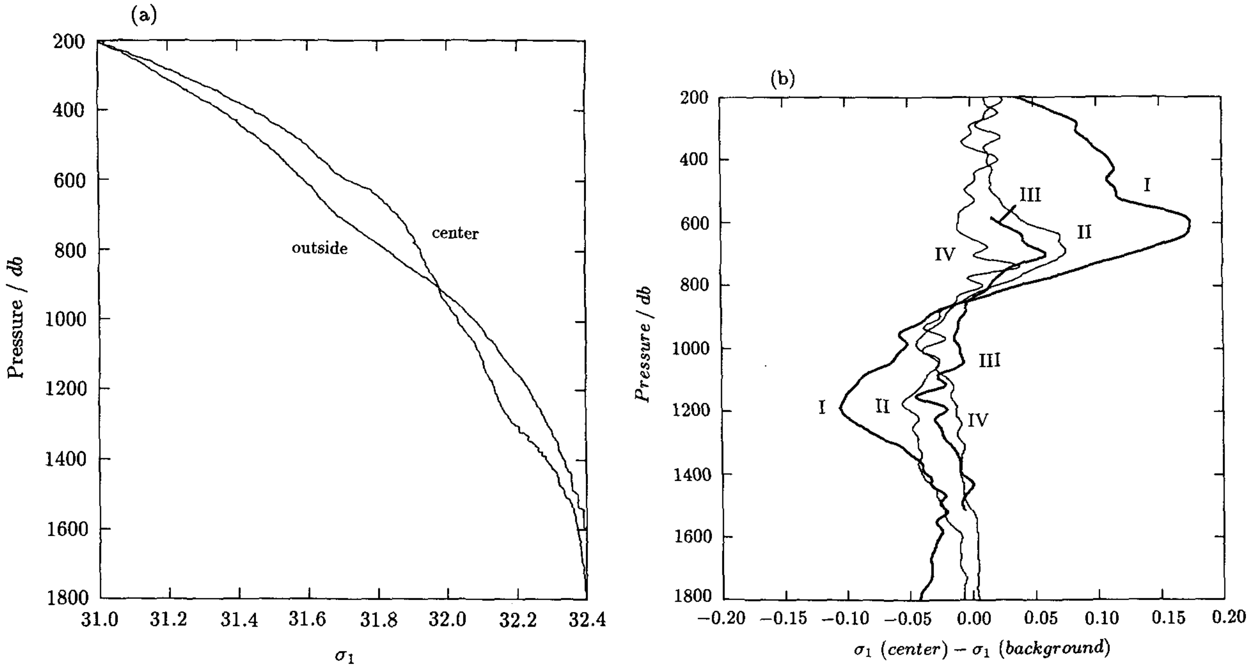


FIG. 5. (a) Vertical profiles of σ_1 through the lens center and outside the lens from survey I. (b) The difference between these curves, for survey I and the other three surveys. This difference has been low-pass filtered removing all variability with wavelengths below 20 db.

Sippican expendable current profilers (XCPs) were used. In the third survey, eight PEGASUS profiles were taken, and in the fourth, a few XCP profiles provided a limited amount of velocity information. We will summarize mainly the structure of the velocity and temperature field observed by XCPs at the second survey, Fig. 7, and investigate the changes over time by looking at radial profiles of velocity at 1000 m depth from the first three surveys, Fig. 9.

In Fig. 7 are shown (a) temperature, (b) azimuthal, and (c) radial velocity components observed via XCPs during the second survey. The finestructure in the temperature profiles gives an indication of the position of the station relative to the core and intrusive regions. Although some high-wavenumber shear is visible, the velocity of the Meddy dominates the azimuthal component. The azimuthal velocity increases with radius to a maximum of −0.19 m s^{-1} at 24 km, and decreases beyond. The vertical shear associated with the Meddy velocity is most pronounced at the top and bottom of the core, with surprisingly uniform (in z) speed within the core.

The azimuthal components of velocity from the current meter measurements accompanying survey II are shown in Fig. 8, along with a salinity profile from a nearby station. The velocities were averaged over a period of 5 days, at a time when the Meddy was moving at less than 2 cm s^{-1} relative to the mooring. The mooring was a distance of 14 km from the Meddy center, where the azimuthal velocity is nearly uniform with depth at 12–14 cm s^{-1}. The mean shear associated with

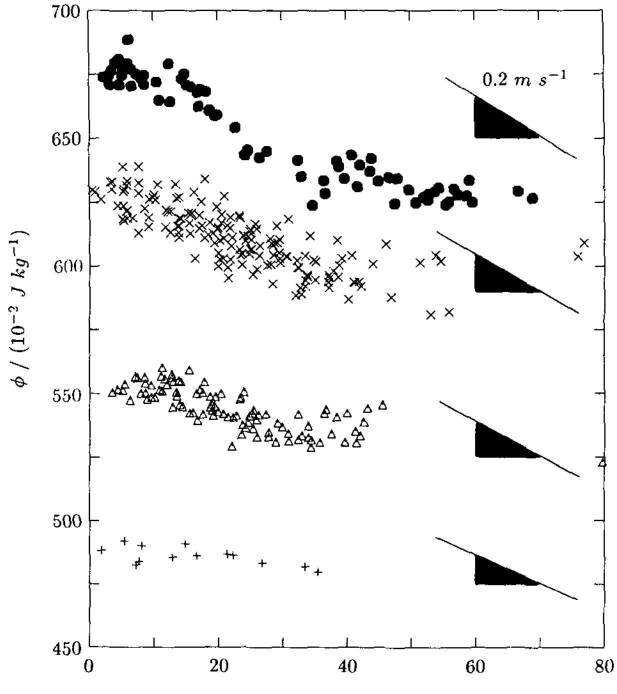


FIG. 6. Geopotential anomaly at 1000 db relative to 1900 db as a function of distance from the lens center. (●) Survey I: October 1984, (×) Survey II: June 1985, (△) Survey III: October 1985, (+) Survey IV: October 1986. Successive surveys have been offset by 2 tick marks. The scales to the right give the gradient in geopotential anomaly appropriate to a 0.2 m s^{-1} geostrophic velocity at the latitude corresponding to each survey.

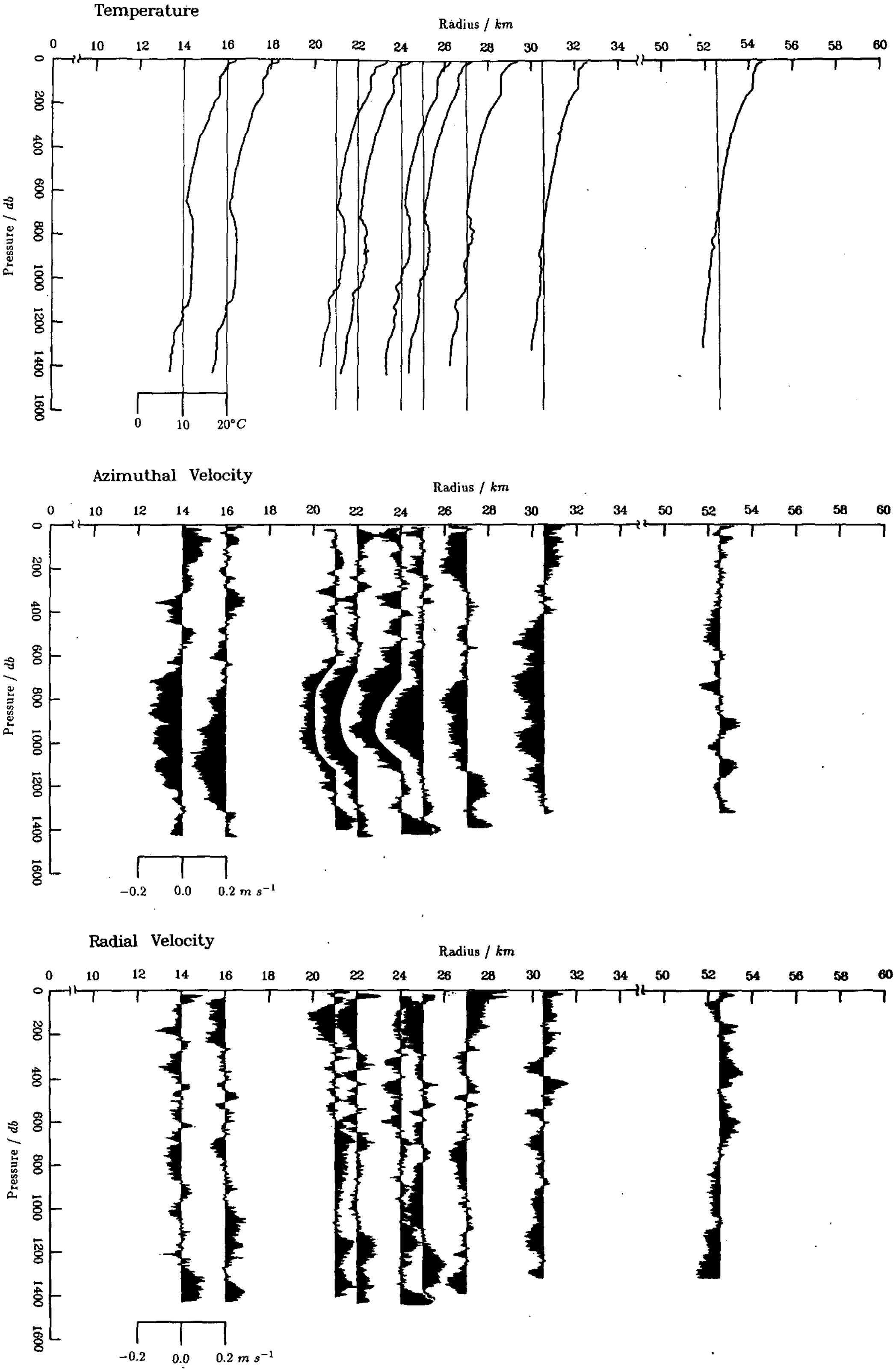


FIG. 7. Vertical profiles of (a) temperature, (b) azimuthal velocity, (c) and radial velocity, observed by expendable current profilers during Survey II. Each trace has been displaced horizontally to indicate the radius of the station. The stations were taken in different quadrants of the lens.

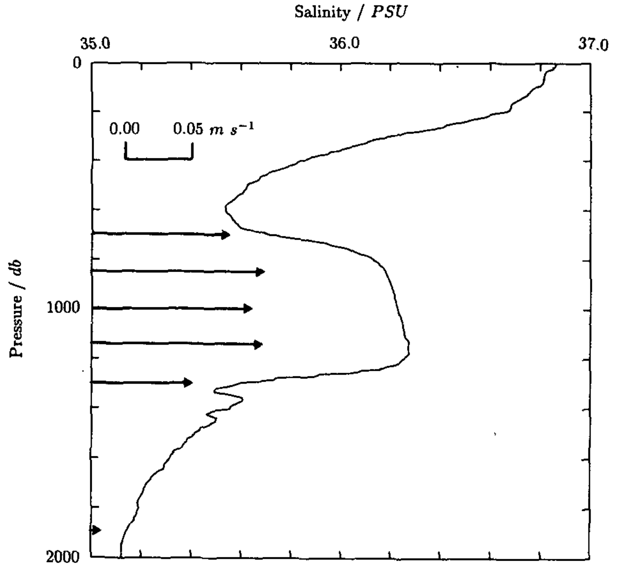


FIG. 8. Azimuthal velocity, averaged over 5 days, from six Aanderaa current meters moored at 14 km radius during survey II. Salinity profile is from a nearby station taken on day 521.

the top and bottom of the core corresponds to a Richardson number O(100). The mean velocity at 1900 m is very small, less than 2 cm s^{-1}, which is approximately the standard error of the average velocities.

In Fig. 9 are shown direct observations of azimuthal Meddy velocity corresponding to the times of the first three surveys. The SOFAR floats sampled a range of radii during their travels, and the angular velocities from Fig. 2 were converted to azimuthal velocities and plotted as a function of radius, for times within ±50 days of each survey. These are shown as the solid points in Fig. 9. The depth of these observations is 1100–1200 db. The PEGASUS observations and the XCP observations are averaged from 950–1050 m, and the current meter observations are from 5-day averages of the meter at nominal depth of 1000 m. The float velocities agree well with the profiler and mooring observations, despite the differences in averaging and depth of observation. The floats sampled the velocity of the Meddy core quite densely, showing nearly solid body rotation in the central portion, corresponding to a rotation period of 5.5 days, and only slight deviations from solid body rotation out to the radius of maximum azimuthal velocity.

The salinity at 1000 db is shown in Figs. 9a–c as a dashed line. In each survey, a region of high salinity gradient or salinity front occurs somewhere outside the radius of the Meddy Core Water. In Fig. 9c, the front is at 23 km, even though intrusions have reached to within 2 km of the Meddy center. In each of the surveys, the maximum azimuthal velocity clearly occurs inside the salinity front. The radius of maximum circulation, $2\pi r v(r)$, where the relative vorticity changes sign, is outside of $v_{\max}$, and seems to correspond to the salinity front.

The radial velocity gradient near the center of the Meddy corresponds closely to the straight lines shown in Fig. 9, which have a slope corresponding to vorticity of 0.35 times the local Coriolis parameter. This indi-

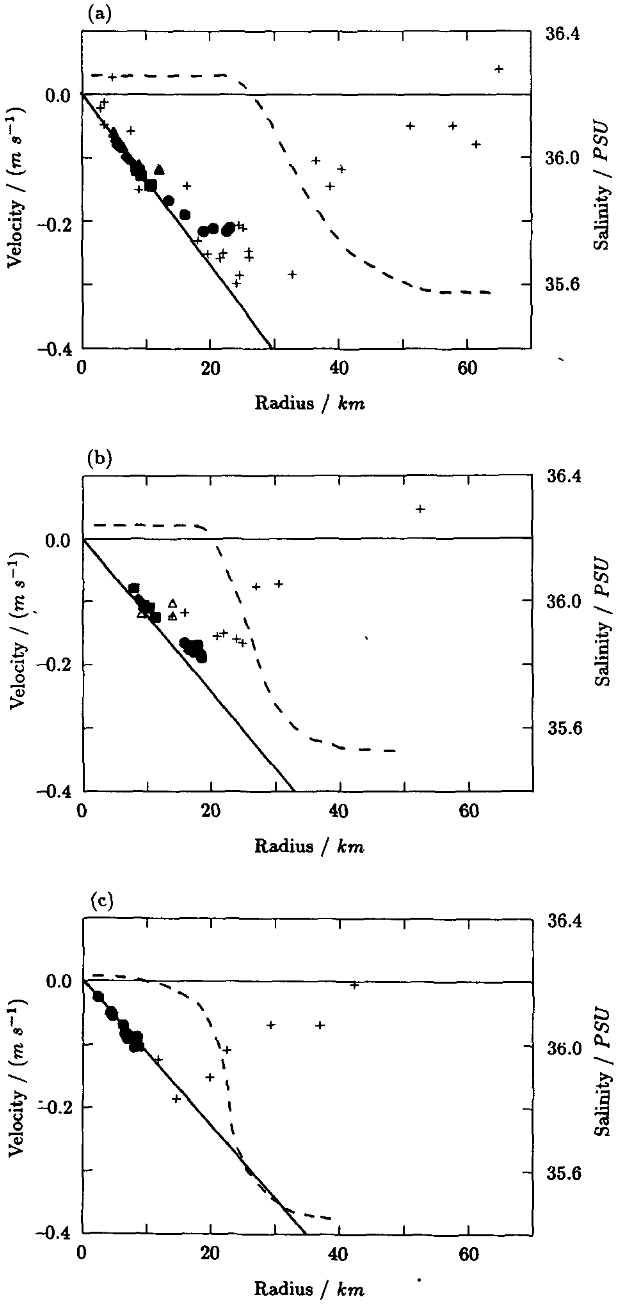
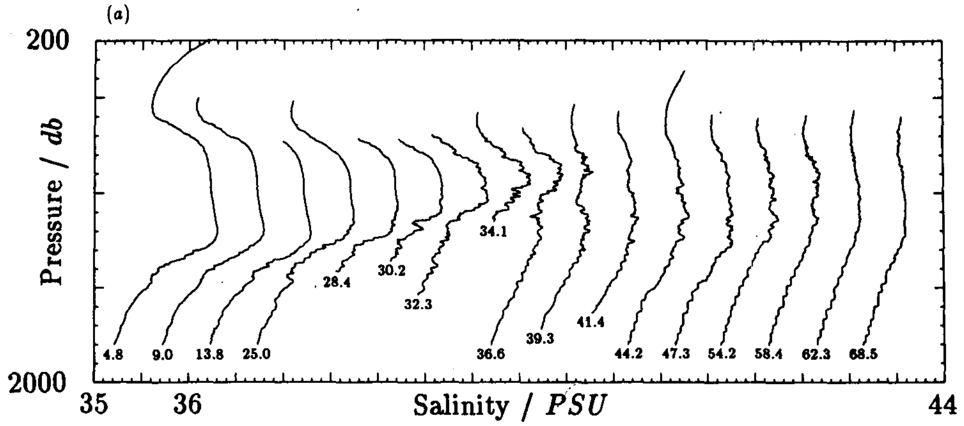


FIG. 9. Azimuthal velocity at 1000 m versus radius, for all surveys. (+) PEGASUS: Surveys I and III, (△) current meter: Survey II, (+) XCP: Survey II, (●) Float 128, (△) Float 143, (■) Float 141. PEGASUS and XCP are 100 m average at 1000 m, current meter is a 5-day average. Dashed line is the salinity at 1000 db. The straight line corresponds to a vorticity of 0.35 times the local Coriolis parameter.


(a)
200
2000
Pressure / db
35
36
Salinity / PSU
44
34.1
28.4
30.2
32.3
41.4
39.3
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9.0
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25.0
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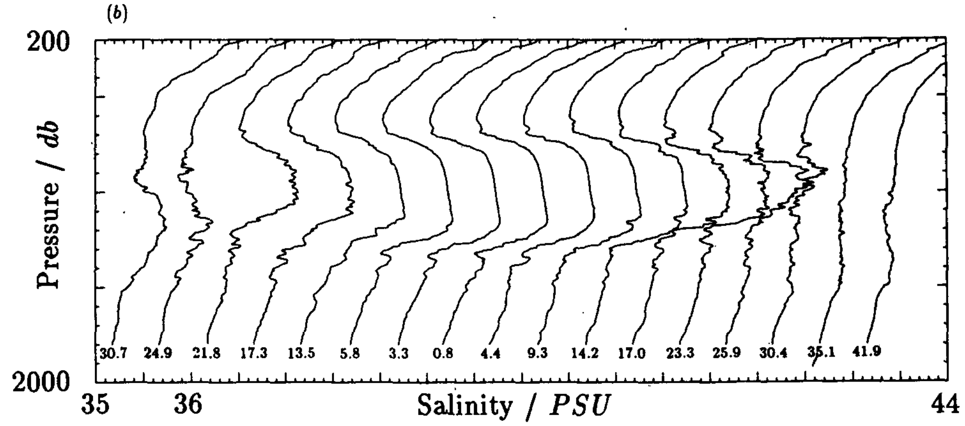
47.3
54.2
58.4
62.3
68.5


(b)
200
2000
Pressure / db
35
36
Salinity / PSU
44
30.7
24.9
21.8
17.3
13.5
5.8
3.3
0.8
4.4
9.3
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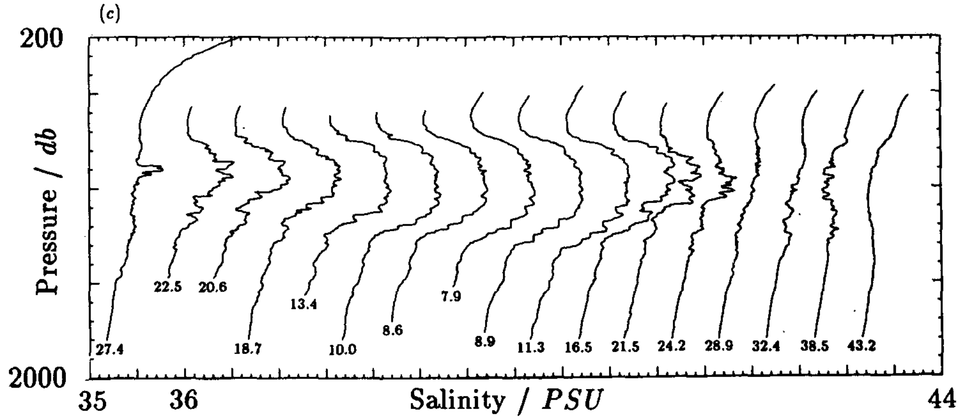
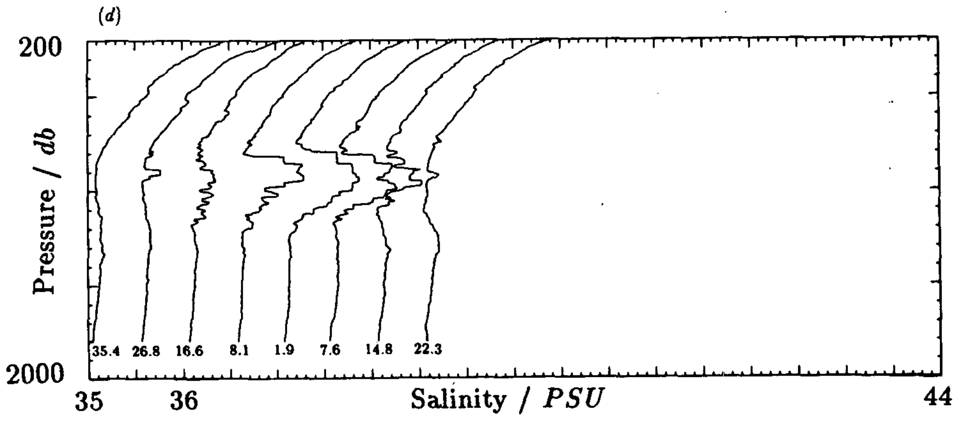
23.3
25.9
30.4
35.1
41.9


(c)
200
2000
Pressure / db
35
36
Salinity / PSU
44
22.5
20.6
13.4
7.9
8.6
27.4
18.7
10.0
8.9
11.3
16.5
21.5
24.2
28.9
32.4
38.5
43.2


(d)
200
2000
Pressure / db
35
36
Salinity / PSU
44
35.4
26.8
16.6
8.1
1.9
7.6
14.8
22.3

cates that the central vorticity of the lens does not change significantly during the first year.

5. Finestructure and microstructure

As was mentioned in the Introduction, the Meddy had a core region surrounded by a zone containing numerous thermohaline inversions, which are indicative of mixing by lateral intrusive motions. We will also see in this section evidence for vertical mixing of the lens via salt fingers and evidence for enhanced microstructure intensity at the top, bottom, and sides of the Meddy.

Figure 10 shows salinity–pressure sections across the Meddy obtained from each of the four survey periods. In the first two surveys, four distinct regions can be delineated:

1) A central core region, stably stratified in both salinity and temperature (recall Fig. 8), and with little or no finestructure.
2) The upper surface of the core, which is unstable to double-diffusive thermohaline convection, is relatively thin, and accompanied by relatively strong velocity shear. Steps can be discerned in some of the profiles, especially near the center.
3) The lower surface of the Meddy, which is unstable to salt finger convection ($R_\rho \approx 1.5$). Steps are obvious in all surveys.
4) An outer, intrusively mixed region, extending over the entire depth range of the core. This region is marked by the fluctuations in salinity, typically of rms amplitude 0.05 psu and vertical wavelength 30 m.

Comparing the four surveys, it is evident that the boundary between the core and intrusive regions moved inward during the first year, from a radius of 31 km in October 1984 to the center in October 1985. The average rate of advance of the boundary is 30 km yr^{-1} = 1 mm s^{-1}. The lateral exchange of warm, salty Meddy water with cooler, fresher Atlantic water causes a lateral salt flux consistent with a radial diffusivity of approximately 0.4 $\mathrm{m}^2\ \mathrm{s}^{-1}$ (Ruddick and Hebert 1988).

One possible cause of the interleaving is thermohaline intrusions (Stern 1967), in which the alternating vertical gradients of temperature and salinity created by the quasi-horizontal motion allow enhanced vertical mixing by double-diffusion (Turner 1973). The resulting buoyancy fluxes produce density and pressure perturbations which drive the interleaving motions. The dynamics and theories of thermohaline intrusions are reviewed, and the predictions of the theories compared with the results of the second survey, by Ruddick and Hebert (1988). Another possible cause of the layering is the differential diffusion of angular momentum and mass (McIntyre 1970), although this was considered by Hebert (1988b) to result in scales somewhat smaller than those observed. Still, another possible cause of the observed thermohaline inversions could be that the Meddy may have spun off small eddies around its edge, and these would be expected to (by barotropic instabilities, Gent and McWilliams 1986) break up vertically and attain an aspect ratio of $O(f/N)$. Hedstrom and Armi (1988) observed that their laboratory eddies broke up into several eddies after many inertial periods. The detailed investigation required to judge which of these three mechanisms is the cause of the observed interleaving has not yet been attempted.

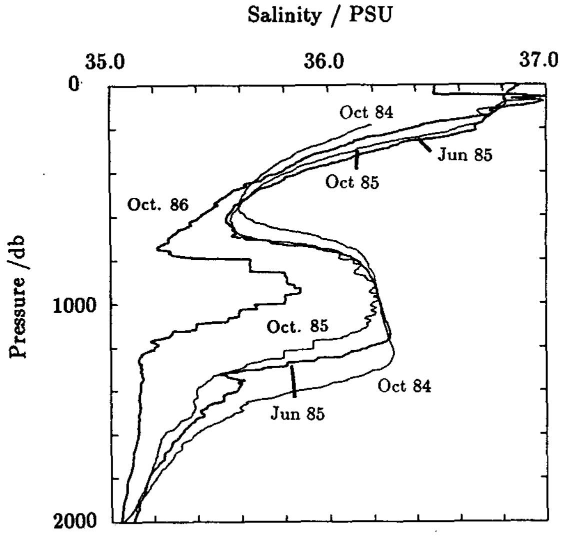


FIG. 11. Vertical profiles of salinity from near the lens center for each survey.

Although intrusions greatly altered the structure of the lens during the first year, the salinity and velocity anomalies remained strong after the intrusions had reached the center. During the second year, the salinity of the center of the lens (no longer a pure core), continued to decrease. The character of the salinity finestructure changed a great deal during this time, becoming more steppy, and attaining a larger vertical scale. The geopotential anomaly also decreased and had a diminished horizontal scale during the second year.

Evidence of vertical mixing at the underside of the Meddy is seen in Fig. 11, where the most central station of each survey is plotted. The core salinity did not change from the first survey to the second (any apparent changes are the result of isopycnal displacement). The presence of intrusions in the third survey, and the profound change in character of the finestructure in the fourth survey can be seen easily. Note especially the

FIG. 10. Vertical profiles of salinity, taken in a sequence passing near the lens center to its edge. Successive traces have been offset to the right by 0.5 psu. The radius of each station in kilometers is marked at the bottom of the trace. Surveys I–IV are labeled (a)–(d), respectively.

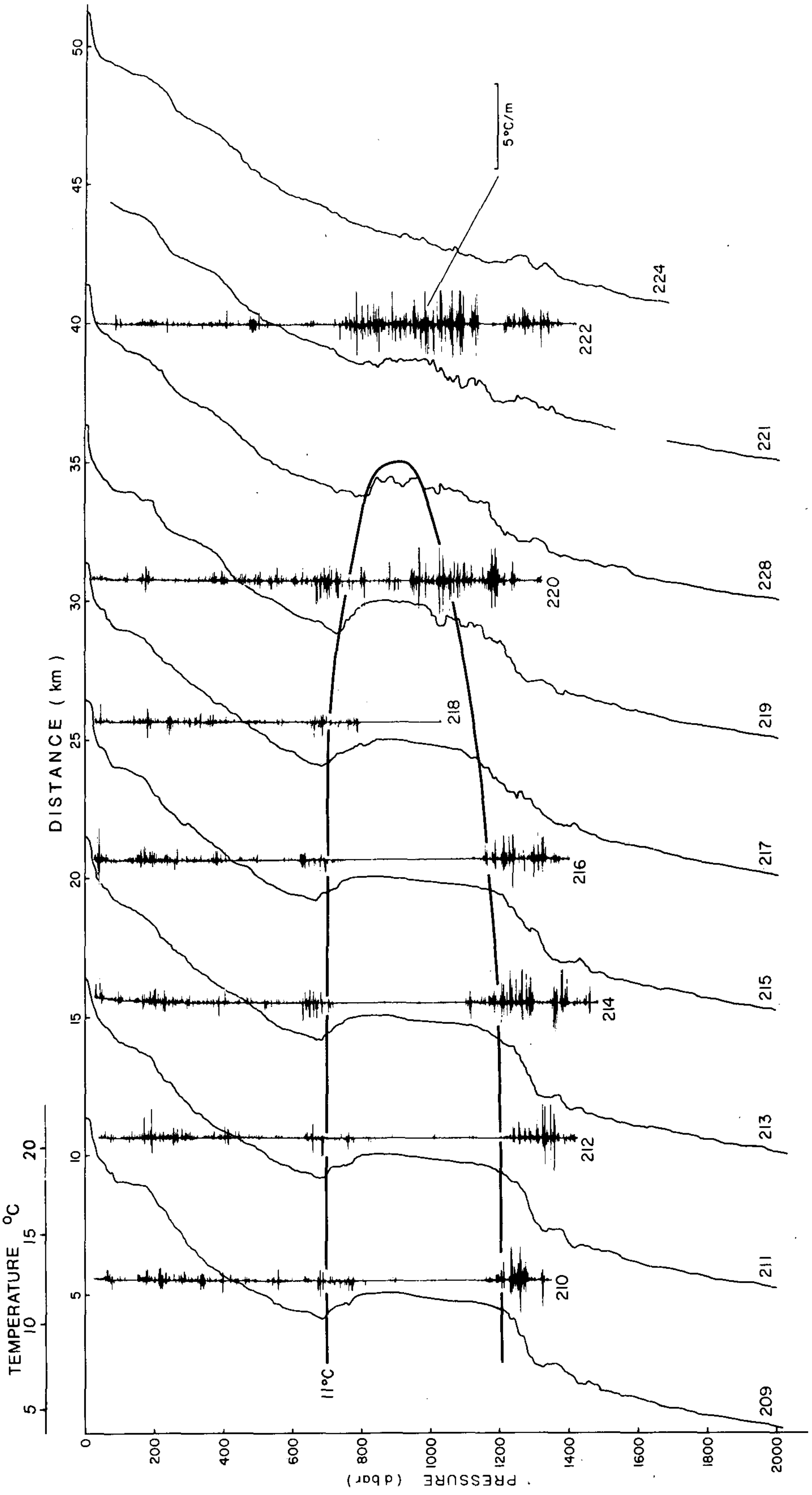


FIG. 12. The temperature structure (thin solid lines) and the corresponding temperature microstructure ("wiggly lines") for the lens during survey II. The heavy 11°C temperature contour is included for reference.

erosion of the bottom of the Meddy in the region which is unstable to salt finger convection. It is possible to detect the 0.15 psu steps in the salinity gradient region. The thickness of the observed steps became larger for later surveys. Although Fig. 11 might lead one to believe that we are seeing the evolution of individual steps, there is no evidence for this. The horizontal coherence of steps was much less than the lens radius. The apparent erosion from below is not simply an artifact of the vertical motion of isopycnals as the Meddy spins down; it takes place with respect to isopycnals as well. The precise thickness and salinities of the layers varied laterally, and from one survey to the next. Steps of this sort are often interpreted as evidence of the dominance of double-diffusive convection over other mixing mechanisms (Turner 1973). By assuming that the vertical erosion at the bottom of the Meddy was due to the divergence of the salt finger fluxes, Hebert (1988c) determined the fluxes in the region of the steps. Comparing these flux estimates with those predicted by applying laboratory flux laws to the observed steps during the January 1985 survey, Hebert (1988c) found that the observed flux estimates were a factor of 30 smaller. Since the interfaces of the observed steps were greater than 1 m, the observed fluxes were compared to estimates using Kunze's (1987) model for thick salt finger interfaces, and good agreement was found. Similar steps can be seen developing more slowly in the region above the core which is unstable to double-diffusive thermohaline convection.

The observed changes in the hydrographic structure of the Meddy suggest mixing by thermohaline intrusions at the sides, by salt fingers at the bottom, and by thermohaline convection at the top, with the intrusive mixing responsible for the largest fraction of the net mixing. During the second survey, direct observations of the temperature and velocity microstructure were made with the tethered free-fall profiler EPSONDE (Oakey 1987). This instrument was allowed to free-fall at a speed of 0.8 to 1.0 m s^{-1} to depths of about 1500 m, measuring temperature and its gradient with a platinum of thin-film thermometer, and two components of microscale velocity shear with probes of the type described by Osborn and Crawford (1980).

A sequence of traces of microscale temperature gradients, along with temperature observed at an adjacent CTD station, is displayed in Fig. 12. The radial position of each station is shown by the scale at the top of the plot. The 11°C isotherm contour is shown as a reference. A correspondence between the microstructure and the lens structure is readily seen; the microstructure is most intense at the top, bottom, and sides, and unusually weak in the core. The microscale velocity fluctuations show a pattern with very low turbulence in the core and high turbulence levels at the periphery.

Conventionally one thinks of vertical mixing (which we estimate from velocity and thermal microstructure variance) as being caused by shear driven mechanical turbulence. Indeed, in the case of the Meddy we find the largest microstructure variance in the periphery where the shear is largest. Oakey (1988) found, however, that in regions where double-diffusive processes were most likely, the temperature variance is much larger than can be explained by mechanical mixing. A working hypothesis is therefore that vertical mixing at the top and bottom and in the intrusions at the sides is a result of a combination of double-diffusion and shear-driven mixing.

6. Overall changes to the Meddy

In this section, we examine some of the bulk properties of the Meddy, its total dimensions and salt and heat content, and its dimensions and how these change over time. We find a qualitative difference in the changes during the first and second years.

To calculate the salt (and heat) content of the Meddy, we vertically integrated the salinity in excess of 35 psu (10°C for temperature) over a pressure range of 500–1500 db. Figure 13 shows the salt content per unit area ($\hat{S}$) as a function of distance from the lens center for each of the four surveys:

$$\hat{S}(r) = \int_{500}^{1500} \frac{(S(p) - 35)}{1000} g^{-1} dp.$$

The rounded appearance of $\hat{S}$ at the center in the first three surveys arises because the thickness of the core decreases with increasing radius (recall that the salinity of the core was nearly uniform at those times). Between surveys I and II, $\hat{S}$ decreased at the center, although the core salinity was unchanged (Fig. 11). This change reflects the decrease in core thickness over the period. The region of rapid decrease of S corresponds to the region of intrusions. At large radius, $\hat{S}$ becomes nearly constant at a background level, although this outer radius region appears to have a very weak gradient, and weak, residual intrusions can be detected in individual salinity profiles.

The total salt (and heat) content of the Meddy relative to a background state were determined by integrating $\hat{S} - \hat{S}_b$ radially over the lens area,

$$\text{total salt} = \int_0^{rb} 2\pi r(\hat{S}(r) - \hat{S}_b) dr$$

where $\hat{S}_b$ is the salt per unit area of the reference state. Because the background temperature and salinity decreased substantially as the Meddy moved southward into fresher, cooler water (at ≈1000 db), we computed salt and heat content relative to two reference states: a fixed background from survey II (Fig. 14), and the local background (Fig. 15). Choosing a constant reference state would lead to an overestimate of the rate of loss and salt and heat. The second choice of reference states

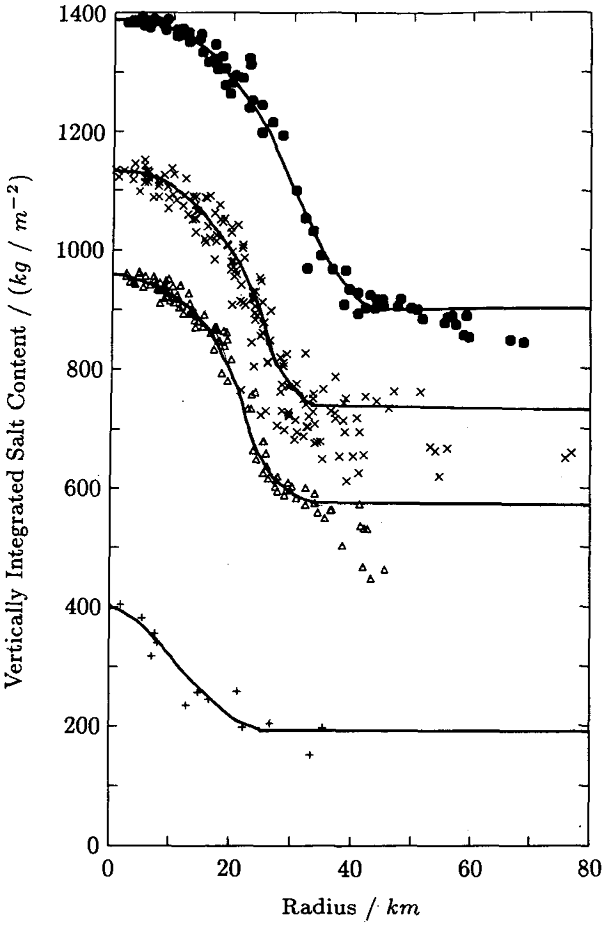


FIG. 13. Depth integral of (S − 35) from 500 to 1500 db as a function of radius. (●) October 1984. (×) June 1985. (△) October 1985. (+) October 1986.

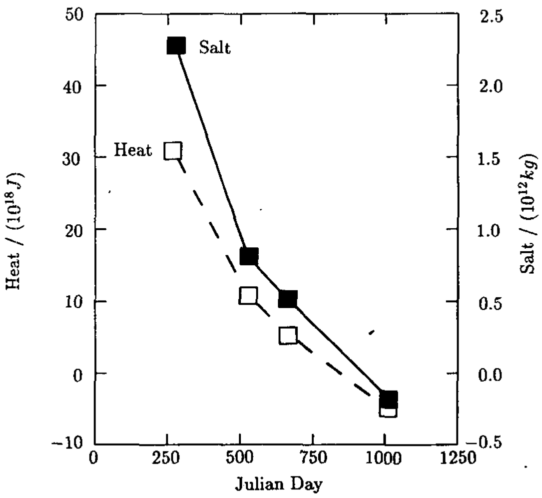


FIG. 14. Variation of total salt (■) and heat (□) content of the Meddy, relative to the background salinity and temperature in June 1985.

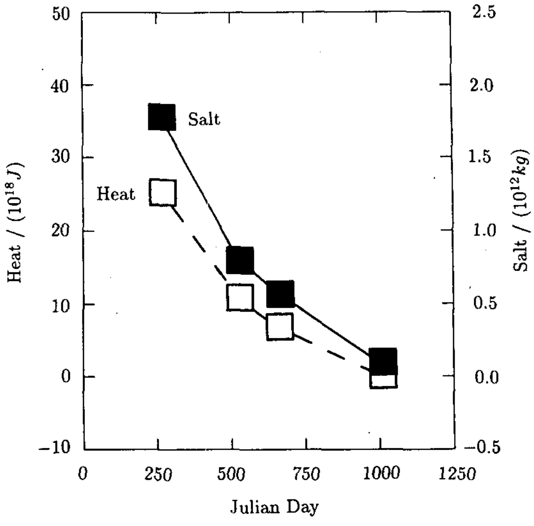


FIG. 15. Variation with time of total salt (■) and heat (□) content of the Meddy, relative to the local background salinity and temperature at the time of each survey.

will underestimate the change in content between surveys.

Figure 14 shows the salt and heat content relative to the background value of the second survey, chosen because it is in the middle of the three detailed surveys. The depth integration is over a constant pressure range which extends above and below the Meddy. Since the background salinity is changing (decreasing) and the Meddy is shrinking, some of the computed salt change is due to the inclusion of background water above and below the Meddy. The changes in salt and heat content relative to a fixed background will overestimate the fluxes. We attempt to correct for this by adding the difference in salt (heat) content above and below the Meddy between the local background and the June 1985 background. To be conservative, we only correct for these background effects above and below the Meddy center, integrated over the area of the Meddy. Thus, the salt and heat losses will still lead to slight overestimates of the true fluxes.

The salt and heat content computed relative to the local background for each of the surveys is shown in Fig. 15. It is evident that the anomalous heat and salt content decreased to nearly zero over the two years, with a more rapid change before survey II than after. The change in density due to the salt lens of the Meddy is compensated by the change in density due to the heat loss, as though isopycnal processes were largely responsible for the mixing.

If the Meddy had simply spread into a resting environment, then the total salt and heat would have been conserved. Apparently the mixing processes carried salt and heat outside the Meddy. The background velocity field then carried this water away, or else selfadvection of the Meddy in the ambient potential vorticity gradient carried it away from the mixed water. In either case, the Meddy presumably left a trail of salty, warm "blobs" of water that mixed or drifted away in the eddy field.

Time variation of total salt and heat relative to the June 1985 background (Fig. 14) is similar to Fig. 15, but of course shows negative anomalies in the final survey because of the choice of reference. The rates of loss of salt and heat computed from Figs. 15 (underestimate) and 14 (overestimate) decrease significantly in the second year, Table 2. If we assume that the Meddy loses salt and heat by horizontal processes and the shape of the Meddy can be represented as a pill box then

$$\frac{\partial}{\partial t}(\text{total salt}) = 2\pi r h F_s$$

where F_s is the horizontal flux through the side of the pill and r and h are the radius and height of the pillbox. Assuming that this radius is proportional to either the total radius or radius of maximum salinity gradient (see below) and that h is constant or proportional to the thickness of the Meddy at the center, we find that F_s decreased by a factor of 5 in the second year. Note that the total heat and salt of Figs. 14 and 15 are nearly exponential with a decay constant of approximately 300 days.

In Fig. 16 we summarize the changes in overall lens dimensions over the two years. Intrusions advanced inward until about day 600, when they reached the lens center. Prior to this time, the total lens radius decreased at about 1 mm s^{-1} (10 km/100 days), but held almost steady after day 600. Comparing these measures of lens radius with the velocity structure in Fig. 9 reveals that there is a fair correspondence between the radius of maximum velocity and the edge of the core (both at 25 km) for survey I, but that the maximum velocity is outside the core in survey III. The radius of maximum lateral salinity gradient at 1000 db is shown as the open squares in Fig. 16. The location of this salinity front corresponds better with the radius of maximum circulation, where the relative vorticity changes sign. In other words, the relative vorticity and salinity fronts appear to coincide.

TABLE 2. Salt and heat lost rates of the Meddy. Lost rates were calculated for both underestimates and overestimates of salt/heat content.

	Survey		
	I—II	II-III	III-IV
Period	Oct 84–Jun 85	Jun 85–Oct 85	Oct 85–Oct 86
Salt/10^4 kg s^{-1}	4.3–6.6	1.8–2.5	1.6–2.3
Heat/10^{11} W	6.4–9.0	3.3–4.6	2.2–4.1

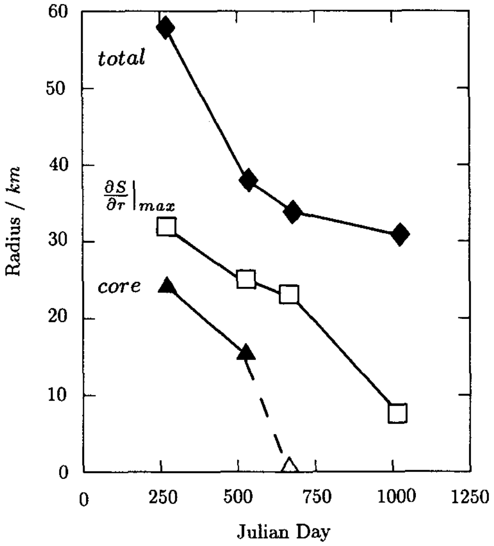


FIG. 16. Bottom curve: the radius of the core (▲), defined as the radius at which the peak-to-peak amplitude of the salinity inversions first exceeds 0.01 psu. The open triangle is used for the third survey since the nearest station to the center occurred at a radius of 2.2 km. Intrusions were present at this station. Uppermost curve: the total radius of the lens (◆), defined as the radius within which the peak-to-peak amplitude of the salinity inversions exceeds 0.05 psu. (□) Radius of maximum radial salinity gradient at 1000 db.

7. Summary and discussion

Meddy Sharon remained a coherent eddy with an intact core which retained floats for roughly two years. During this time, it moved 1100 km south in an irregular fashion, and the central core continued to rotate with a period of 5–6 days. From the velocity measurements, we see that the region of the Meddy within the velocity maximum, is approximately in solid body rotation. The Meddy suffered a net loss of heat and salt, in a ratio suggesting that isopycnal mixing processes dominated, and with an *e*-folding time of about 1 year. The salinity structure shrank both horizontally and vertically, as the Meddy underwent two somewhat different patterns of decay:

1) During the initial 8–12 months, the Meddy had a central core that was intrusion-free, with a negligible horizontal salinity gradient. This region is bounded by an intrusive region, with large salinity gradient. The azimuthal velocity maximum coincided with the core/intrusion boundary, and the circulation maximum, at which the vorticity changes sign, coincided with the maximum salinity gradient. As the intrusions penetrated to the center of the core, the velocity and salinity structure decreased in radius, with the central vorticity remaining nearly constant. The outer boundary of the intrusive region also decreased in radius during this time.

2) After the intrusions reached the center, the central salinity began to decrease. However, the central vorticity remained nearly constant and the salinity front remained out at 20 km radius, moving in to 15 km during the second year. The outer radius of the intrusive region decreased only a few km during the second year. The central salinity anomaly became weaker during the second year, and vertical temperature and salinity profiles through the intrusions became more steplike.

Microstructure observed during the second survey was most intense at the top, bottom, and in the intrusive regions, suggesting that vertical mixing was not purely mechanical in origin, but may involve double-diffusion. The development of thermohaline steps and layers above and below the core, and in the core by the time of the fourth survey also supports the notion that double-diffusive mixing may be involved. However, the lateral intrusive mixing at the sides appears to be responsible for most of the salt and heat loss from Meddy Sharon.

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