Oceanography

Submarine salt lenses

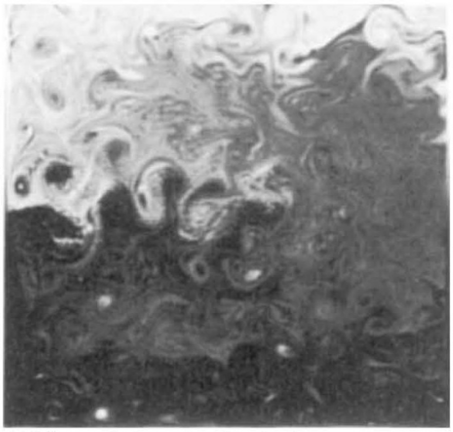
John Marshall

LAURENCE Armi and collaborators report, on page 649 of this issue[1], a unique series of oceanographic observations in which, over a period of 2 years, they document the life history of a subsurface coherent lens of salty water formed from outflow through the Strait of Gibraltar. Meddies, as they are called, have a vertical extent of about 900 metres and are typically 50 kilometres in diameter[2]. Spinning in the opposite sense to the Earth, particles of fluid circle the axis of the Meddy in about a week. They have a lifetime of perhaps 2 years and have been detected drifting at a depth of 1 kilometre as far west as the Bahamas. The experiment suggests a rather fascinating mechanism by which the salty water of the Mediterranean finds its way into the North Atlantic. Rather than the salty influence being diffused or advected by large-scale circulation into the interior, it can be transported in concentrated spinning blobs. The salt 'tongue', spreading westwards from Gibraltar to beyond the mid-Atlantic ridge, could be formed from the decay of Meddies releasing their salty contents.

Imagine the Mediterranean outflow as a giant submerged tap dripping into the North Atlantic. The blobs of fluid settle at their neutrally buoyant level of about 1 kilometre. The volume and salinity of observed Meddies suggest that a birth rate of one every 10 days would be sufficient to carry the entire outflow of salty water. With a life expectancy of 1–2 years, there could be 50 Meddies existing at any one time in the North Atlantic.

The Meddies carry with them properties of their formation region — the weakly stratified, salty waters of the Mediterranean outflow. The single most important factor controlling their dynamics is not that they are salty, but that they are tagged by anomalously low values of the dynamically active tracer, potential vorticity. In the present context the potential vorticity PV can be defined as $(\zeta + f)/h$: f is the planetary vorticity, the Coriolis parameter measuring the Earth's spin in the direction of the local vertical; ζ is the relative vorticity measuring the spin of the vortex relative to the Earth; and h is the vertical distance between surfaces of constant density (isopycnics), a measure of the stratification. Convective overturning of the upper layers of the Mediterranean destroys the stratification, forming a reservoir of low-PV water which drips into the North Atlantic. In adiabatic, inviscid motion, PV is conserved following the motion like any other fixed feature of a parcel of fluid. Thus, the blobs of water remember the small values of PV typical of the Mediterranean reservoir.

A further crucial dynamical factor is that the Meddy is in balanced motion; Coriolis forces acting on the spinning vortex are balanced by radial pressure gradients (it is in geostrophic balance) and gravity is balanced by vertical pressure gradients (hydrostatic balance). In such a balanced vortex, anomalously low PV must manifest itself both as a weakening of the stratification and as anticyclonic relative vorticity[3] (opposite in sign to the spin of the Earth). Observed horizontal scales, on or near the 'Rossby' radius of 50 kilometres, suggest that the anomaly in PV is equally partitioned between relative vorticity and stretching. Thus the Meddy appears as a double-convex lens (a thickening of isopycnal layers) in anti-cyclonic motion.



Eddies and rings at a depth of 400 metres in a numerical simulation of idealized ocean gyres as seen through the potential vorticity field; dark (light) indicates fluid of low (high) PV spinning in the opposite (same) sense as the Earth. The model is driven by an imposed wind stress at its upper surface, and has two counter-rotating gyres in a 3,000-kilometre-square basin. At their confluence in mid-basin, eddies and rings are formed through the instability of the internal jet (the model's Gulf Stream). The typical eddy scale is set by the 'Rossby' radius of deformation, chosen here to be 50 kilometres. Dark coherent blobs of very-low-PV fluid can readily be seen and dynamically have much in common with Meddies. White blobs are their mirror images.

The coherence and persistence of Meddies arises from the fact that their PV is so anomalous that a closed circulation is induced which traps the fluid inside it; closed PV contours are the walls which allow the Meddy to carry its anomalous contents large distances (including the neutrally buoyant floats used to track them) and form the deep-water laboratory studied by Armi and collaborators[1].

The vertical influence of the Meddy's PV anomaly will decay over the Rossby height scale fL/N, where L is the horizontal length scale of the anomaly and N is a measure of the static stability. In the upper mid-thermocline, $N/f \approx 50$, suggesting that they have a vertical extent of perhaps 1 kilometre, if L is taken to be 50 kilometres. It is likely, then, that the Meddy induces flow at the surface (not the bottom) but that the influence is weak and unlikely to be strong enough to permit trapping of fluid properties at the surface. Meddies are thus difficult (if not impossible) to detect remotely in, say, sea-surface temperature or ocean colour imagery.

So the blob of low-PV water floats serenely at mid-depth, isolated from frictional torques associated with surface and bottom boundary layers. But this state of affairs cannot persist indefinitely. At the edge of the blob there are strong PV gradients on which small-scale instabilities can feed; Armi *et al.*[1] find evidence of both lateral and vertical mixing (thermocline intrusions and salt fingering) and high levels of inertial activity. Radiation of energy through the agency of Rossby waves (horizontal undulations of the ambient PV field) is also a possible decay mechanism. In the face of these dissipative processes, it is remarkable that the vortex can survive for so long.

An interesting question is raised by the observed track of the Meddy; why did it move southwards, rather than, say, westwards as might have been expected[4]? There is no clear explanation, but perhaps the large-scale geometry of the PV field is the clue. The PV contours are the free paths, the rails along which information (and Meddies) travel with least resistance. In textbook Rossby-wave theory, the large-scale PV gradient is set by the meridional variation in f, the so-called β-effect, and so information from the east travels westwards. But perhaps here we should reinterpret the theory as meaning 'pseudo-westward' along the free paths set by the large-scale PV field. At mid-depth in the thermocline, they depart from latitude circles and have a significant north–south component associated with the subtropical gyre of the North Atlantic[5]. So one possible interpretation of the observed path of the Meddy is that it is propagating along the PV rails induced by the gyre.

What are the wider implications of the study? Evidence from high-resolution numerical models of eddy-rich ocean gyres (see figure) suggest that coherent vortices are a ubiquitous feature of the oceans. Meddies are just a spectacular example of one of the canonical forms; their mirror images, double-concave lenses in cyclonic motion are associated with fluid of anomalously high PV. Cyclonic and anticyclonic coherent structures will be formed wherever there are instabilities feeding off large PV gradients at the interface between water masses of very different PV characteristics. Warm and cold rings, for example, are formed through a hydrodynamical instability of the Gulf Stream marking the frontal region between the high-PV slope waters to its north and the low-PV waters of the Sargasso Sea to its south (see figure). Warm rings are coherent vortices of low-PV water which are dynamically similar to Meddies. But unlike Meddies they are somewhat shallower, readily eroded by active surface processes and hence shorter lived.

The problem for the dynamical oceanographer is that our ways of thinking and mathematical paradigms are too often couched in terms of linearized studies of wave propagation and normal mode instability analyses, and so are ill-equipped to handle a fluid populated by highly nonlinear coherent vortices. Studies such as the one described by Armi *et al.* remind us that perhaps we should take more notice of those theories that emphasize the particle rather than the wave-like aspects of geophysical fluids. □

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Nitrogen fixation

A third bacterial nitrogenase

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NITROGENASE is the enzyme in bacteria responsible for fixing atmospheric nitrogen to ammonia. When isolated from various microorganisms, it was found to be an iron–sulphur protein containing molybdenum. Microorganisms could not fix nitrogen if molybdenum was excluded from the growth medium. Actually, this was not quite true; with some organisms it was extremely difficult to prevent nitrogen fixation entirely. This was attributed to the extraordinary ability of the bacteria to scavenge traces of molybdenum from the culture media and vessels. Two years ago, it was found that strains of *Azotobacter vinelandii* and *A. chroococcum* could produce an alternative nitrogenase containing vanadium instead of molybdenum (see my News and Views article[1]). Now, a third nitrogenase has been isolated from *A. vinelandii* which contains neither element and appears to use iron instead[2,3]. These results, which were presented at a recent symposium in Cologne[3-5], overturn the accepted view that molybdenum is an essential trace element for nitrogen fixation by bacteria.

The existence of alternative nitrogenases had been suspected for many years. Convincing evidence for this idea was difficult to obtain because it turned out that biosynthesis of the alternative nitrogenase is strongly repressed by molybdenum in the growth medium. Moreover, the alternative nitrogenase is not very active in the reduction of acetylene to ethylene, a reaction which had become the standard method for detecting nitrogenase activity[6].

The existence of one alternative nitrogenase was demonstrated genetically by deleting the structural genes, *nifHDK*, encoding the conventional molybdenum-nitrogenase, from *Azotobacter* species, and isolating an enzyme (V-nitrogenase), which contained stoichiometric amounts of vanadium and only trace amounts of molybdenum[4,6-8]. P. E. Bishop's group in North Carolina State University has now isolated another nitrogenase from such a deletion strain. This protein contains iron as the only metal ion in significant amounts[2,4], and is probably responsible for the earlier observations[9] of nitrogen fixation by *A. vinelandii* grown on molybdenum-free medium. Eady and collaborators at the AFRC Nitrogen Fixation Laboratory at Sussex University have carried the genetic experiment one stage further[3], also deleting the genes *nifHDK** encoding the V-nitrogenase. Sure enough, the bacteria could still fix nitrogen, and a third nitrogenase could be extracted.

Such substitutions of one metal for another are unusual in enzyme systems: cells are generally specific in inserting the 'right' element. Although metal ions involved in catalysis can sometimes be removed artificially from enzymes and replaced with other elements, the effect on catalytic activity is considerable. In this case, the molybdenum-, vanadium- and iron-containing nitrogenases are all different proteins, although they have a similar structure.

The new iron-containing enzyme (Fe-nitrogenase), the V-nitrogenase and the well-established Mo-nitrogenase, are all similar in that they each comprise a large protein, sometimes called dinitrogenase, where the nitrogenase is actually fixed, together with a smaller iron–sulphur protein, termed dinitrogenase reductase (see figure). The Fe-nitrogenase and the V-nitrogenase differ slightly in that they seem to contain a small third subunit whose function is unknown[2,5]. The amino-acid sequences of the three types of nitrogenase are very similar[3,4]. To emphasize this similarity, it has been possible to extract the inorganic cofactors, termed Fe–Mo–co and Fe–Va–co, from the Mo- and V-dinitrogenases, respectively. These cofactors are similar in their spectroscopic properties, and can restore catalytic activity to a mutant Mo-nitrogenase which lacks the cofactor[10]. When Fe–Va–co is inserted, the mutant enzyme acquires the ability to reduce ethylene to ethane, which is the property of the V- and not the Mo-nitrogenase. This observation supports the view that it is the cofactor which is the site of nitrogen fixation in the enzyme. The properties of the putative

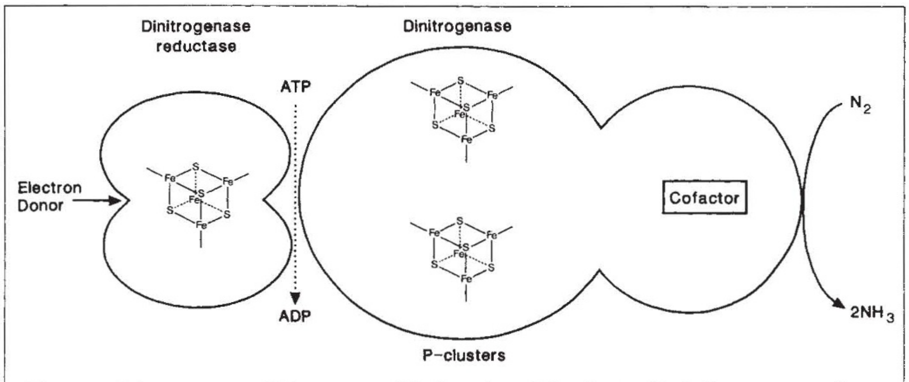

Diagram of the structure of nitrogenase. The location of the clusters in dinitrogenase, only one half of which is shown, is unknown.

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