MEDDIES AND SUB-SURFACE EDDIES

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Introduction

Meddies and related types of circular motion in the ocean belong to a class of eddy activity characterized by a highly coherent, axisymmetric circulation in the horizontal plane. These stable features have a lifetime measured in years, during which time they may drift thousands of kilometers, carrying with them waters from where they were formed. They play an important, but as yet inadequately defined and quantified, role in the transport and exchange of waters between different regions. Understanding these processes is of fundamental importance for a correct characterization of subsurface eddy processes in the ocean and their representation or parametrization in ocean circulation models.

These subsurface eddies, shaped as very thin disks or lenses with an aspect ratio of $\sim 1:50$ to $\sim 1:100$, have a core body that rotates virtually as a solid disk, surrounded by a perimeter region of strong radial shear. Among the largest and most conspicuous of this type of eddy motion, the meddy (for Mediterranean eddy), can have diameters exceeding 100 km and life spans measured in years. We now know that this type of eddy motion, discovered in 1976, occurs in many regions of the world ocean, at shallow depths and deep, in tropical, subpolar, and arctic waters. Some eddies, such as the meddies, rotate anticyclonically, but, evidently just as likely, lenses may rotate in the other direction. From the growing observational database it now appears that the meddies do not merely drift with, but can in fact move through the surrounding waters. Their ubiquity, longevity, and mobility render them of potentially great importance in the transport, exchange, and mixing of waters between different water masses in the ocean. But there is much about these enigmatic features we have yet to understand.

Definitions

On scales of tens of kilometers and larger in the ocean, fluid motion is in geostrophic balance, meaning that the pressure gradient is balanced by the Coriolis force. These forces act at right angles to the direction of motion and thus do not tend to accelerate or alter the pattern of flow. For the circular motion of eddies discussed in this article, particle motion is curved rather than straight. This adds a radial acceleration, v^2/r, also perpendicular to the direction of motion, into the momentum balance, giving rise to a cyclogeostrophic balance or flow:

$$fv + \frac{v^2}{r} = -\frac{1}{\rho}\frac{\partial p}{\partial r} \qquad [1]$$

where r is the radius of the curved motion, v is the azimuthal velocity, p is pressure, $f(=2\Omega\sin(\text{latitude}))$ is the Coriolis parameter, Ω is the angular velocity of the earth, and ρ is the density of the fluid. Again, because the forces act at right angles to the direction of motion, they do not alter the pattern of flow, i.e., the pattern is self-preserving. We call the clockwise motion of the (northern hemisphere) meddies anticyclonic, because they have a pressure maximum in the center. Low-pressure cyclonic eddies rotate in the opposite direction. Cyclones and anticyclones rotate in the opposite direction in the southern hemisphere.

Potential vorticity expresses the circulation per unit volume of fluid and for our purposes can be written as $(f+\zeta)/h = \text{constant}$, where f is the Coriolis parameter and ζ represents the relative vorticity of a layer of fluid with thickness h. The conservation of this quantity, in the absence of forcing or dissipation, severely constrains the movement of fluids. For steady axisymmetric motion, a fluid parcel's potential vorticity is automatically conserved.

A measure of the intensity of rotation is given by the ratio of the relative vorticity of the core of the lens to the planetary vorticity, the Rossby number: $R = \zeta/f$. Typical R values for meddies range between -0.1 and -0.6, with the most extreme value reported $= -0.85$. Another number, the Burger number, expresses the ratio of strength of relative vorticity to the vortex stretching terms in the potential vorticity equation and is normally written as $N^2H^2/(f^2L^2)$. The Burger number can also be defined as the ratio of the available potential energy to kinetic energy of the lens.

SOFAR (sound fixing and ranging) and the related RAFOS floats reveal how fluid parcels drift, disperse, and mix in the ocean from their trajectories, which are determined by acoustic triangulation. SOFAR floats transmit signals to stationary hydrophones; RAFOS floats listen to moored acoustic sound sources. The travel times multiplied by the speed of sound in the ocean give the distances to within a few kilometers accuracy. Isopycnal RAFOS floats can also drift with the waters in the vertical. Because isopycnals move up or down or as fluid slides up or down along isopycnals such as across the Gulf Stream, isopycnal floats will accurately follow that motion. These acoustically tracked floats have been major contributors to our knowledge of the subsurface eddy field.

History

During an oceanographic cruise in the Fall of 1976 to study ocean currents east of the Bahamas, a large body of very warm and salty water was observed at 1000 m depth. Shaped as a thin lens, it had a core diameter of nearly 150 km and a thickness of 500 m. Nothing like this had been observed before. Several SOFAR floats deployed in it to study the currents revealed a clockwise circular motion with a 10-day rotation period for the innermost float at 10 km radius. The proximity of this warm saline lens to the well-known Mediterranean Salt Tongue that stretches west across the ocean (centered near 30°N) clearly suggested a Mediterranean origin. This discovery stimulated a search for similar temperature–salinity anomalies in the eastern Atlantic, and before long it became clear that these lenses, coined meddies for Mediterranean eddies, have a widespread distribution in the eastern Atlantic west of Spain and Portugal. We now know that these lenses belong to a class of coherent motion most characterized as thin spinning disks with a thickness to diameter (or aspect) ratio of about 1 : 100. While meddies rotate only anticyclonically, other subsurface eddies or lenses may rotate in the other direction. Their overall diameters range from perhaps less than 10 km to as large as the 150 km of the original meddy, which remains one of the largest ever found. During lifetimes of months to years, they may travel thousands of kilometers. The focus here is first on the well-studied meddies, their structure, origin, patterns of drift, and decay. Other observations that illustrate the ubiquity of this class of eddy motion are then discussed.

The Meddy

Structure

The typical meddy has a very distinctive density and velocity field. A vertical cross-section will reveal a spreading of the isopycnals such that the core or center of the eddy has weak stratification bounded by layers above and below with very high stratification (**Figure 1**). This leads to a pressure field that is higher inside the lens than outside, which requires for equilibrium an anticyclonic rotation (clockwise in the northern hemisphere). The top panels show typical profiles of temperature, salinity, and density of meddy 'Sharon' in 1984 and in 1985, one year later. Averaged over the volume of the meddy the contributions of high temperature and salinity to density must cancel and equal the average density of the displaced waters (Archimedes' principle). Hence, the core waters at 12°C and 36.2 PSU, have the same density as the surrounding waters at 8°C and 35.6 PSU at 1000 m where the density profiles can be seen to cross. But the vertical spread of the isopycnals results in radial density gradients such that for the lower half of the meddy the density inside is less, and for the upper half is higher, than that of the surrounding waters. If we imagine that at great depth the pressure is the same everywhere, then as we ascend into the meddy, the hydrostatic pressure will decrease less rapidly than outside so that pressure in the center of the core exceeds that of the surrounding waters by about 500 Pa (5 mbar). It is this excess pressure that maintains the orbital or rotary motion of the eddy in cyclogeostrophic balance. If we continue up through the meddy, the greater density of the core waters leads to a more rapid pressure drop than outside such that topside of the meddy at the surface the radial pressure all but vanishes. (This does not always apply, some meddies, especially recently formed ones, may have a surface signature.)

Meddy 'Sharon,' by far the best-documented meddy, was visited four times over a 2-year period during which detailed surveys of the density, velocity, and microstructure were conducted. Orbiting SOFAR floats trapped in the meddy made it easy to relocate for subsequent visits. Vertical profiles of horizontal velocity show a maximum at about 1000 m depth and increasing linearly outward. Beyond a certain radius the velocity field decreases rapidly. **Figure 1D** shows the azimuthal velocity as a function of radius. The sharp transition from a linear increase to radial decay indicates the radial limit of solid body rotation. This rotation rate has a maximum at mid-depth (near 1000 m) and decreases slightly above and below. But at each depth the rotation appears to be that of a solid body; that is, the meddy can also be characterized as a stack of disks, each rotating at its own rate with the one in the center having the highest rotation frequency

(**Figure 1E**). This is consistent with a density field that is nearly uniform in the horizontal yet stratified in the vertical.

Between the visits to the meddy in 1984 and 1985, the strong core of undiluted salt had shrunk substantially as intrusions of fresher waters from the

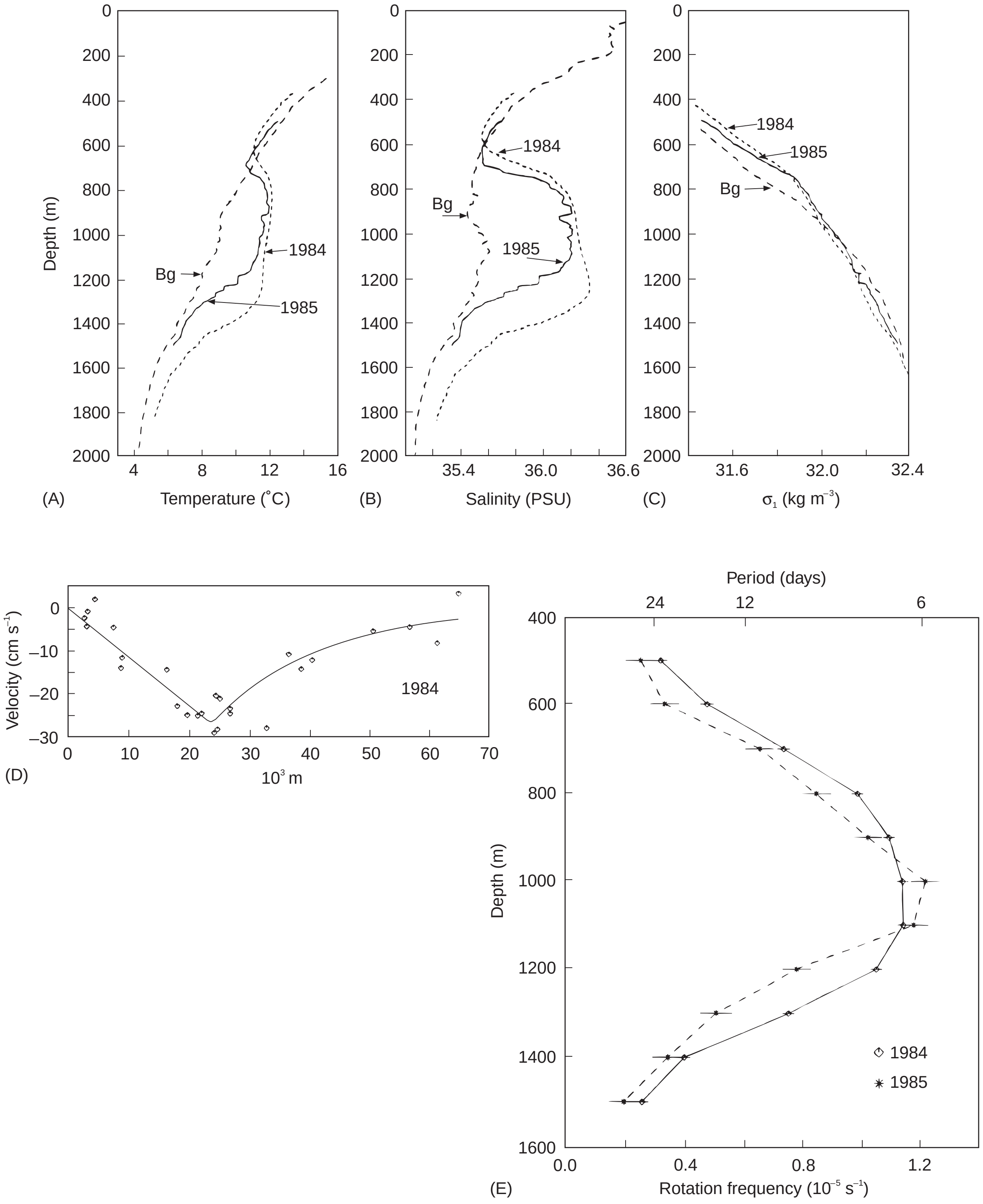

Figure 1 Temperature (A), salinity (B) and density (C) in the core of meddy 'Sharon' in October 1984 (solid), October 1985 (dotted) and background (dashed). Panel (D) shows azimuthal velocity in cm s^{-1} as a function of radius in 1984 and panel (E) shows angular velocity (bottom) and period of rotation (top) as a function of depth.

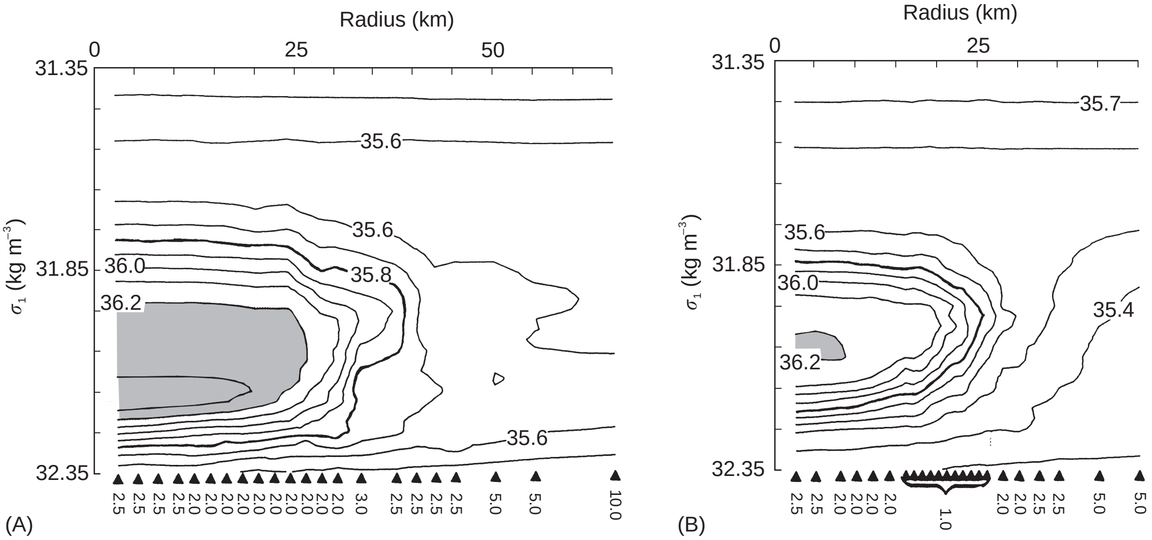

Figure 2 Radial σ_1 distribution of salinity (PSU) in meddy 'Sharon' for 1984 (A) and 1985 (B). σ_1 is density relative to a pressure of 1000 dbar.

outside reached toward the center. This was not the case for the velocity field. Although it had shrunk in diameter, the core still evinced solid body rotation with a sharp transition to a region of radial decay beyond. Thus the dynamical structure is preserved even as the meddy loses its water mass anomaly. **Figure 2** shows cross-sections of the salinity for the two surveys. Note the substantial loss of core waters but retention of a well-defined velocity structure. Evidently small-scale leakage and diffusion along isopycnals can 'tunnel' through the larger-scale dynamics. But what maintains the sharp velocity transition at the velocity maximum (panel (D) in **Figure 1**)?

Fluid parcels do not remain at exactly the same radius as the meddy spins, but slowly wander in toward the center and out in an apparently random fashion. As SOFAR floats orbit around the meddy, they gradually drift in and out relative to the center, indicating a radial exchange of fluid within the core as it rotates. The very weak departures from solid body rotation within the core can be viewed alternatively as facilitating radial exchange and mixing or as the result thereof. Either way, this indicates a continuing process of homogenization of the core. This homogenization applies only to regions where the potential vorticity itself remains sufficiently uniform so as to allow the process to continue, i.e., within the core out to the radius of maximum velocity. The sharpness of the potential vorticity front for both years can be seen in **Figure 3**. Note how the radial boundary remains sharp despite the reduction in size. This stands in contrast to the continuing loss of salt inside the core of the meddy (**Figure 2**).

Meddy Formation

At the south-west corner of Portugal, Cape St. Vincent, the continental slope makes a sharp turn to the north. The Mediterranean outflow, a warm saline flow in geostrophic balance along the slope at about 1000 m depth, tends to follow the slope north. But sometimes, especially when the flow is strong, the current appears to overshoot and continues as an unbalanced flow to the west and curving to the north owing to the Coriolis force. If the curved motion is strong enough, it can fold back on itself, forming a closed loop and resulting in the genesis of a meddy. The negative relative vorticity of the meddy comes from the curvature of the flow and the negative lateral shear between the undercurrent and the bottom. The formation process was demonstrated by a series of RAFOS floats released into the Mediterranean Outflow over the period of a year. Some of these turned north along the bathymetry, but others exhibited the orbital motion we associate with meddies. These immediately broke away from the continent and started their drift to the south west. Other meddies were spawned farther north near the Estremadura Promontory, where the bathymetry also makes a sharp turn to the right. **Figure 4** shows an example of such a trajectory. The timescale for eddy formation is estimated at 3–7 days with, in all, about 15–20 meddies spawned per year.

Decay of the Meddy

It seems rather remarkable that these slender lenses with a core rotation period measured in days can

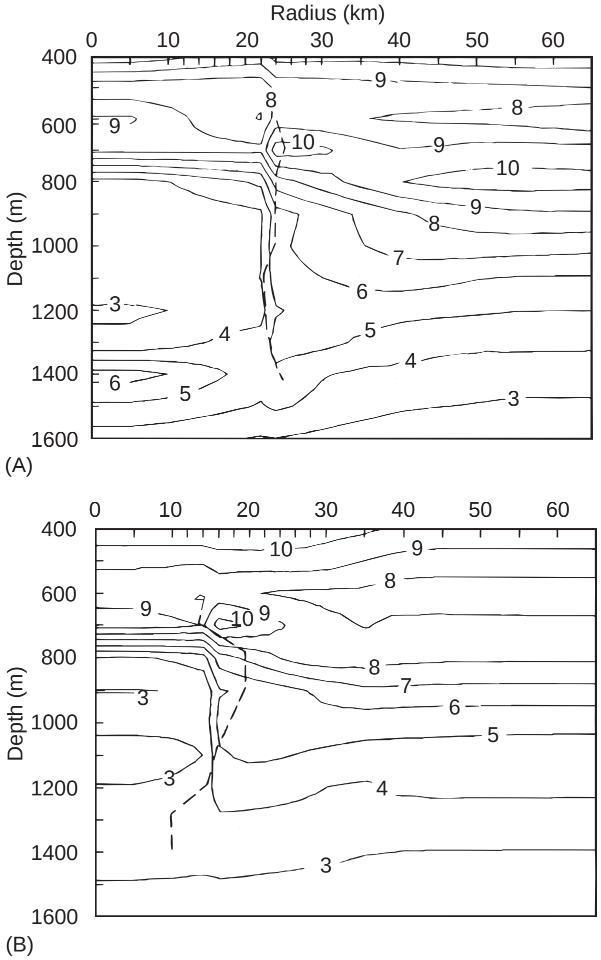

Figure 3 Potential vorticity distribution in meddy 'Sharon' for 1984 (A) and 1985 (B).

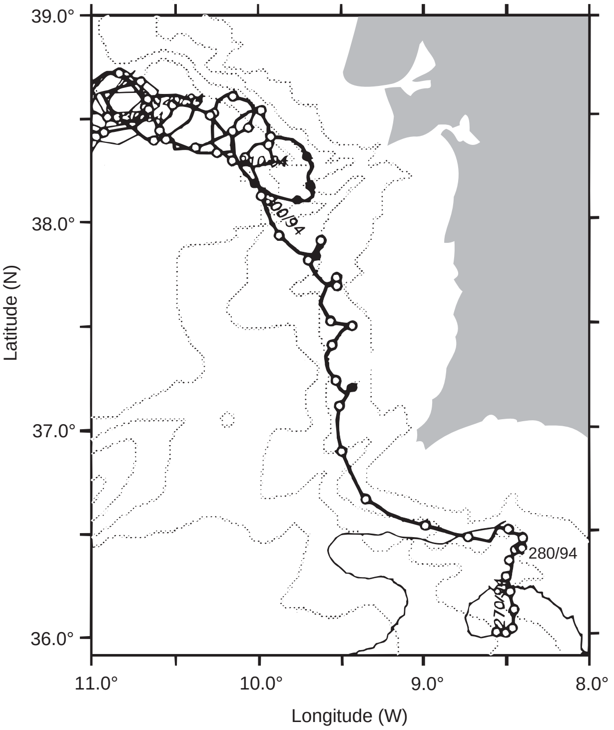

Figure 4 Formation of a meddy off Cape St. Vincent as indicated by the trajectory of a RAFOS float. (Reproduced from Bower *et al.* (1997) with permission of the American Meteorological Society.)

last for hundreds of revolutions. Those that drift west to south-westward from Portugal toward the mid-Atlantic Ridge may reach 4–5 years of age. Meddy 'Sharon,' which was visited four times over a 2-year period during its 1100 km drift south, was probably at least a year old at the time of discovery. These repeat visits documented in detail both a radial and a vertical erosion. The organized orbital motion leads to substantial and sustained vertical shear across the large surfaces at the top and bottom of the meddy. However, the increased stability associated with the crowding of the isopycnals more than suffices to suppress shear flow instabilities. Double-diffusive processes, which depend upon the fact that heat diffuses more rapidly than salt, appear to play a more important role. Vertical erosion occurred both above and below, with the greater losses along the lower perimeter due to salt-fingering. Radial erosion, as indicated by the loss of salt in the core, appears to take place by means of intrusions along isopycnals. Between the first and last visit two years apart, the vertical and horizontal scales had been more than halved such that the identifiable volume had been reduced by a factor $(8\,\mathrm{km}/30\,\mathrm{km})^2 \times (300\,\mathrm{m}/700\,\mathrm{m})$ to about 3% of its original size. The greater radial than vertical reduction points to some form of ablation at the perimeter rather than erosion at the top and bottom surfaces. The decrease in radial scale relative to the vertical might indicate an increase in Burger number (i.e., kinetic to potential energy ratio), but the uncertainties associated with this estimation process have left the matter unresolved. In any event, the faster radial than vertical erosion is testimony to the efficacy with which vertical stratification suppresses diapycnal exchange processes, even in the presence of enhanced vertical shear due to the rotation of the lens.

Energetics

Two measures define the energetics of the meddy, the available potential energy (APE) and its kinetic energy (KE). The former is defined as the energy that would be released by restoring all the density surfaces to a reference state at which all pressure gradients and hence motion associated with the meddy will vanish. It is defined as the integral

$$\mathrm{APE} = \int_v 1/2\rho N^2\pi^2\,\mathrm{d}V \qquad [2]$$

While easy to state, the accuracy of the integration depends upon a determination of the background rest state, i.e., the accuracy with which the vertical displacement π in the integral can be estimated. The N^2 term represents the vertical stratification. The corresponding KE integral

$$\mathrm{KE} = \int_v 1/2\rho v^2\,\mathrm{d}V \qquad [3]$$

can be estimated fairly accurately. For most subsurface eddy studies the ratio of KE/APE, the energy Burger number, tends to be somewhat greater than unity, particularly as they age. This reflects the tendency for the aspect ratio of the lens to increase with age owing to the greater erosion around the perimeter than from above and below. For young meddies, APE and KE are of order 10^{14} J, which equals the output of a 1 GW electric utility plant for one day.

Sudden Death

Most meddies do not have the privilege of reaching a great age. Instead, there is a high probability of collision with one of the large number of seamounts in the eastern North Atlantic west of the Iberian Peninsula. Sometimes they fragment into smaller lenses that can continue for months to years. It has been estimated that perhaps 90% of all meddies eventually collide with a seamount, with an estimated average age at collision of 1.7 years. Those that do survive might live up to 5 years.

Apparently spontaneous breakup of meddies into smaller units has been observed, but the extent to which these occur owing to internal instabilities or result from interactions with other currents or eddies that shear them apart needs further study. Given the great age that meddies can reach, it would appear that the probability of spontaneous fission is quite small. Sharp lateral shear in the ambient flow could also wear at the meddy, but the large and organized relative vorticity of the meddy, typically 0.2–0.6 times the Coriolis parameter, renders it immune to the surrounding eddy field. Examples also exist of coalescence of smaller eddies into larger ones.

Significantly, almost all information about eddy interactions comes from the trajectories of SOFAR and RAFOS floats, which give us considerable spatial information as they drift about. Given the tight structure of the meddy, a single float will suffice to tell us the trajectory of the meddy, its collision with seamounts, and its possible demise. On the other hand, almost all our information on the mechanisms of aging comes from 'Sharon,' which, as noted above, shrank in volume by two orders of magnitude during the 2-year study. Curiously, meddies farther to the west appear to be much larger and vigorous at a comparable or greater age. Thus, it remains unclear how well 'Sharon' represents the meddy population as a whole. This is of more than passing interest because meddies have been suggested as a mechanism for maintaining the Mediterranean Salt Tongue (MST) that extends across the ocean near 30°N. If meddies are common in the eastern Atlantic, and it has been estimated that there might be of the order of 30 meddies at any given time, it seems remarkable that not a single meddy has been found west of the mid-Atlantic Ridge since the original meddy observation in the fall of 1976. **Figure 5** shows a summary of all meddy sightings in relation to the salinity anomaly of the Mediterranean Salt Tongue. Whereas many meddies drift south, note the conspicuous absence of meddies west of ~30°W along the axis of the salinity anomaly, the maintenance of which also remains an enigma.

Indeed, there is strong circumstantial evidence that the original meddy did not have a Mediterranean origin but came from quite far north in the north-west Atlantic. Near 50°N where the North Atlantic Current abruptly turns east as the Subpolar Front, a strong anticyclonic rotation is maintained by the current. It has been observed that this

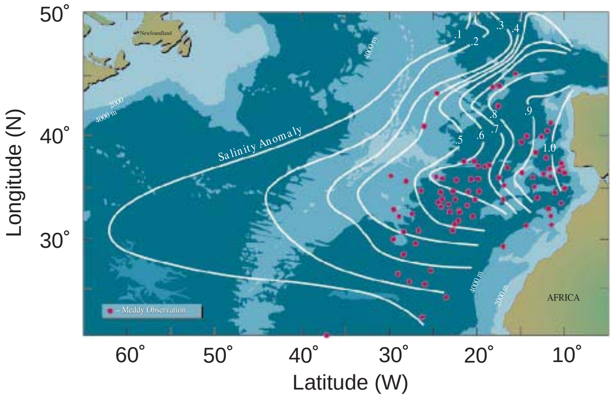

Figure 5 Summary of historical meddy observations. The diameter of the dots in the figure is about 50 km, somewhat smaller than the typical 100 km diameter of meddies. The contours show salinity anomaly relative to 35.01 PSU near a depth of 1100 m. (Reproduced from Richardson *et al.* (2000) with permission of Pergamon Press.)

semidetached circulation can subduct and move south across the Newfoundland Basin as a subsurface eddy and continue west and south across the Sargasso Sea. With the help of the Gulf Stream recirculation system, the transit time may only be 2–3 years instead of 5 years, despite the large distance involved. Other subsurface warm-core lens sightings in the western Atlantic lend further support to this alternative origin.

Other Subsurface Lenses

Numerous other lenses have been observed and described. The structure of 'Sharon' seems to apply to others after appropriate scaling for size. Thus, an eddy about 50 km in diameter between 1000 and 2000 m depth located about 400 km west of Bermuda had a very similar structure. The isopycnals bend up and down forming a core region with weak stratification. The cold fresh waters in the core clearly point to a Labrador Sea origin, but where the lens itself was formed remains uncertain (analogous to the formation of meddies off Portugal containing waters originating in the Mediterranean Sea). One of the smallest yet very energetic subsurface eddies ever observed was tracked for 2 months in real time with a SOFAR float at 700 m depth west of Bermuda. A detailed hydrographic survey when the float was picked up indicated a diameter of ~ 20 km and 300 m thickness. The core exhibited a distinct water mass anomaly with temperature, salinity, oxygen, and nitrate characteristics suggesting that the waters came from a low latitude, but where the eddy itself originated remains unclear; perhaps it was advected by the Gulf Stream north, perhaps it was formed by the meandering of the current. In any event, this lens, with a 1.5:100 aspect ratio, had a very fast rotation rate, about 3.5 days. An even faster rotation rate, 2 days, was observed for a small lens in the Gulf of Cadiz. This is very close to the theoretical limit where the relative vorticity of the lens exactly cancels the planetary vorticity. While the number of detailed lens studies remains limited, smaller lenses seem to have a higher rotation rate than larger ones. This suggests that, as the lenses age, they do so by decreasing their radius more rapidly than their height, so that their aspect ratio increases. The effect of this is to increase the Burger number of the lens. For a given pressure anomaly in the center, a smaller radius means a higher azimuthal velocity. The high angular velocity of these two small eddies compared to that of larger ones suggests a possible end fate in which the core remains intact as the ablation around the perimeter proceeds.

Curiously, almost all reports have focused on anticyclonic lenses despite the fact that we know from float observations that cyclonic lenses occur with near equal probability. Cyclonic lenses have received much less attention. For these, the density surfaces must bow in rather than out, inviting the description 'concave lenses.' The best-documented examples of these have been observed in the West European Basin. Interestingly, these also carry a positive salt anomaly, apparently to the north west toward the mid-Atlantic Ridge. Indeed, there is growing evidence that cyclonic eddies tend to drift poleward, whereas anticyclonic eddies drift equatorward. The classical argument for this is that as they age and lose their relative vorticity, they compensate for this by changing their latitude. In the case of meddy Sharon, the peak angular velocity actually increased, but the vertically averaged rotation rate clearly decreased (**Figure 1E**).

Discussion and Summary

The discovery of the meddy has a curious history. One of the first lenslike subsurface eddies to be identified as such was found just north-east of the Dominican Republic in the fall of 1976. It was nearly 150 km in diameter and 500 m thick, and the temperature–salinity characteristics of the core of the eddy and its proximity to the axis of the Mediterranean Salt Tongue suggested a Mediterranean origin. The report of this finding stimulated the search for similar lenses in the eastern Atlantic, and soon enough many others had been found. But what makes the original discovery all the more remarkable is that no other meddy has since been sighted west of the mid-Atlantic ridge. In addition, the probability of meddies getting that far decreases rapidly owing to the high risk of collision with seamounts. Even if a meddy did cross the mid-Atlantic ridge, the additional 2000 km distance to the original sighting makes that observation seem all the more extraordinary if not implausible. Instead, it now appears that the original 'meddy' actually originated in the north-west Atlantic where the North Atlantic Current turns east at 50°N. While the distance from that location almost matches that from Cape St. Vincent, Portugal, a lens originating in the North Atlantic Current (NAC) can be carried or advected rapidly to the south and west by the recirculating waters east of the NAC and south of the Gulf Stream, reducing the transit time to 2–3 years instead of 5 years. The decrease in latitude favors the anticyclonic eddy, but the nearly 50% reduction in Coriolis parameter suggests that the lens must undergo considerable adjustment.

Perhaps the extraordinary width and flatness of the original meddy has its explanation here: As the Coriolis parameter f decreases, a decrease in thickness h would indicate a tendency to conserve its potential vorticity $(f+\zeta)/h$. On a more speculative note, if the lens did indeed flatten and widen, this could help explain the extraordinary diameter of the original 'meddy' and simultaneously give it an additional lease of life against radial erosion.

The fact that subsurface eddies larger than $\sim 100\,\mathrm{km}$ in diameter have not been observed suggests an upper limit at formation time set by inertia. Meddies form at Cape St. Vincent at the south-west corner of Portugal where the Mediterranean Undercurrent must make a sharp turn to the north along the continental slope. Owing to inertia, the current may overshoot, becoming geostropically unbalanced where the bottom turns north. This causes the current to curve to the right owing to the Coriolis force. For faster than normal flow, this curving flow can almost fold back on itself, resulting in a closed loop leading to the genesis of a meddy. Given the frequent rate of formation of meddies at Cape St. Vincent site, this would be an excellent place to study the formation process in greater detail. Other sharp topographic features have been identified as sites for the formation of anticyclonic lenses. In contrast, remarkably little is known about how cyclonic lenses get spun up. Perhaps they result from instabilities of fronts and/or fission from larger eddies. No lower limit to the size of subsurface lenses has been established, but, at some limit, viscosity and double-diffusive processes will dissipate what is left. Before that limit is reached, however, the lenses can still remain remarkably energetic. But the very small pressure gradients needed to balance the cyclogeostrophic motion all but guarantees that they can only be detected and identified as such by Lagrangian means.

See also

Double-diffusive Convection. Drifters and Floats. Intrusions. Rossby Waves.

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MEDITERRANEAN SEA CIRCULATION

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Introduction

The Mediterranean Sea is a mid-latitude semi-enclosed sea, or almost isolated oceanic system. Many processes which are fundamental to the general circulation of the world ocean also occur within the Mediterranean, either identically or analogously. The Mediterranean Sea exchanges water, salt, heat, and other properties with the North Atlantic Ocean. The North Atlantic is known to play an important role in the global thermohaline circulation, as the major site of deep- and bottom-water formation for the global thermohaline cell (conveyor belt) which encompasses the Atlantic, Southern, Indian, and Pacific Oceans. The salty water of Mediterranean origin may affect water formation processes and variabilities and even the stability of the global thermohaline equilibrium state.