by decreases in temperature, oxygen content, decrease in food availability or increase in pressure. Comparative analyses of fish from different regions show similar depth trends even in isothermal regions (e.g., the Antarctic) for species which live at similar depths but at different oxygen concentrations. Several lines of research indicate that the metabolic decline is related to a reduction in locomotory abilities with increasing depth. It is suggested that the higher metabolic rates at shallower depths in groups with image-forming eyes is the result of selection action to favor the use of information on predators or prey at long distances when ambient light is sufficient. Hence, good locomotory abilities will be beneficial in order to escape predators. This idea is supported by the fact that major gelatinous groups that lack image-forming eyes do not show a decline in metabolic rate with depth. Thus, the lower metabolic rates found in fish living deeper where visibility is lower, result from the relaxation of selection for locomotory abilities, and is not a specific adaptation to environmental factors at great depths. If so, high metabolic rate in the surface waters indicates a metabolic cost of predation risk because good locomotory abilities require high metabolism. At greater depths the predation risk is much lower and the need for locomotory abilities decreases.

See also

Fiordic Ecosystems. Fish Feeding and Foraging. Fish Locomotion. Fish Migration, Vertical. Fish Predation and Mortality. Fish Reproduction. Fish Schooling. Fish Vision. Large Marine Ecosystems.

Further Reading

Andersen NR and Zahuranec BJ (eds) (1977) *Oceanic Sound Scattering Prediction*. New York: Plenum Press.

Baliño B and Aksnes DL (1993) Winter distribution and migration of the sound scattering layers, zooplankton and micronecton in Masfjorden, western Norway. *Marine Ecology Progress Series* 102: 35–50.

Childress JJ (1995) Are there physiological and biochemical adaptations of metabolism in deep-sea animals. *Trends in Ecology and Evolution* 10: 30–36.

Farquhar GB (1970) *Proceedings of an International Symposium on Biological Sound Scattering in the Ocean*. MC Report 005. Maury Center for Ocean Science. Washington, DC: Dept. of the Navy.

Giske J, Aksnes DL, Baliño B *et al*. (1990) Vertical distribution and trophic interactions of zooplankton and fish in Masfjorden, Norway. *Sarsia* 75: 65–81.

Gjøsæter J and Kawaguchi K (1980) *A Review of the World Resources of Mesopelagic Fish*. FAO Fish. Tech. Paper No. 193. Rome: FAO.

Kaartvedt S, Knutsen T and Holst JC (1998) Schooling of the vertically migrating mesopelagic fish *Maurolicus muelleri* in light summer nights. *Marine Ecology Progress Series* 170: 287–290.

Kristoffersen JB and Salvanes AGV (1998) Life history of *Maurolicus muelleri* in fjordic and oceanic environments. *Journal of Fish Biology* 53: 1324–1341.

Marshall NB (1971) *Exploration in the Life of Fishes*. Cambridge, MA: Harvard University Press.

Rosland R (1997) Optimal responses to environmental and physiological constraints: evaluation of a model for a planktivore. *Sarsia* 82: 113–128.

MESOSCALE EDDIES

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Introduction

Mesoscale eddies are energetic, swirling, time-dependent circulations about 100 km in width, found almost everywhere in the ocean. Several modern observational techniques will be used to profile these 'cells' of current, and to describe briefly their impact on the physical, chemical, biological, and geophysical aspects of the ocean.

The ocean is turbulent. Viewed either with a microscope or from an orbiting satellite, the movements of sea water shift and meander, and eddying motions are almost everywhere. These unsteady currents give the ocean a rich 'texture' (**Figure 1**). If you stir a bathtub filled with ordinary water, it will quickly be populated with eddies: whirling, unstable circulations that are chaotically unpredictable. There is also a circulation of the water with larger scale, that is, broader and deeper movements. The 'mission' of the eddies is to fragment and mix the flow, and to transport quantities like heat and trace chemicals across it. In a remarkably short time (considering the smallness of viscous friction in water) the energy in the swirling basin will have greatly diminished. The bath will also cool much more quickly than one would estimate, based on simple conduction of heat across the fluid into the air above.

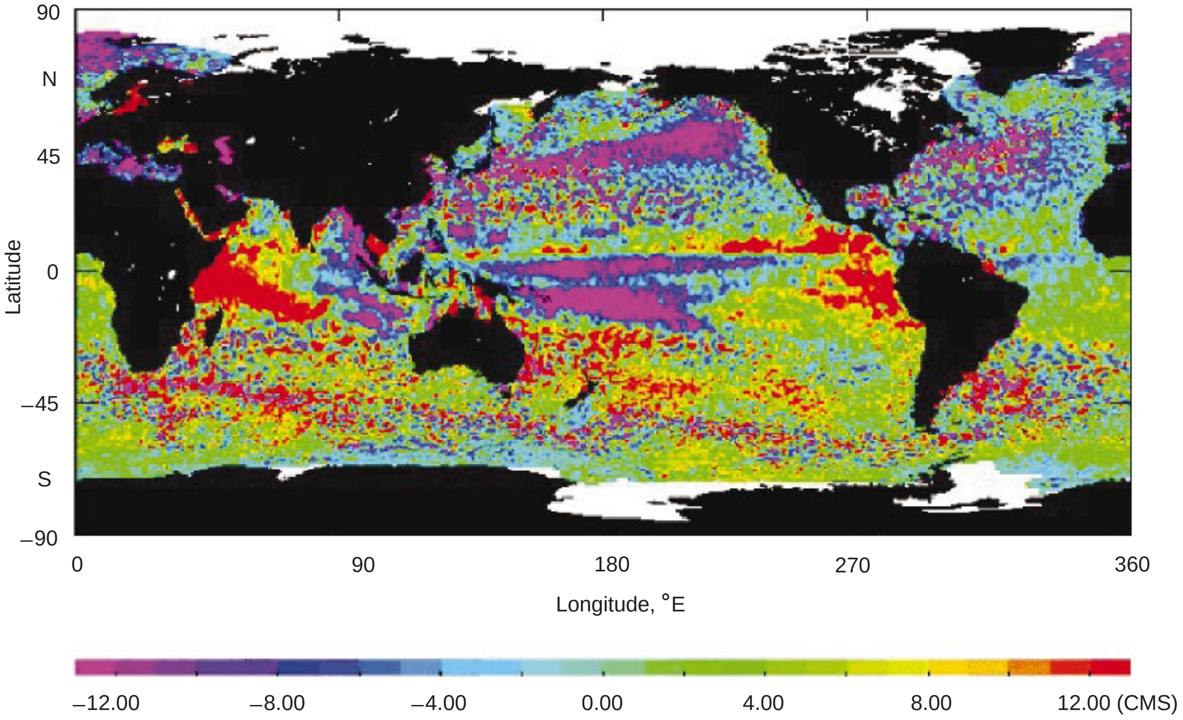

Figure 1 Sea surface elevation (cm) from the Topex-Poseidon and ERS satellites, 25 March 1998. The mean sea surface elevation for this time of year has been subtracted, so that only 'anomalies' from normal conditions are shown. The speckled pattern shows mesoscale eddies almost everywhere. In addition there are larger-scale patterns associated with El Niño (where the Equatorial Pacific has more level sea surface than normal) and large bands of high and low sea surface at middle latitudes. These may be associated with climate variability. The home web site for Topex-Poseidon satellites is http://topex-www.jpl.nasa.gov

One may think about the fineness of the pattern of fluid motion in analogy to the resolution of an image on a computer screen. In a bathtub, the fluid eddies have scales from about 1 mm to 1 m, hence spanning a thousandfold range of sizes. In the oceans, the smallest circulations are also a few millimeters in size, but the largest are of the order of 10 000 km in diameter: this represents a range in scale of about 10^{10} between the smallest and the largest. There is thus room for many sizes of motion, each with a distinct dynamical nature: from tiny eddies that strongly feel viscosity, to 'mesoscale eddies' that strongly feel the Earth's rotation, to great 'gyres' of circulation filling entire oceans that feel also the curvature of the Earth. At scales in between are also numerous types of wave motion.

Mesoscale eddies are whirling and localized yet they densely populate the ocean. Typically 100 km across, their size varies with latitude and other factors of their environment: energy level, nearly bottom topography, and the nature of their generation. Eddies need not necessarily be round, with circular streamlines. They are often generated by unstable meandering of an intense current like the Gulf Stream. In this case the waving deflection of the Stream is itself a form of latent eddy, which may eventually grow and 'break' to form a circular eddy (as an ocean surface wave grows and 'breaks' at a beach).

Eddies are important because they have so much kinetic energy, and because they can transport momentum and trace water properties. They have deep 'roots' that often reach 5 km or more downward, carrying energy and momentum to the seafloor. They are responsible for the irreversible mixing of waters with different properties. Mesoscale eddies are typically as energetic as the concentrated currents that give birth to them. They may owe their existence to several sources other than meandering of strong currents: for example, direct generation by winds or cooling at the sea surface; flow over a rough seafloor or past islands and coastal promentories; or generation by mixing or waves of smaller scale.

'Geography' of Mesoscale Eddies

Before describing the 'physics' of mesoscale eddies, we should discuss their 'geography.' A satellite image of the surface of the global ocean can be assembled from many orbits, as the Earth turns below. A particularly basic measurement is that of the height of the sea surface. If ordinary waves are averaged out, we are left with a surface smooth to the eye yet varying by a meter or so relative to the 'geoid,' which determines the gravitational horizon (the geoid itself is permanently distorted by seafloor topography and, by itself, yields useful approximate maps of the seafloor elevation). Small variations in height of the sea surface correspond to small variations in pressure in the ocean below. Lines of constant pressure (isobars) are approximate lines of flow, or streamlines for horizontal circulation.

If one subtracts from this field the time-averaged sea surface height the result (**Figure 1**) is a dramatic display of time-varying mesoscale eddies: they are nearly everywhere. Additionally one sees in this image from the Topex-Poseidon and European Remote Sensing satellites the large-scale variation of the sea surface along the Equator in the Pacific Ocean. This anomalous state is characteristic of El Niño, when the Trade Winds fail to blow westward with normal intensity. Usually the winds pile up water at the west end of the Equator, but if they are absent the sea 'sloshes' back, one-quarter of the way round the Earth, toward South America. Animations of this field can be seen on the World Wide Web (for example, at http://topex-www.jpl.nasa.gov), and many of the features are seen to move westward.

Mesoscale eddies (as currents at the ocean surface) are particularly apparent in **Figure 1** along the paths of intense, major ocean currents. These delineate the Antarctic Circumpolar Current round Antarctica, which has a 'saw-tooth' form, flowing south-eastward across the South Indian and Pacific Oceans, and jogging northward where it encounters major seafloor ridges or gaps (at the Campbell Plateau south of New Zealand and the Drake Passage between South America and Antarctica, for example). In each subtropical ocean there are western boundary currents like the Gulf Stream and Kuroshio, which are marked by time-dependent energy after they leave the coasts and flow eastward and poleward. The jetlike equatorial currents show fine-scale energy that is more related to meandering than to separated, circular eddies. The westward flow in the low subtropical latitudes develops eddies in mid-ocean. Altimetry measurement has a large 'footprint' that misses eddies smaller than about 50 km in diameter. From direct measurements in the sea we know that the texture of the circulation includes mesoscale eddies smaller than this, particularly at high latitudes.

Orbiting satellites do more for us than produce images. Freely drifting instruments on the sea surface, and at great depth below the surface, tell us 'where the water goes.' These can be tracked by satellites and acoustic networks. Rather than delineating a smooth pattern of general circulation, drifters in the North Atlantic (**Figure 2**) show a tangle of tracks, with intense mesoscale eddies causing the gyrelike circulation to be nearly obscured. This region of the Atlantic involves the subpolar gyre, circulating counterclockwise north of 48° N latitude, and the subtropical gyre, circulation clockwise to the south. The Gulf Stream leaves the US coast at Cape Hatteras, in the southwest corner of the figure. It flows east-northeast and rounds the Grand Banks of Newfoundland, flowing north to about the latitude of Newfoundland, where it separates from the coast again, joining the subpolar gyre. The intense boundary current running westward around Greenland is clearly visible as the drifters invade from the east. The kinetic energy associated with eddies exceeds that in the time-averaged currents by factors ranging from 1.5 or so (in the jetlike current cores) to 50 or more (in the 'quiet' regions far from intense mean currents).

Radiometers on satellites record images at many different wavelengths; in the infrared (typically between 3.7 and 13 μm wavelength), and at even longer wavelengths of 'microwaves,' the radiation is strongly related to the temperature of the water at the sea surface (sea surface temperature, SST). Images in visible light show the texture of ocean color, which is strongly correlated with biological activity. These same images record 'sun glitter' patterns that are textured by ocean currents. Radiometers typically cannot resolve features less than a kilometer wide, though visible-light imaging can distinguish features down to tens of meters. Satellites actively transmitting beams of radiation can sense the sea surface elevation, slope, and roughness. Fine ripples and sharp surface wave crests give other sensors (as with synthetic aperature radar (SAR) satellites) resolution down to 20 m or so. These measurements tell us much about the surface currents and winds just above the sea surface.

Using SST sensors we now zoom in on a smaller region of ocean. SST patterns are shaped also by the movement of heat in ocean currents. The Gulf Stream (**Figure 3**) is visible as a warm, red band with sharp edges, carrying tropical heat northward on the west side of the North Atlantic. It shows a warm mesoscale eddy breaking off its northern edge. There are also many features evident of finer scale than was visible using the altimeter data (**Figure 1**). As with the global pictures of sea surface elevation, SST satellite images can be viewed as animations (e.g., www.nesdis.noaa.gov/). This

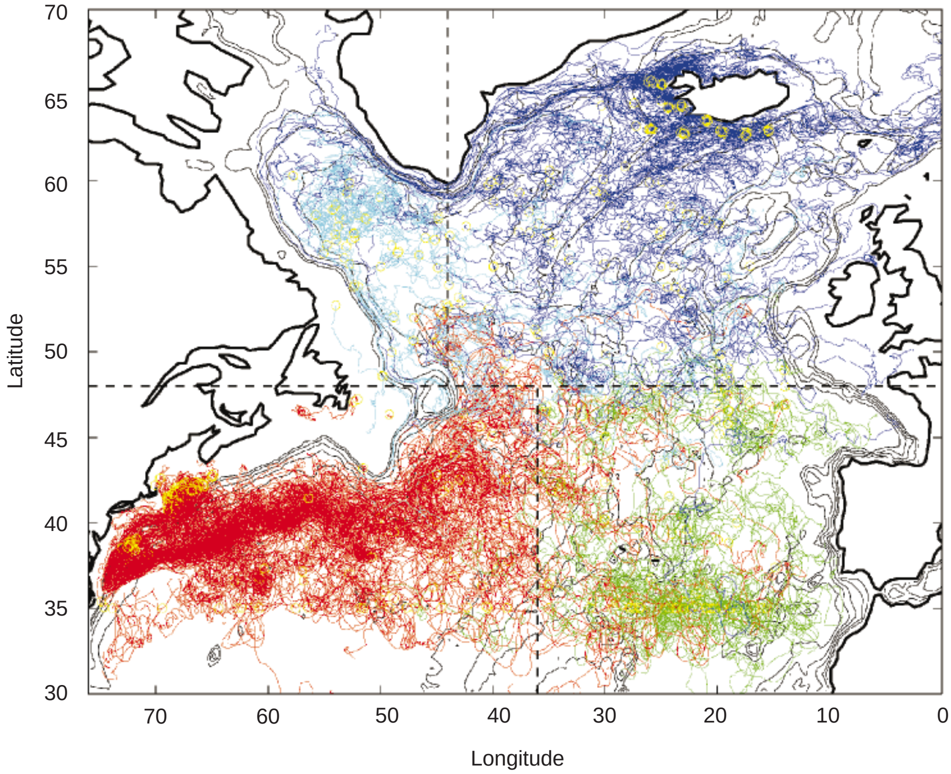

Figure 2 Tracks of drifting buoys ('drifters') on the sea surface, launched during 1996–1999 by Dr. P.P. Niiler, analyzed by J. Cuny. Tracks are colored corresponding to the 'box' (dashed lines) they were launched in. The tracks show intense eddy activity, superimposed on the general circulation. Typical duration of a track is 200 days. There is a mean movement of surface waters counterclockwise around this pattern; the Gulf Stream dominates the yellow tracks moving from west to east, and progressing into the other boxes. The purple tracks from the north-east move quickly westward, round the Labrador Sea (the north-west box) in strong boundary currents. This figure symbolizes the challenge of describing the ocean circulation in the presence of mesoscale eddies. There are several kinds of drifting floats, many of which also move vertically to record profiles of temperature, salinity and other properties; these involve some remarkable new technologies. Examples of web sites showing surface and deep-ocean currents using Lagrangian drifters include www.http://www.whoi.edu/science/PO/dept and www.http//flux.ocean.washington.edu/

involves removing the obstacle of clouds (though some sensors, like the radiometers in the TRMM (Tropical Rainfall Measuring Mission) satellite can see SST right through clouds). Viewing these animations, the trained eye will see a wealth of phenomena, from the swing of the seasons, to boundary currents, tropical instability waves, upwelling of cold waters at the coasts and Equator, and ubiquitous mesoscale eddies.

Fritz Fuglister of Woods Hole Oceanographic Institution, once an artist during the Great Depression, pioneered the mapping of Gulf Stream eddies with painstaking ship surveys. It was a task befitting his training, and the 'false color' renditions used here to show temperature, are surely a high form of natural art. As well as being a warm current, the Gulf Stream is also a front separating the warm (red, orange) saline tropical waters of the Sargasso Sea to the south, from the fresher, colder (green, blue, purple) subpolar waters to the north. Despite the time of year (August), waters flowing south from the Labrador Current chill the coastal region as far south as Cape Hatteras. The Gulf Stream front was first mapped in 1768 by Benjamin Franklin, whose cousin Timothy Folger was familiar with it, as a site where whales could be found.

The roundish feature breaking off the north wall of the Gulf Stream in **Figure 3** is an example of an eddy formed by instability of a current and its associated temperature front. This instability can draw its energy from two sources: the kinetic energy of the current or the gravitational potential energy of the tilted stratification. As the instability grows, the Stream meanders wildly. Like an oxbow in a sinuous river, it can break off and become an isolated eddy. Here the eddies are sometimes called 'rings' because they are like rings of Gulf Stream water enclosing a trapped, foreign water mass. Meanders toward the north thus break off on the north side of the Stream and form warm eddies (relative to the

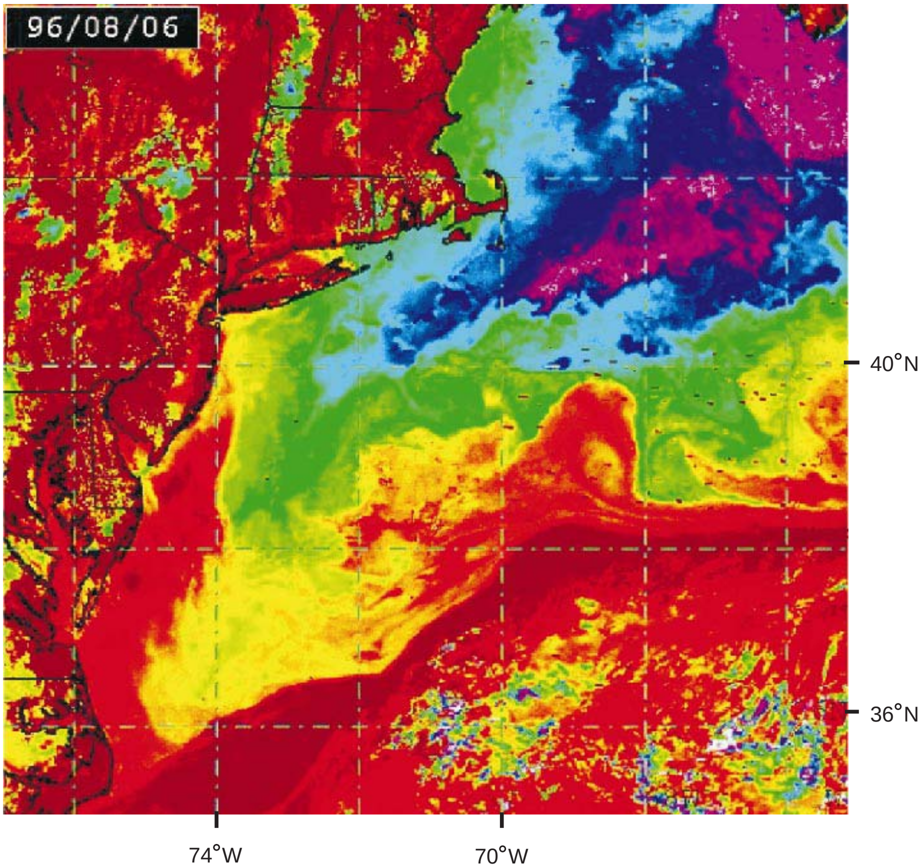

Figure 3 Sea surface temperature (SST) patterns in the Gulf Stream and adjacent warm waters of the Sargasso Sea (to the south) and cold, shallow water on the continental shelf. Color indicates temperature, ranging from purple, blue, green, yellow, orange to red as one moves from cold to warm. The Gulf Stream is the narrow, deep red feature flowing rapidly from south-west (left) to north-east. Its instability spawns mesoscale eddies. Each gridded box is one degree wide, and hence the north–south size of each box is 111 km.

cold waters around them). Conversely, southward meanders break off, encapsulating cold water to form 'cold' rings that wander south-westward and are often absorbed back into the Gulf Stream. The net effect is an exchange of water across the front: the Gulf Stream is a 'mixer.'

Biological communities are strongly affected by ocean circulation and eddies. In the East Australia Current (**Figures 4** and **5**) the color of the sea surface can be used to estimate chlorophyll concentration (**Figure 4**) in green plants (phytoplankton). This current is, like the Gulf Stream, a western boundary current. The sea surface temperature for the same region at approximately the same time is shown in **Figure 5**. The two figures show the differing texture of the two properties, temperature and phytoplankton (plant growth). Temperature is strongly affected by the atmosphere, which erases the memory of SST patterns. Biological activity can persist for longer times, and hence the patterns show streakiness – longer persistence of fine details.

Baroclinic and Barotropic Eddies

Eddies produced by the shearing motion of a current or by its store of gravitational potential energy are part of a life cycle of energy transformation. There is a natural evolution of the eddies toward greater width, and toward greater vertical penetration. With the right circumstances the cycle can continue until the eddies reach to the seafloor with nearly identical horizontal currents at every depth. This is known as a 'barotropic' state, whereas currents that decrease or increase with depth are termed 'baroclinic.'

Baroclinic currents obey a balance of Coriolis forces and pressure forces in the horizontal, and gravity and pressure forces in the vertical: this is known as the 'thermal' wind balance.' It establishes a close relationship between horizontal variations in fluid density (as in an ocean front separating warm water from cold) and vertical variations in current velocity (as in a current whose velocity decreases as

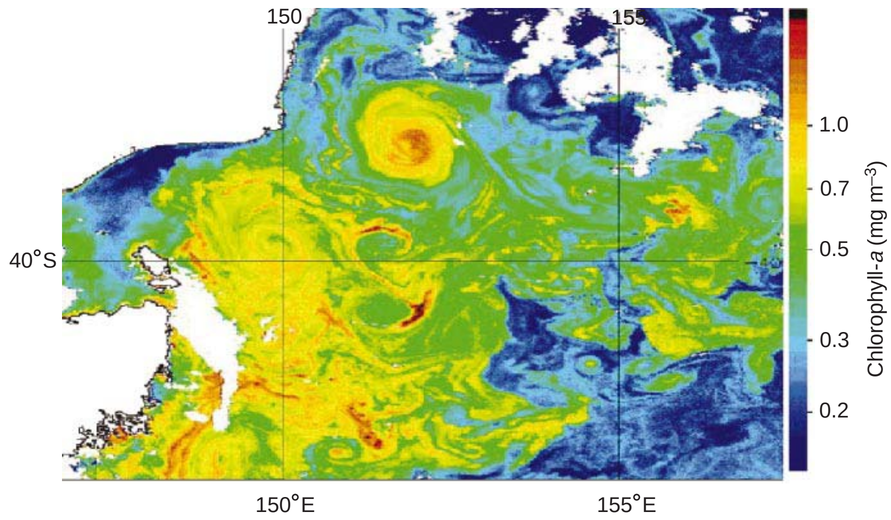

Figure 4 Chlorophyll-*a* concentration inferred from ocean color, SeaWIFS satellite. This is the East Australia Current along the coast of New South Wales. Note the richer content of finely textured eddies. Characteristically, ocean color and other 'tracers' can develop a more finely filamented structure than can temperature, whose patterns are erased by heat exchange with the atmosphere. Latitude and longitude (the parallels 40°S latitude, 150°E and 155°E longitude) are shown (http://www.marine.csiro.au/ ~ lband/SEAWIFS/).

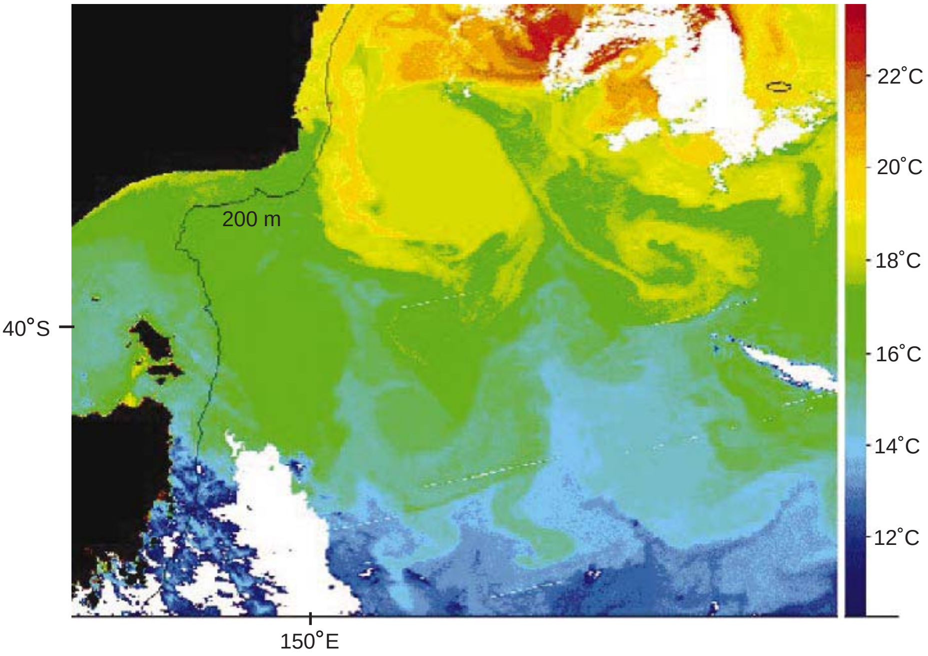

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Figure 5 Sea surface temperature (°C) in the East Australia Current, showing a field of anticyclonic eddies. This is approximately the same region and time as in **Figure 4**, with warm waters in the north flowing from the tropics, meeting cold waters of the Southern Ocean. White regions are clouds. Temperature scale shown at right. (This image is from http://www.marine.csiro.au/ ~ lband/SEAWIFS/; there are many web sites providing SST imagery, for example http://www.rsmas.miami.edu/groups/rrsl/,http://./www.elñino.noaa.gov/, and http://fermi.jhuapl.edu/avhrr/sst.html).

one moves downward from the sea surface). It is a key connection which, for more than a century, has allowed oceanographers to infer currents from observations of the temperature and salinity in the ocean (for temperature and salinity and pressure together determine the fluid density). Thus, for example, the Gulf Stream front, which in cross-section has tilted lines of constant density, is the site of strong vertical variations in current. These relationships are visible in **Figure 6**, showing a cross-

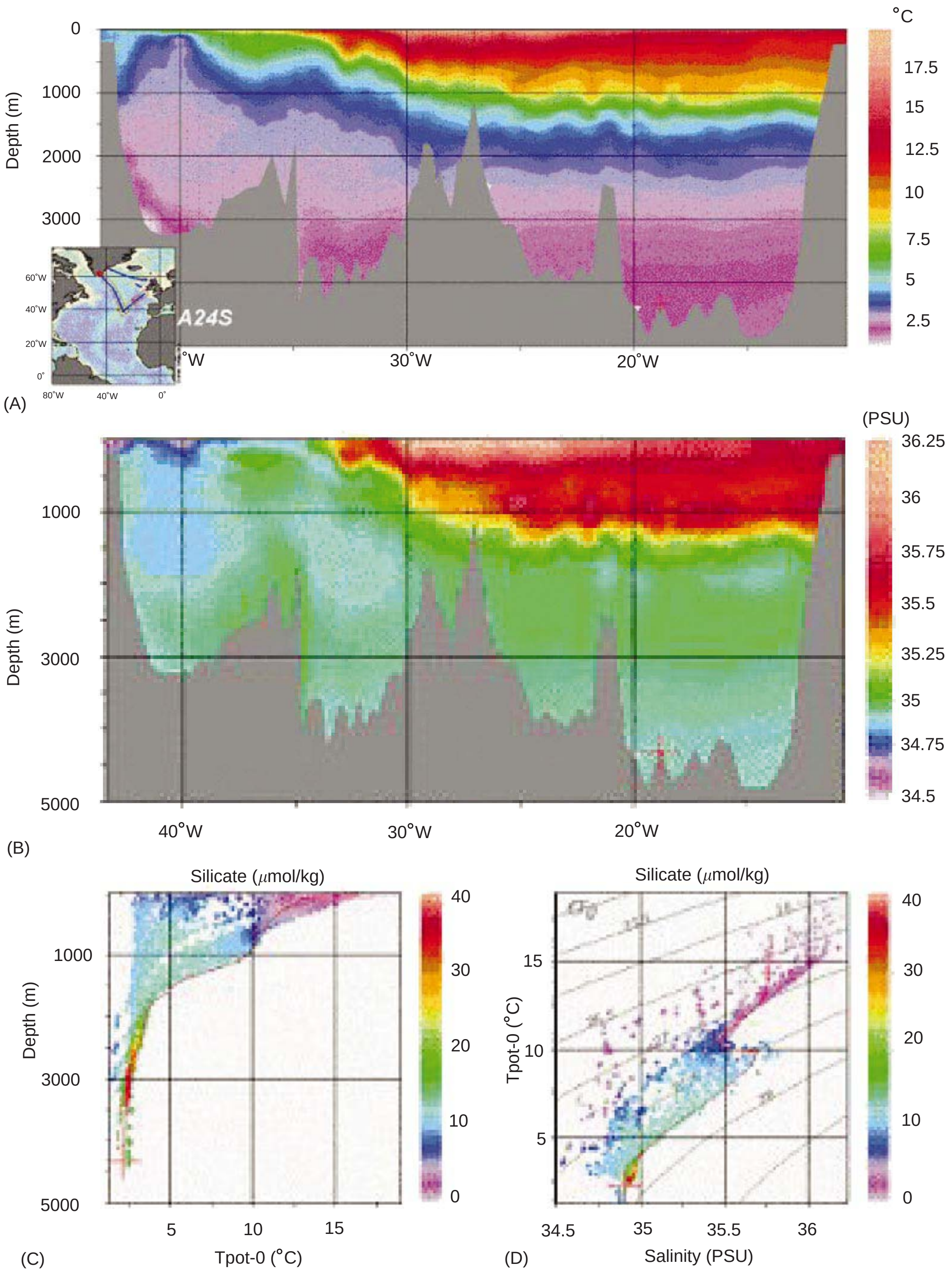

Figure 6 Section view of (A) temperature and (B) salinity along a ship-track in the northern Atlantic (the vee-shaped path shown in the map inset), from the WOCE hydrographic program. Surfaces of constant fluid density have a form broadly similar to the temperature and salinity surfaces. Also shown are salinity along the same section (lower left), vertical profiles of potential temperature (lower center) and plots of potential temperature against salinity (lower right). (Plot courtesy of Dr. Rainer Schlitzer.)

section of potential temperature and salinity in the northern Atlantic. These high-resolution data show the upper layer of warm water that dominates the southern and eastern parts of the section, floating on a bed of much colder, denser water. The sloping surfaces of constant temperature and salinity are evidence of thermal wind velocities associated with the general circulation, and the smaller-scale wiggles show mesoscale eddies. The seafloor topography is dominated by the Mid-Atlantic Ridge.

Near Cape Farewell, Greenland (the left end of the section), the subpolar waters reach right to the surface. The salinity section shows the warm water to be saline (of subtropical origin), while the deeper and more northern waters are of much lower salinity, owing to the sources of fresh water at high latitude. (Plots like this can be seen, or made to order, using software available at http://odf.ucsd.edu/OceanAtlas (the OceanAtlas system) or http://www.awibremerhaven.de/GEO/eWOCE (the Ocean Data View system).) The lower plots show the vertical profiles of potential temperature versus depth, and potential temperature versus salinity, for the entire dataset (with colors indicating the very low values of dissolved silicate in this highly ventilated part of the world ocean).

When we see eddies in the surface temperature we can thus infer that there will be variations in the currents from one vertical level to the next. Typically, warm eddies appear in cross-section as depressions in surfaces of constant temperature, while cold eddies are 'domes' of deep water elevated toward the surface. The sea surface has upward deflection opposite to that of the underlying density layers (provided the currents diminish as one moves downward from the surface). Usually this is the case, and this fits the picture of warm anticyclonically rotating eddies and cold cyclonically rotating eddies. In the Northern Hemisphere, cyclonic means counterclockwise, and the reverse in the Southern Hemisphere. There are exceptions to this rule, typically occurring when the eddies are generated deep beneath the surface.

Capping off this description of the vertical variation in ocean currents, we note that the sea surface elevation reveals not only the existence and shape of surface ocean current patterns but also their sense of rotation. The 'lows' in sea surface elevation are low-pressure cells beneath, and hence are cyclonic, while 'highs' in sea surface elevation are anticyclonic.

These difficult dynamical connections take on practical significance when one considers the biology of the ocean. Nutrients are richly abundant deep in the ocean, yet they need to be drawn up to the sunlit surface waters to produce chlorophyll-rich phytoplankton. Stable density layering of the oceans, however, provides a strong barrier to vertical movement of water. Anything that can lift deep water nearer the surface is likely to promote life, and this is just what cold, cyclonic eddies do.

Formation of Eddies

Eddies and thermal wind balance are also strongly in evidence in the coastal zones of the ocean. The long stretch of the eastern Pacific, shown in **Figure 7**, extending from California to Washington, shows cold waters upwelling where the north winds of summer blow surface waters offshore. The southward-flowing California Current, and narrower upwelling region are strongly unstable, and mesoscale eddies grow rapidly. Nutrient-rich cold waters promote growth right through the entire food chain, from plankton to whales and sea birds. Eddies act to exchange water between the shallow continental shelf and deeper ocean to the west.

Eddies formed by convection can be seen over most of the Earth, but they are particularly energetic in the cold, high latitudes. A laboratory experiment (**Figure 8**) shows mesoscale eddies generated by cooling of the water surface. Rotation of the fluid organizes the eddies, which are much bigger than the convective plumes directly generated by cooling. In the Labrador Sea, cold winds from the Canadian Arctic sweep over the water and cool it intensively (at a rate exceeding $800\,\mathrm{W\,per\,m^2}$ of sea surface, in a cold-air outbreak, and averaging $300\,\mathrm{W\,m^{-2}}$ for an entire winter month).

Eddies formed directly by winds blowing on the sea surface are thought to occur widely, and yet the large size of wind patterns is not well-matched to the small, roughly 50 km diameter of mesoscale eddies. However, near ocean boundaries, wind forcing can have demonstrable effect on eddies (for example, the westward Trade Winds spilling across the lowlands of Central America create a strong eddy-rich circulation in the eastern Pacific). Larger-scale eddies, more in tune with wind forcing take on the characteristics of Rossby waves (see below).

Eddies formed by flow over an irregular seafloor are common, and can be identified in tracks of floats and drifters. These range across the spectrum of turbulent sizes, all the way to the grand scale setting the path of the Antarctic Circumpolar Current.

Eddies formed by flow past an irregular coastline are seen widely. When fluid flows past a cylindrical island, it sheds a regular pattern of eddies with alternating rotation direction. This is known as a Karman vortex street. The interesting thing is that,

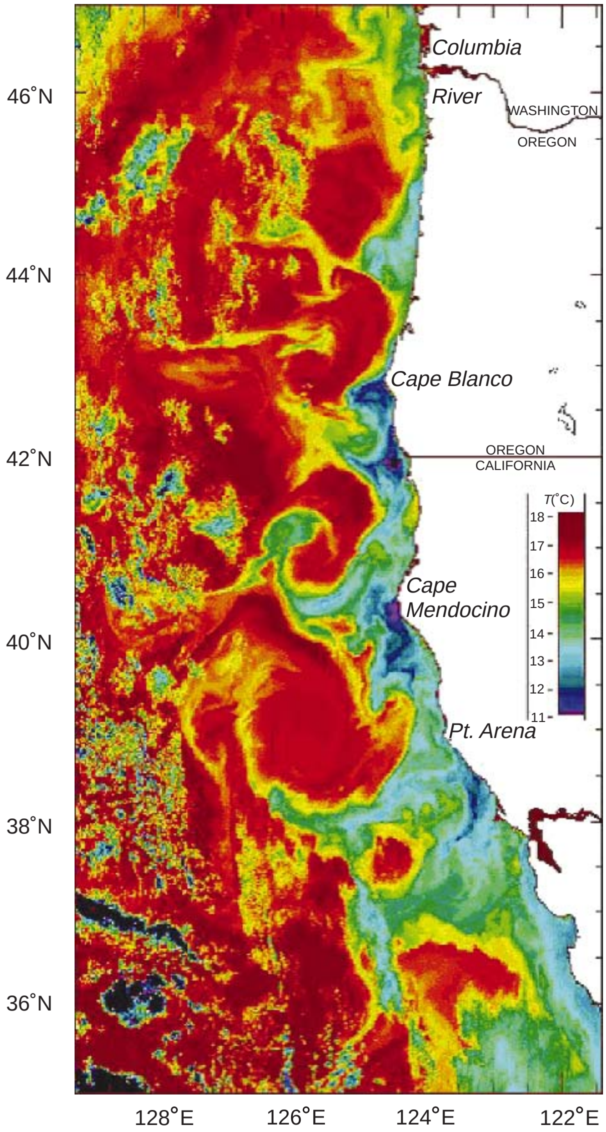

Figure 7 Coastal upwelling and eddies in the California Current. (Oregon State University.). Blue (cold) coastal waters are drawn up from below the surface, and are rich with nutrients. New instruments enable us to do 'cat-scans' of the upper ocean using instruments 'flying' behind a rapidly moving vessel, tethered with a cable (e.g., http://www.oce.orst.edu/research).

when the same experiment is done in a laboratory, the regularity of the vortex street disappears as the flow is made stronger or the cylinder is made larger. At the much greater scales of oceanic flow it is at first surprising that the turbulence regime is not encountered. The likely reason is that fluid motions restricted to two dimensions cannot fragment their energy into a full state of turbulence as readily as can a fluid with full freedom to move in all three dimensions. Thus, your kitchen sink looks more turbulent than does a much larger ocean basin.

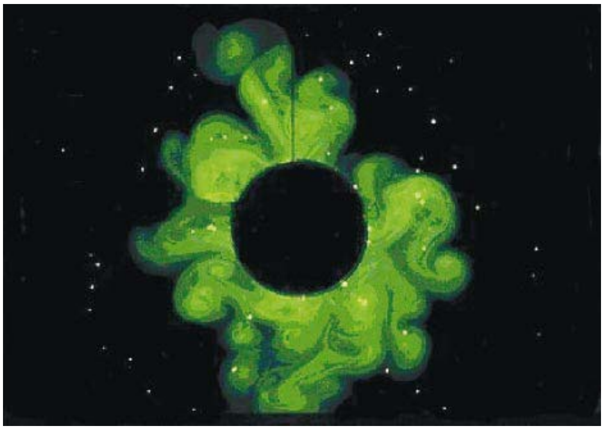

Figure 8 Eddies formed by cooling a rotating fluid in the laboratory. The dark central disk sits at the water surface and cools it, mimicking a region of cooling to the atmosphere. Coriolis forces give the thermal convection form, initially as small plumes (a few hundred meters across in the ocean), subsequently as mesoscale eddies with scale of 10–100 km, which dominate the scale model experiment here (oceanic flows and waves can be studied using scale models in the laboratory (e.g., Geophysical Fluid Dynamics Laboratory, University of Washington, http://www.ocean.washington.edu/research/gfd/gfd.html).

The Physical Properties of Eddies

Some basic physical effects If it were not for the Earth's rotation, its associated Coriolis forces, and its spherical shape and (or) complex bottom topography, the eddies shown in these figures would be much larger in scale. To discuss these effects we need to review some of the basic physics of the ocean.

On the great scale of the circulation of the oceans, there are several physical forces at work, particularly buoyancy forces and Coriolis forces. Buoyancy arises because both the water temperature and the concentration of dissolved salts (called the 'salinity' – kg of dissolved salt per kg of sea water) affect the density (expressed as the mass of 1 m^3 of sea water). Coriolis forces arise ultimately from the rotation of the Earth.

Buoyancy produces a layered ocean, with dense fluids beneath less dense fluid. A measure of its importance is the buoyancy frequency or Brunt–Vaisala frequency, N, measured in radians per second. If a region of sea water were lifted upward and then released, it would settle back to its original depth, bobbing about it with a frequency N (*see* **Internal Waves**). The bobbing period ($2\pi/N$) varies from a few minutes in the upper ocean to several hours at great depth. Stable stratification greatly limits vertical motion of the fluid, for tremendous energy is required to lift fluid against gravity. Yet the deep ocean is 'ventilated' at high latitude. Cold air from the continents and the Arctic is particularly effective at cooling the ocean, making the waters dense enough to sink.

Coriolis forces greatly restrict the motion of the fluid oceans and atmosphere. Their importance is measured simply by the rotational frequency, Ω, of the planet (2π per day). At locations other than the poles, this effect is diminished by the sine of the latitude (θ); hence the important frequency, say f, is $2\Omega \sin(\theta)$ which is just equal to the frequency of a Foucault pendulum.

Horizontal structure and size A number of factors are at work determining the diameters of mesoscale eddies. One central idea is that if the buoyancy forces and Coriolis forces are of similar strength, the width, call it λ, will be approximately given by $\lambda = NH/f$, where N and f are as defined above, and H is the vertical scale of the eddy. This is known as the Rossby deformation radius, after Carl Gustav Rossby, a pioneer in both oceanography and atmospheric sciences. For eddies with vertical scale comparable with the ocean depth, the size λ ranges from a few hundred kilometers in the tropics to 10 km or so at high latitudes. This great range of variation comes from the tendency for the high-latitude ocean to have weaker density stratification (small N) and larger Coriolis frequency f. λ also represents the horizontal distance traveled by a simple internal gravity wave in a half-pendulum day. The same dynamical eddies exist in the atmosphere, yet are much larger in horizontal scale. They are the basic high- and low-pressure cells seen on weather maps. Their 1000 km diameter (roughly) is also estimated by λ, which is much larger because the buoyancy frequency of the atmosphere is so much greater on average, than that of the ocean.

Vertical structure The oceans are full of three-dimensional structures. The general circulation involves 'arteries' of flow, often narrow horizontally (say, 50 km wide) and vertically (say, 1 km or less, thick). Cross-sections of velocity or trace properties marking the circulation illustrate this. Because eddies are often spawned as instabilities of major currents, they too may be three-dimensional, and of limited extent in the vertical. Such structures, which are termed 'baroclinic,' may have a range of vertical scales, H.

In addition, both the general circulation and eddies can exist in a form with no variation of horizontal current from the top of the ocean to the seafloor. These 'tall' currents and eddies, termed barotropic, are distinct and important. They disturb the density field only slightly, and hence are invisible in classic hydrographic sections. For this reason, they were not well understood or observed by early oceanographers. Barotropic flows have a signature at the sea surface, but otherwise have no gravitational potential energy. Tall, barotropic eddies evolve rapidly and are strongly associated with Rossby waves.

Rossby waves; potential vorticity Finally, the shape of the planet is important. Its nearly spherical form causes Coriolis effects to change with latitude, and this leads to a new, rather exotic phenomenon known as Rossby waves. Water on a spinning planet is endowed with a 'stiffness' along lines parallel with the planet's axis. This stiffness does many things to the circulation, tending to restrict motion to lie east and west. More generally, in the presence of valleys and ridges on the seafloor, currents can circulate freely along curves of constant $\sin(\theta)$ divided by depth. These are simply curves of constant ocean depth, if we measure the depth parallel to the Earth's axis rather than vertically. Such pathways of freely flowing water are known as 'geostrophic contours.'

The physics of mesoscale eddies is described well by an exotic property of the fluid: the potential vorticity. We are interested in many different things in fluids: their velocity, temperature, density, salinity, etc., but certain of these properties are particularly illuminating. The fluid density, for example, is active in determining buoyant forces in the fluid. After correcting for pressure effects, the density is also a marker of fluid motion, so long as mixing and diffusive effects can be ignored: it stays the same (after that correction), if one follows a moving parcel of fluid. Maps of this corrected 'potential' density both give us dynamical information about currents and show us something about the mass distribution of the oceans. Potential vorticity also has the property that it remains constant, as we follow a parcel of fluid, until mixing or external forces or heating is felt. The quantity describes the 'spin' of a fluid parcel, including the rotation of the Earth, and also including a measure of the thickness of the fluid layer. From knowledge of the field of potential vorticity, one can calculate much about the currents and displacement of the mass field of the ocean. As a more general definition, geostrophic contours become lines of constant potential vorticity, which cover surfaces of constant (potential) density.

This same stiffness imparted by the Earth's rotation produces wave motions if fluid is pushed across, rather than along, geostrophic contours.

These Rossby waves are 'information carriers' that help to form the general circulation. They are themselves unsteady currents, whose patterns radiate principally horizontally from where they are generated. A laboratory experiment, **Figure 9**, shows Rossby waves in a basin centered on a virtual North Pole. All of the motion in this experiment is generated by a small, oscillating body in the lower left of the figure (beneath the black rectangle). The Rossby waves are seen as wavy deflections of the central band of dye. Constant–latitude circles become marked with colored dyes as east–west currents develop in response to the Rossby waves' shaping of the general circulation.

These Rossby waves are 'weak' eddies. If they 'break,' that is, deform the basic fluid greatly and irreversibly, they fulfill our picture of turbulence: chaotic, with active stirring and mixing of trace properties, like the colored dyes here. The 'rotational stiffness' that makes the waves possible also greatly limits the north–south movement of fluid. Thus, the polar cap in this experiment is virtually unmixed, and is chemically isolated from the lower latitudes. This is just the physics at work in the atmosphere, in defining the polar ozone depletion zones ('ozone holes').

Rossby waves, and their more violent cousins the mesoscale eddies, help to set the fundamental force balances of the general circulation. They redistribute the momentum of ocean currents horizontally (as in **Figure 9**), establishing and reshaping currents in horizontal planes. But the ocean is three-dimensional, and these waves and eddies are also active in transferring momentum downward from the sea surface. In **Figure 1** the Antarctic Circumpolar Current is driven eastward by the strongest sustained winds on Earth. It thus becomes the greatest of ocean currents (in terms of transport and potential and kinetic energy). The eastward force of the winds is balanced by pressure forces exerted by the ridges and gaps of the seafloor topography. To connect these opposing forces, Rossby waves and eddies are active in transporting momentum downward. Elsewhere in the world ocean, eddies also provide essential communication of momentum downward from the surface. They drive deep gyres known as inertial recirculations, and establish the form of the deep roots of currents like the Gulf Stream. Mesoscale eddies also stir and mix the potential vorticity field. With weak ocean currents, the geostrophic contours, or free-flow pathways, tend to lie east and west. In order to develop the great gyres of circulation, with substantial north–south flow, the ocean has to reorganize its potential vorticity field accordingly. This is accomplished both by eddy activity and by the dynamical reshaping of the large-scale oceanic density field.

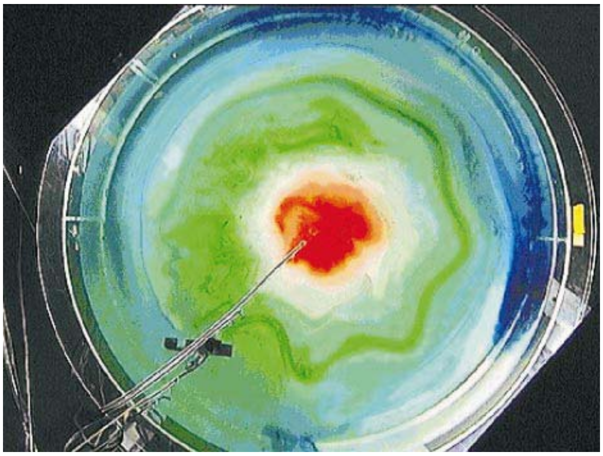

Figure 9 Rossby waves in a laboratory simulation of the circulation of an ocean centered on the North Pole. The waves are visible as undulations of the dye line, and are propagating eastward away from the wave source. Nevertheless, the wave-crests seem to move westward (clockwise). The source of the wave motion is a small oscillating cylinder at the lower left (black band). Geophysical Fluid Dynamics Laboratory, University of Washington.

We have argued that long waves, involving much subsurface activity, are an important cousin of mesoscale eddies. Such waves are particularly visible in the tropical oceans. El Niño is an interaction between atmosphere and oceans. While it recurs somewhat unpredictably, in ways not yet fully understood, oceanic wave propagation along the Equator adds a 'delayed memory' to the process (such propagation is clearly visible in satellite altimeter and SST animations; see www.pmel.noaa.gov). Precursors to El Niño are recognizable, and give roughly six months of predictability at present. Sea surface temperature anomalies on 18 January 1999, during La Niña (the opposite phase to El Niño) involved an unusually cold eastern tropical Pacific and warm core in the subtropical North Pacific (**Figure 10**). The pattern is decorated with mesoscale eddies of much smaller scale and unstable waves on the equatorial westward jet. It is interesting that as one moves from high latitude toward the Equator, the Rossby scale, λ, increases markedly and mesoscale eddies become larger and more wavelike. Energy sources in the strong Equatorial current system give rise to tropical instability waves, which appear to play an important role in both dynamics and biology.

Modelling Techniques

Figures 8 and 9 showed laboratory simulations of mesoscale eddies and Rossby waves. Some, but not

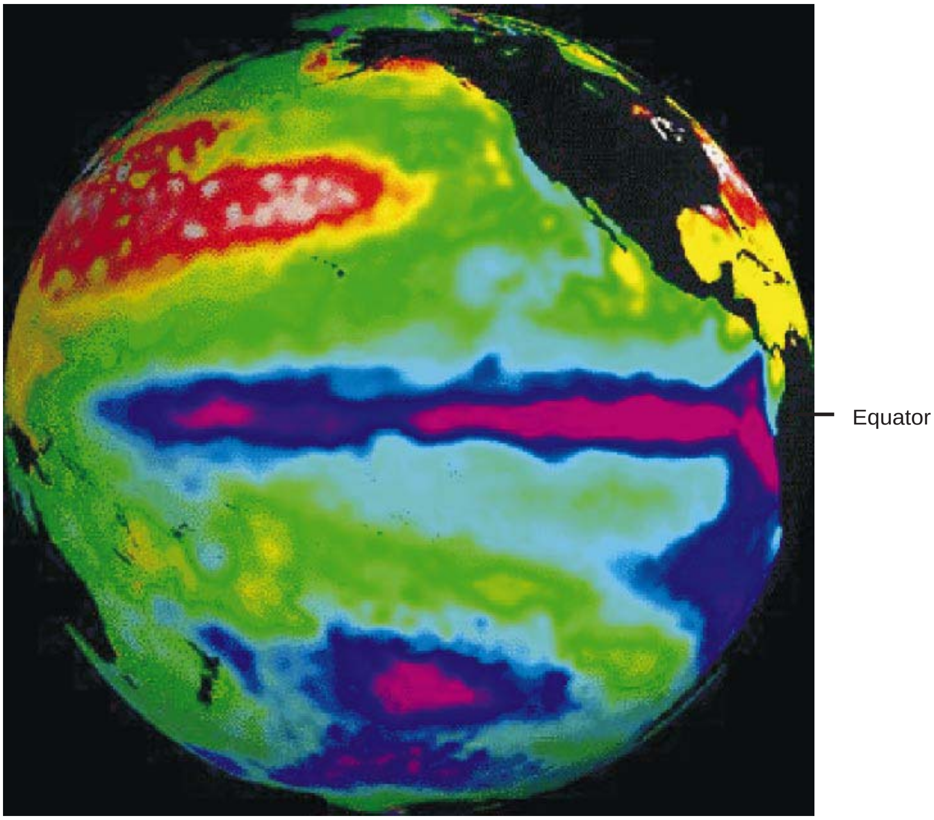

Figure 10 Sea surface temperature map (showing the temperature anomaly, or difference between the temperature and its seasonal mean at each point) in the eastern Pacific Ocean for 18 January 1999 (http://podaac.jpl.nasa.gov/sst/intro.html). The low (purple, blue) temperatures along the Equator represent the unusually strong easterly (that is, westward) winds associated with La Niña. Mesoscale eddies appear in middle latitudes, and also as tropical instability waves along the Equatorial circulation. Both satellite observations and *in situ* instruments, moored or drifting or shipborne, contribute to our understanding of the tropical oceans (e.g., http:// www.pmel.noaa.gov).

all, physical effects active in ocean circulation can be modeled in the fluids laboratory. A persistent problem is the exaggerated effect of friction and molecular diffusion of heat and salt in the small scale of a model. Beginning in the 1970s, computers were developed with enough speed and memory to solve adequately the physical equations of motion, using methods of numerical approximation. Fully turbulent flows that have eluded theoreticians for hundreds of years have suddenly become accessible to 'numerical experiments.' These experiments have problems analogous of those in the fluids laboratory: limited resolution of fine details. Yet analysis of the flow is far easier in a computer model than a laboratory model: everything about the computer-modeled flow is measurable.

We have pointed out the range of length scales needed to describe oceanic motions, from 1 mm to 10 billion times that large. Computer models currently describe a range of scales, typically, of only a thousandfold; with these we can simulate a flow that is a few hundred eddies 'wide.' What does this mean in terms of representing the global ocean?

Computer experiments were originally developed for the atmospheric fluid, with weather prediction a principal goal. There are many similarities between atmospheric and oceanic circulations and eddies, but there are also striking differences. Particularly, Rossby's deformation scale, λ, is much smaller in the ocean than the atmosphere. λ is an estimate of the diameter of mesoscale eddies, and this means that the great high- and low-pressure patterns on a weather map, with cyclonic and anticyclonic systems typically having 1000 km diameter, are dynamically similar to 100 km wide ocean eddies. The texture in **Figure 1** is much more fine-grained than that of a weather map showing atmospheric pressure patterns. These eddies are the most energetic features of the circulation and must be resolved by the models for many purposes. Computer models of the ocean are thus global in extent yet need gridpoint spacing significantly less than λ. Ten-kilometer spacing of gridpoints is typical in

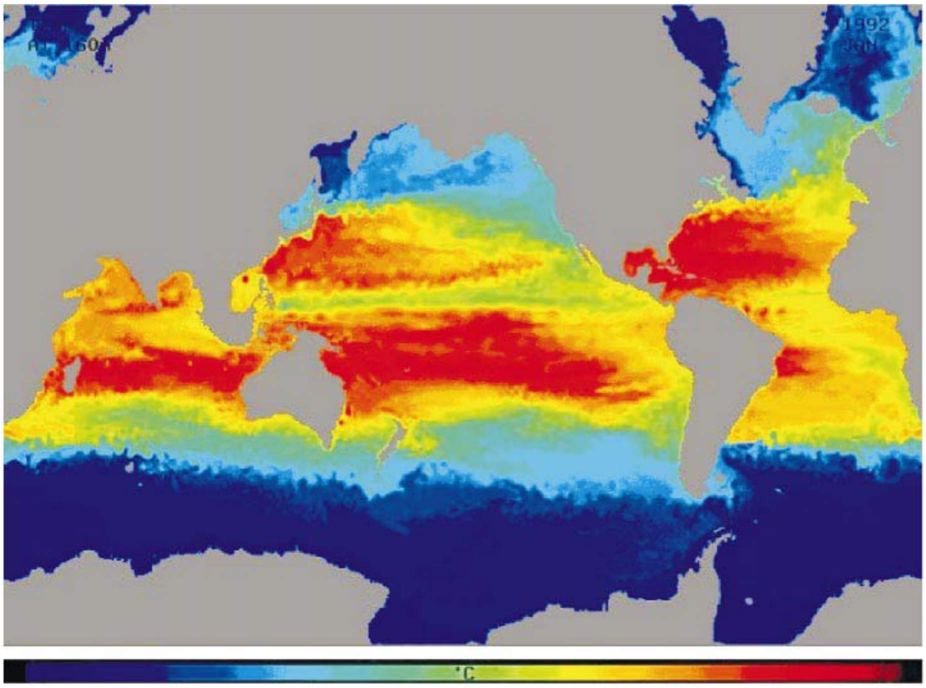

Figure 11 Temperature at 160 m depth, from the Parallel Ocean Processing model (http://vislab-www.nps.navy.mil/ ~ braccio/) of the Naval Postgraduate School and Los Alamos National Laboratory. This is a snapshot during a single day in January 1992. The numerical model is driven by observed meterological winds and is also 'restored' back toward surface ocean observations. Notice the fine pattern of mesoscale eddies superimposed on the warm, (red) subtropical gyres and the cool (blue) high-latitude circulations. Grid points of this computer model are spaced 1/6° of latitude apart, giving reasonable coverage of mesoscale eddies at low and middle latitudes. This map of temperature differs from **Figure 10**, which shows only the anomaly field.

a modern 'eddy resolving' ocean model (with vertical resolution of a few hundred meters), and even this is not enough to resolve fully eddies and boundary currents. Atmospheric models with grids having ten times greater spacing are considered to have 'high resolution.'

There is another striking, nearly devastating, obstacle to ocean modeling: evolution of the circulation is much slower than with comparable features of the atmospheric circulation. As we know from experience, the atmosphere adjusts to changes in solar heating after a period of a few months. Its weather features are rapidly destroyed by friction at the ground after just a few days. Thus a 10-year simulation of the atmosphere is very long indeed. However, the oceanic circulation responds much more slowly to changes in forcing, and this requires much longer simulation experiments. If the winds or solar heating at the sea surface are changed, the ocean will begin to respond quickly. Rossby waves will transmit the changes across major oceans in a few weeks. The tall, barotropic part of the flow will begin to adjust. Currents along the western boundaries and the Equator will quickly change. But the deeper, more baroclinic flow will take more than 10 years to adjust, and the great, global meridional overturning circulation will not fully redistribute heat, salt, and trace chemicals and biological fields for several thousand years. These key features – the smallness of strong ocean currents and their slow evolution in time – can be seen in animations of computer model runs (for example at http://vislab-www.nps.navy.mil/ ~ braccio/ for the Naval Postgraduate School and Los Alamos National Laboratory POP model; or www.http://panoramix.rsmas.miami.edu/micom/ for the University of Miami isopycnal ocean model). These simulations (**Figure 11**) use the full power of our largest computers, and are wonderful renditions of an entire world of ocean physics.

Computer simulations of weather and climate have to be run for many thousands of years if they are to encompass the full range of oceanic adjustment. In practice this cannot yet be done with 10 km grid spacing, and climate modelers instead use coarse resolution (typically 100–400 km grid spacing) and simulate the action of mesoscale eddies. They do this with exaggerated friction, and diffusion of heat and salinity that is much larger than in reality. These 'sticky, conductive' oceans may provide models of some of the important oceanic transport of heat and fresh water, and have much interesting structure, but they lack the full detail of both boundary currents and mesoscale eddies. The art of 'parametrizing' the effects of eddies so as to allow their neglect in detail is an active area of current research.

Conclusion

We have argued that mesoscale eddies contain large kinetic energy, comparable with that of the time-averaged ocean circulation. Eddies are crucial to the transport of heat, momentum, trace chemicals, biological communities, and the oxygen and nutrients relating to life in the sea. They are also active in air–sea interaction, both through response to weather and in shaping the patterns of warmth that drive the entire atmospheric circulation.

As a member of the huge family of turbulent motions, eddies contribute to the stirring and mixing of the oceans, to the creation of its basic, layered density field, and to its general circulation. The fundamental physics of eddies is expressed in terms of its potential vorticity, which is a tracer-like property that 'moves with the fluid.' The distribution of potential vorticity can be turned into knowledge of the currents and fluid density variations. The smallness and great energy of mesoscale eddies, the great thermal and chemical capacity of the oceans, and the slowness of the circulation conspire to challenge computer models, but rapidly increasing computer power is producing ever better representations of the ocean's fabric. At present, rather short-lived experiments (a few decades duration) can be carried out that resolve the global field of eddies, intense currents, and wind-driven gyres, whereas the slower features important to long-term climate change cannot be examined while also resolving mesoscale eddies. Nevertheless, several important physical processes like turbulent mixing, convection, upper mixed layer dynamics, and interaction with complex bottom topography are not yet well simulated by computer models. Many of the important applications of physical circulation in the oceans involve vertical motion: for biological communities, for transport of trace gases and their exchange with the atmosphere, for ocean/atmospheric climate interaction. This vertical motion of the fluid is particularly difficult to predict without fully resolving the detail of mesoscale – and smaller – features.

See also

General Circulation Models. Ocean Circulation. Ocean Colour from Satellites. Rossby Waves. Satellite Remote Sensing SAR. Satellite Remote Sensing of Sea Surface Temperatures.

Further Reading

Summerhayes CP and Thorpe SA (1996) *Oceanography, An Illustrated Guide*. New York: Wiley.

METAL POLLUTION

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Introduction

Marine pollution has been defined as 'the introduction by man, directly or indirectly, of substances or energy to the marine environment resulting in deleterious effects such as hazards to human health; hindrance of marine activities, including fishing; impairment of the quality for the use of sea water; and reduction in amenities' (GESAMP, 1990). Approximately 45% of people on Earth live within 150 km of the coast and marine pollution occurs as a consequence of increases in population density and industrialization. The problems of marine pollution are generally limited to nearshore waters rather than the open ocean, with the main impacted areas being estuaries, fjords, rias, and their adjoining shelf seas (**Figure 1**).

In the marine environment, metals such as iron, vanadium, copper, and zinc are essential for certain biochemical reactions in organisms, but even in moderately contaminated estuaries these metals contribute to stress in marine biota. By virtue of their toxic and bioaccumulative properties both cadmium and mercury are regarded as 'Black List' substances, while lead is on the 'Grey List'. These elements have little or no biochemical function and, while tolerable in minute quantities, exhibit toxic effects above critical concentrations. Mercury has a complex marine chemistry and exists in various forms, such as inorganic mercury, organically complexed mercury (with natural dissolved organic carbon), as a dissolved gas, Hg^0, and as the methylated species