phase and amplitude behaviour. The mean lifetimes are found to be ~50 days at order 20 with a reduction of ~1 day per order as the order of the mode increases.

The mean frequencies of the $l = 0$ and $l = 1$ modes were found for each year from 1977 to 1985. Considering the $l = 0$ modes with $n = 14$–26, no net frequency shift was found. This should be contrasted with an earlier preliminary analysis of data from 1980 to 1984[4] which indicated a slight, although not statistically significant, positive shift. This analysis of the $l = 1$ modes confirms that no conclusive evidence for a frequency shift is found.

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The history and decay of a Mediterranean salt lens

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Subsurface coherent vortices called Meddies[1] are formed by the outflow of salty water from the Mediterranean Sea[1,2] into the North Atlantic. In October 1984 we began a study to observe the life history and large-scale changes of a Meddy by identifying a specific Meddy, and carefully mapping it and seeding it with Sofar floats[3]. (These neutrally buoyant floats are tracked acoustically and can be located aboard ship.) As this Meddy moved southward across the Madeira Abyssal plain, it was resurveyed three more times during a span of two years. Being able to find this same lens (100 km in diameter) on successive surveys was itself a unique achievement that allowed us to observe the Meddy evolution and to gain new insight into the importance of different mixing mechanisms that cause Meddy decay. We find evidence of mixing by at least three processes: (1) lateral mixing by the exchange of layers of water ('thermohaline intrusions')[4,5], (2) vertical mixing at the underside of the lens by salt fingers[6] and (3) mixing by turbulence. Together these cause the net heat and salt anomalies to decay with an e-folding time of about one year. Despite the mixing, the relative vorticity at the core remained constant for the first year and the Meddy retained its coherent shape over a two-year period.

The life of Meddies is of interest to oceanographers for at least two different reasons. One reason for tracking Meddies is to assess their role in the lateral dispersion of heat and salt[2,7,8]. The high-salinity Mediterranean outflow spreads into the North Atlantic to form a 'tongue' which can be observed from the coast of Portugal to well beyond the Mid-Atlantic Ridge. Also, many Meddies (formed from water from the same source) have been found in the Canary Basin to the south of this tongue[2,7,9], and evidence for one near the Bahamas has been reported[1]. It is interesting to speculate that the salt tongue is due all or partially to decayed Meddies. To answer this we would need to know the number produced per year and their decay rate. By following one particular Meddy, the changes in lens properties can be observed, and the rates and mechanisms of exchange with the surrounding water can be inferred. A second reason for studying these lenses is that a Meddy might also be viewed as an isolated deep-water laboratory with its own dynamics, whose mixing behaviour observed over an extended period of time may be compared with the estimated changes from smaller-scale processes. To this end, the second visit included a complete survey of temperature and velocity microstructure using the deep-ocean microstructure profiler Epsonde[10], to examine the role of turbulent mixing in the energetics of Meddy decay. In addition, there were velocity measurements from an acoustically tracked velocity profiler, Pegasus[11], during the first and third

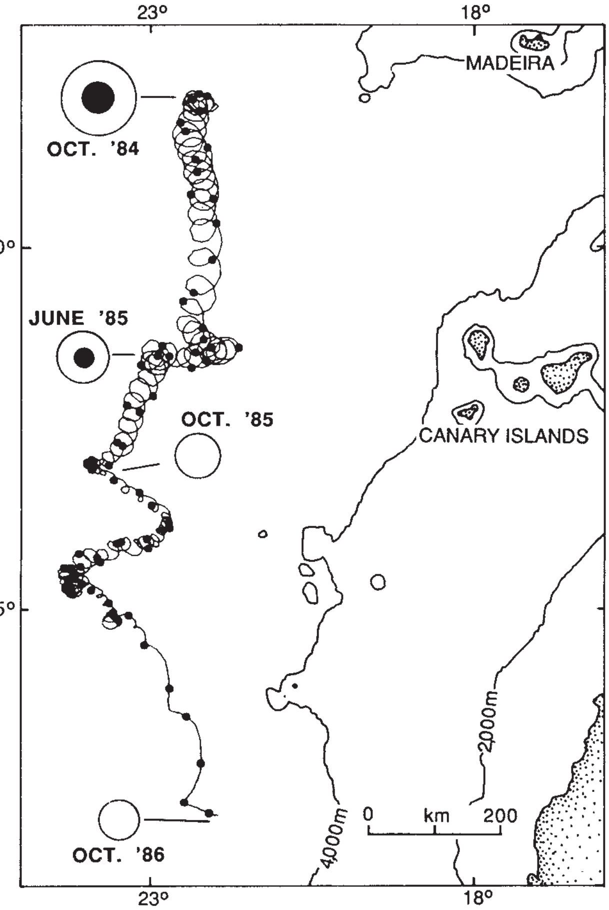

Fig. 1 Track of Sofar float EB128, which remained in the Meddy for nearly two years at a depth between 1,100 and 1,200 dbar. The dots indicate 10 day intervals. The 2,000 and 4,000-m isobaths are shown for reference. The circles indicate the size, structure, and position of the Meddy at each of the four surveys. Solid circles: Meddy Core Water. Open circles: Meddy Mixed Water.

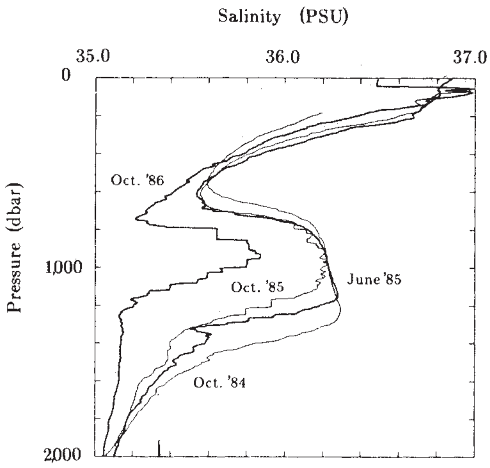

Fig. 2 Salinity profiles through the Meddy centre at each of the four surveys.

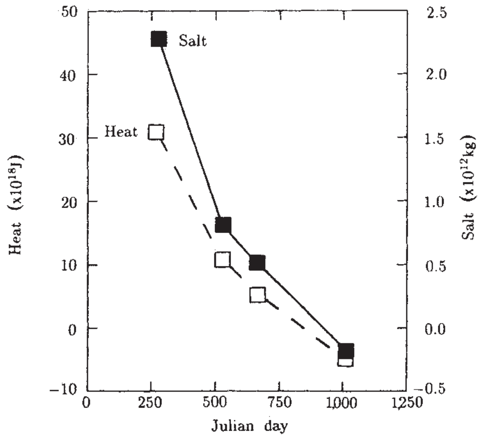

Fig. 3 Vertically and radially integrated salt (■) and heat (□) content for each of the surveys, computed relative to the background of the June 1985 survey. Day 1 is 1 January 1984.

surveys, and from a mooring and expendable current profilers (XCPs) during the second survey, which allowed us to examine temporal changes in the vorticity as the Meddy decayed.

The two-year track of one of the Sofar floats implanted in the lens in October 1984 is shown in Fig. 1. The float trajectory consists of a slow, irregular translation due to the mean motion of the Meddy centre, plus a looping motion. The translation was mainly to the South, covering 1,100 km in two years. There is no clear scientific explanation why the Meddy moved southward rather than westward as suggested by Killworth[12]. The irregular motion would be consistent with the advection of the lens in the mesoscale eddy field. The looping motion is due to the anticyclonic motion about the Meddy centre which has a period of about six days. This period remained nearly constant throughout the experiment, except near the end, when both the period and the radius of looping increased.

In the discussion to follow, we define the anomalously warm, salty water of Mediterranean origin, smoothly stratified in both temperature and salinity as Meddy Core Water. In the initial survey this Meddy Core Water, which is anomalous in its temperature and salinity characteristics from the surrounding water in the Canary Basin (typically 11.9 °C and 36.2 PSU (practical salinity unit)) was found out to a distance 50 km from the lens centre before significant exchange with the background water was evident. Significant exchange was defined operationally as salinity profiles where the intrusions caused peak to peak fluctuations in salinity $S_{pp} > 0.01$ PSU. The region beyond the core will be called Meddy mixed water (a mixture of core water and background water) and is delineated from the background by the operational criterion of $S_{pp} > 0.05$ PSU Vertical profiles of salinity through the centre of the Meddy from each of the surveys are shown in Fig. 2. When first observed in October 1984 the core extended from 650 to 1,400 dbar in total, with the region from 800 to 1,300 dbar being stable to double-diffusive processes. The core was thinner by June 1985, but still fairly smooth in vertical profile, showing no major effect of intrusions or mixing with the background water at the centre. The salinity of the core water was the same as in the previous survey: any apparent change in salinity is due to isopycnal displacement. By October 1985 intrusions reached the centre, as evidenced by the presence of salinity inversions. We refer to these signatures of Meddy mixed water as intrusions, but we know little of their horizontal structure. Some closely spaced conductivity-temperature-depth (CTD) profiles in the first three surveys indicate coherence of these inversions over distances of several kilometres. Although the Meddy Core Water was replaced by Meddy Mixed Water to the centre in about a year, the salinity anomaly was still ~0.6 PSU, very little less than the salinity anomaly of the original Meddy Core Water. By the following year (October 1986) the inversions became much more step-like (suggestive of salt-fingering processes), and the salinity anomaly was much smaller. It was also apparent that the Meddy has drifted into fresher water, characteristic of 22° N.

The radial extent of the Meddy Core Water at each survey is shown as the filled circles in Fig. 1. Surrounding the core was a region of mixed water with a signature similar to the central profile of October 1985 of Fig. 2. This part of the lens contained many thermohaline inversions of up to 30 m vertical extent, and is represented in Fig. 1 by the area between the filled and open circles. By the second survey, the core water and surrounding mixed water decreased significantly in size. Did the Meddy slowly mix to this state, as suggested by the continued presence of the Sofar float in the lens, or were portions of it torn away by instabilities and turbulence? Although little turbulent mixing was observed in the Meddy core, turbulence and microstructure strongly suggestive of double-diffusive processes were very much in evidence at the Meddy periphery during the second survey[10]. By the third survey, the Meddy Core Water was entirely supplanted by Meddy Mixed Water. Inversions characteristic of intrusions were ubiquitous, but the salinity anomaly was greater than 0.6 PSU out to 19 km. This anomaly decreased markedly by the fourth survey. The total radius of the lens, including the mixed water region, decreased between the first and second survey, but did not decrease appreciably after that.

Figure 2 also documents the development of steps in the region underneath the Meddy core which is unstable to salt fingers. The steps have a salinity change of about 0.1 PSU, and become thicker and more sharply defined over time. Although Fig. 2 might suggest that we are seeing the evolution of individual steps, there is no evidence for this. The horizontal coherence of steps over distances much less than the lens radius was small even on a single survey. The apparent erosion from below is not simply an artefact of the vertical motion of isopycnals as the Meddy spins down; it takes place with respect to isopycnals as well. The precise thicknesses and salinities of the layers varied laterally, and from one survey to the next. Steps were observed at the base of the core for all surveys. Near the top of the Meddy, which is unstable to double-diffusive convection, steps were also observed but were not as pronounced as those below.

We computed the total excess salt content of the Meddy, relative to the background found at the June 1985 survey, as

$$\text{Total salt} = \int_0^{\max} 2\pi r \, \mathrm{d}r \int \left(\frac{S(r,p) - S_{\text{ref}}(p)}{1{,}000}\right) g^{-1} \, \mathrm{d}p \quad (1)$$

where the reference state S_{ref} is the salinity outside the Meddy during survey 2. The pressure integration extends only over the depth range occupied by the Meddy at the central station to reduce the erroneous contribution of the changing background salinity. The excess heat content of the Meddy relative to the background was computed in a similar manner, and both are shown in Fig. 3. The values for the final survey are negative because of the choice of reference profile.

The initial excess salt content, 2.5×10^{12} kg, corresponds to the excess salinity contained in about 10 days of Mediterranean water flow through the Strait of Gibraltar at a volume transport of $10^6\ m^3\ s^{-1}$ and an excess salinity of 2.5 PSU (ref: 13).

The Meddy has been envisaged as a lens of water, with salinity greater than 35.8 PSU, originally containing mostly core water and increasing amounts of mixed water as it decays. The Meddy lost substantial amounts of heat and salt. Salt was not conserved in our study because we chose to look only in the region of the strongest anomaly as described above. It is apparent that the mixing process carried salt and heat outside the well defined anticyclonic velocity core. The background velocity field may have carried this mixed water away, or otherwise the self-advection of the Meddy in the ambient potential vorticity gradient[14] carried the Meddy away from the mixed water. In this case, the Meddy would presumably leave a streaky convoluted 'salty trail' of mixed water as it moved. In fact, in the second survey, many 'blobs' of salty water with anomalies as high as 0.2 PSU were found to the east and southeast of the main Meddy. These may have been shed as the lens moved westward, preceding the time of the June 1985 survey.

The ratio of salt to heat loss was nearly constant throughout the two years. In terms of density effects, the two rates of loss were nearly equal, as expected for isopycnal processes. The rates of loss were twice as large ($6.5 \times 10^4\ kg\ s^{-1}$ and 9×10^{11} W respectively) in the first year, when an unadulterated core still existed, than they were in the second year, when the core was riddled with intrusions and the salinity anomaly was smaller. The loss rates correspond to an e-folding time of roughly one year, but are somewhat uncertain because of the changing background. The change in rate of loss may be related to the time at which intrusions reached the centre of the Meddy, or may simply be because the salinity anomaly was smaller in the second year.

On the basis of the above preliminary results, we put forth the following life history for this Meddy: (1) the Meddy remained a coherent, vortical structure for at least two years; (2) temperature and salinity inversions or intrusions filled the entire Meddy by the end of the first year as Meddy Core Water mixed laterally with background water to fill the entire Meddy volume with Meddy Mixed Water; (3) the mixed water outside the region of strong Meddy circulation was either left behind or swept away by background currents and eddies, causing a net loss of salt and heat from the Meddy; (4) during the second year, when the core was completely riddled with intrusions, the salinity anomaly at the centre decreased, and salt was lost more slowly than in the first year; (5) steps (a thermohaline staircase?) formed underneath the Meddy, where salt fingering is possible, and to a lesser degree above the Meddy where diffusive convection could occur; (6) the mixing processes did not appear to strongly transport angular momentum into or out of the core region. This is suggested by the roughly constant core vorticity, shown by the float track of Fig. 1, and by the supporting velocity profile studies. Whereas the salinity and vorticity in the core changed little over the first year, a net loss of angular momentum did occur as the core became smaller, with the removal of the mixed water from the vicinity of the Meddy; (7) turbulent mixing processes are active at the periphery of the Meddy, not only at the upper and lower boundary, but particularly in the mixed water region.

This informal collaborative experiment grew from the initial proposal of Armi and others joined with their respective contributions. The authors' names are assigned alphabetically. Dave Hebert was the scientist in charge of the reduction and analysis of the data from all four surveys.

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A deep hydrological front between intermediate and deep-water masses in the glacial Indian Ocean

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Ocean circulation and climate are strongly interconnected. Under climatic conditions very different from those of today, deep and intermediate water circulation was subject to drastic changes[1–7]. For instance, during the last glacial maximum (LGM), deep ocean water was cooler than now by several degrees[8]. These temperature changes in the deep ocean were associated with striking variations in chemical characteristics of the intermediate and deep water masses of the Atlantic and Pacific Oceans[3,8–13]. Here we reconstruct the hydrological structure of the deep and intermediate water of the Indian Ocean during LGM (~18,000 yr BP). The carbon and oxygen isotope analyses of the benthic foraminifera genus *Cibicides* show that the water-column structure of the Indian Ocean during LGM was marked by the presence of a deep front separating intermediate and deep-water masses with very different characteristics. Intermediate-water mass temperatures and $\delta^{13}C$ were similar to those of today. By contrast, the deep water was cooler than now by at least 1.5 °C, more depleted in ^{13}C and poorly oxygenated.

Under present conditions, the hydrological situation of the Indian Ocean is different from that of the other oceans. Intermediate water in the South Indian Ocean has a strong component of surface Antarctic water and is recognized by a salinity minimum to the north as far as 10° S (ref. 14). By contrast, in the North Indian Ocean (north of 10° S), intermediate depths are mainly occupied by highly saline water from the Red Sea and the Arabo-Persian Gulf. Another contribution between 10° S and 15° S comes from the Pacific Ocean through the Indonesian Archipelago, and occupies depths between 500 and 1,200 m (ref. 15). Below 2,000 m, the Deep Indian Ocean Water originates mainly from the Southern Ocean[16,17].

To determine the impact of the last glaciation on the Indian Ocean hydrological pattern, we have measured the foraminiferal $\delta^{13}C$ and $\delta^{18}O$ values in seventeen sediment cores from the two major basins of the North Indian Ocean, in the depth range from 1,250 m to 3,420 m (Table 1 and Fig. 1).

Kroopnick[18] has demonstrated that the distribution of $^{13}C/^{12}C$ ratio of the $\Sigma\ CO_2$ of sea water delineates the general distribution of water masses and that modern $\delta^{13}C$ gradients in the deep ocean follow the net flow of the deep waters. Some species of benthic foraminifera (genus *Cibicides*) closely record the modern $\delta^{13}C$ distribution in the world ocean, providing a good proxy for the reconstruction of the past $\delta^{13}C$ gradients in the