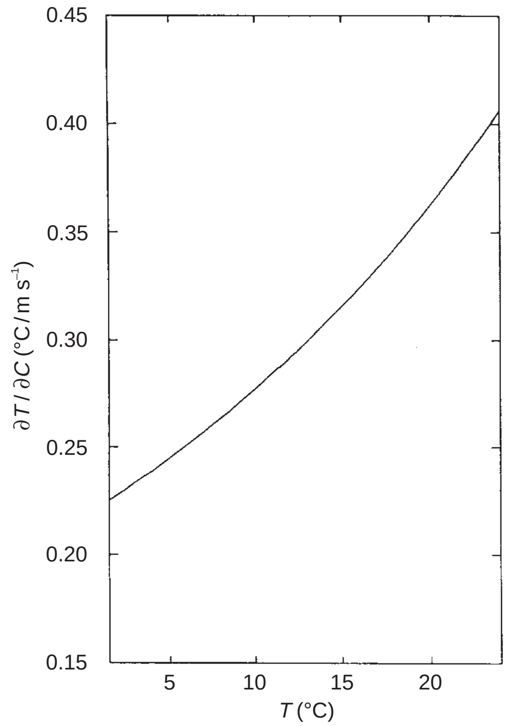

Figure 13 The derivative $\partial T/\partial C$ as a function of temperature. Adapted from Dushaw BD, Worcester PF, Cornuelle BD and Howe BM (1993) Variability of heat content in the central North-Pacific in summer 1987 determined from long-range acoustic transmissions. *Journal of Physical Oceanography* 23: 2650–2666.

where the integral allows for the dependence of $\partial T/\partial C$ on temperature.

See also

Acoustics, Arctic. Acoustics in Marine Sediments. Deep Convection. Internal Tides. Inverse Models. Tides.

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TOPOGRAPHIC EDDIES

J. H. Middleton, The University of New South Wales, Sydney, New South Wales, Australia

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Introduction

Topographic eddies in the ocean may have a range of scales, and arise from flow separation caused by an abrupt change in topography. This abrupt change may be of large scale, such as a major headland, in which case the topographic eddy is essentially a horizontal eddy of scale many tens of kilometers in a shallow coastal ocean. Eddies also occur at much smaller scales when ocean currents flow around small reefs, or over a rocky seabed. In this case the topographic eddies are perhaps only meters or centimeters in scale. A rule of thumb is that topographic eddies are generated at the same length scales as the generating topography.

Perhaps the earliest recorded evidence of a topographic eddy in the ocean comes from Greek mythology, where there is mention of a whirlpool occurring beyond the straits of Messina, between Sicily and Italy. Jason and the Argonauts in their vessel the Argo had to find the path between the Cliff known as Scylla, and the whirlpool having the monster Charybdis. The whirlpool still exists and occurs as the tides flood and ebb through the narrow straits. Another well-known tidal whirlpool, intensified at times by contrary winds and often responsible for the destruction of small craft, occurs off the Lofoten Islands of Norway. The Norwegian word maelstrom is associated with the whirlpool.

More recently, the fishing and marine lore of the Palau District of Micronesia, and the knowledge of ocean currents held apparently for hundreds, if not thousands, of years has been investigated. In fact, it was found 'The islanders had discovered stable vortex pairs and used them in their fishing and navigation long before they were known to science.'

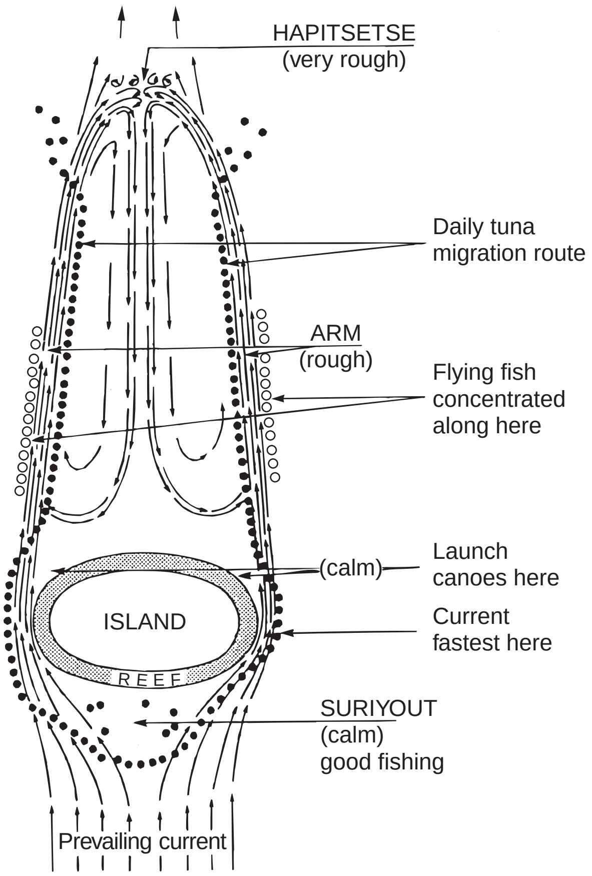

Figure 1 Island Wake of Tobi in Micronesia, showing flow patterns and concentrations of tuna and flying fish. (Reproduced from Johannes, 1981.) ●, Tuna concentrations; ○, Flying fish concentrations.

A sketch, drawn from the fishermen's description, is shown in **Figure 1**. The flow appears to comprise a stable vortex pair in the lee of the island, with identifiable zones of rougher water which would result from the conflicting directions of currents and waves, and calmer waters directly upstream from the island. A most interesting feature is the description of concentrations of tuna and flying fish, which clearly have a preference for congregating in certain zones, perhaps because there they find food more prevalent. This diagram underscores a fundamental importance of topographic eddies; they serve not only as a feature of the circulation, but also to provide preferential environments for the marine biota.

Although such whirlpools, eddies, and wakes had been well known for centuries by seafarers, in the early 1900s pilots and aerodynamicists 'rediscovered' eddies. The additional feature that they discovered was that eddies and wakes draw their energy from the mean flow, and provide a 'form drag' on the incident flow, tending to slow it down.

In the ocean, topographic eddies (or recirculating flows) comprise horizontal eddies generated by coastal currents flowing past coastal headlands, coral reefs, islands, or over undersea hills or ridges. They are important as they profoundly affect not only the horizontal distribution of nutrients, pollutants, bottom sediments and biota through direct horizontal transport, but also the vertical distribution through the associated three-dimensional flow field. In addition, a cascade of turbulent energy to smaller scales provides a continued source of smaller-scale turbulence, which itself acts to further diffuse and transport such matters.

Topographic eddies may also be produced by smaller-scale reefs (submerged wholly or partly) with scales typical of the width and height of the reef, in which case the turbulent eddies are fully three-dimensional in nature. These eddies are also unstable and break down into turbulence of progressively smaller scale, stirring the ocean, and creating strong spatial gradients, which enhance mixing and diffusion of passive materials.

Perhaps it is appropriate now to discuss the terms turbulence and diffusion. Turbulence refers to a state of flow which is chaotic and random in its detail, such that any instantaneous state of flow will not ever be reproduced at any later time. However, there may be underlying physics which imply that measurements of properties made at any point will, after much averaging over time, produce an average which is predictable and reproducible. Diffusion refers to the stirring and mixing of waters as they flow in a turbulent manner. Diffusion tends to smear out or dilute unusually large concentrations of some property, such as a pollutant. The stronger the turbulence, the more rapid the diffusion.

Larger Scale Topographic Eddies

Many coastal headlands protrude several kilometers into coastal currents, where the ocean depth is often less than 100 m or so. The coastal currents may be tidally induced, changing over a period of 12 h or so, or may be relatively steady, changing perhaps only once every 7–10 days as a result of local synoptic scale atmospheric systems (*see* **Wind Driven Circulation**), or as a result of coastal trapped waves (*see* **Coastal Trapped Waves**). Any resulting eddies are somewhat two-dimensional, with horizontal size many times that of vertical size, and occur downstream of the headland.

The generation of such recirculating flows or eddies has traditionally been considered to occur as follows. Flow separation occurring as a coastal current passes a headland is a result of the inability of the pressure field to allow the flow to follow the coastal contours, resulting in an adverse pressure gradient at the boundary. The separated flow has a very strong shear layer (with high vorticity), and a large-scale eddy may form, and either remain attached to the headland, or be carried downstream. In some cases, a string of eddies (known as a vortex street) may be generated. **Figure 2** shows a characteristic flow pattern behind Bass Point (near Sydney), with an overall larger-scale wake pattern, superimposed on which there are a number of smaller eddies.

There are several dimensionless numbers which represent various balances between physical processes, and hence terms in the equations of motion, which have been proposed in an attempt to simplify the physical balances which exist. For example, classical laboratory studies of the breakdown to turbulence have utilized the Reynolds number

$$R_e = UL/v$$

where U is the scale for the incident flow, L is the horizontal scale of the obstacle (reef or headland), and v is the kinematic viscosity of the fluid. For example, Reynolds numbers between 4 and 40 for two-dimensional flows around a circular cylinder indicate a trapped and steady recirculating eddy-pair. For $R_e > 40$ the trapped eddy-pair maintains its presence, but the downstream wake begins to become unstable. At Reynolds numbers larger than $R_e = 80$, the eddy-pairs are swept downstream as a von Karman vortex street. Reports of such studies invariably cite the need to have no 'environmental noise' in the system to ensure reproducibility of the wake at low R_e, that is, a perfectly smooth incident flow upstream.

Field observations show some features which are at first sight similar to the laboratory observations, however, characterization of wakes and eddies based on the Reynolds numbers (and/or other simple dimensionless parameters) have often produced conflicting results. For field observations, relevant dimensional quantities include the incident current speed U, the distance the headland protrudes into the free stream L, the Coriolis parameter f and the water depth D. Vertical density stratification plays a role in deeper water, and the effects of the wind-driven surface layer and the frictional bottom boundary layer play a role in shallower water.

Figure 2 Attached eddies and vortex street in the wake of Bass Point as simulated by a computer model. (Reproduced from Denniss *et al*., 1995.) The domain width is 6.67 km, and the maximum current vector, as indicated by the longest arrow, is $0.42\,\mathrm{m\,s^{-1}}$.

Quantities arising from the flow itself are the horizontal eddy diffusivity v_x and vertical eddy diffusivity v_z associated with horizontal and vertical turbulent diffusion, respectively. Values of v_x are usually several orders of magnitude greater than values of v_z for most oceanic flows, indicating that horizontal diffusion dominates over vertical.

The assumption that turbulent Reynolds stresses are proportional to the mean velocity gradient allows an eddy-diffusivity approximation for the mean components of a turbulent flow. Reynolds numbers for oceanic flows are then evaluated using the horizontal eddy diffusivity v_x rather than the molecular viscosity. As an example, for flows around Bass Point Sydney, $R_e = UL/v_x \sim 1000$ using the overall headland width, and $R_e = 5\text{–}10$ for smaller-scale eddies produced by reefs at the tip of the headland, where $L \sim 100\,\mathrm{m}$ and $v_x \sim 15\,\mathrm{m^2\,s^{-1}}$. Thus there are at least two different scales of topographic eddies in the recirculation processes depicted in **Figure 2**.

Other relevant dimensionless parameters include the Rossby number

$$R_o = U/fL$$

which gives a ratio of advective acceleration (non-linear) terms to Coriolis terms in the momentum equations. The Coriolis parameter f denotes the local rate of the earth's rotation about the vertical axis. Low R_o flows ($R_o \ll 1$) have the background rotation of the earth controlling the dynamics, with relatively slow flows, and a tendency to stable flow patterns. High R_o flows ($R_o \sim 1$) have a stronger tendency to produce eddies, as the non-linear terms which characterize energetic flows tend to dominate. Most larger-scale flows in the ocean have $R_o \ll 1$, indicating the rotation of the earth is a dominating effect, whereas for the Bass Point example described above, $R_o \sim 1$, indicating that the advective acceleration terms may be strong enough to produce eddies.

Derived parameters include the bottom boundary layer or Ekman layer thickness δ, which scales as

$$\delta \sim (v_z/f)^{1/2}$$

This height is a measure of the vertical extent above the bottom where the flow is affected by transfer of vertical stresses. This results in a deceleration of current from the free stream value U in the flow above to zero at the sea bed. In this bottom boundary layer, currents will change in direction, turning to the left (right) in the Northern (Southern) Hemisphere as the seabed is approached from above. If the bottom depth $D \gg \delta$, then the boundary layer provides a frictional decay on the overall flow. If, however, $D \sim \delta$, then the bottom turbulent layer dominates the entire water column, and somewhat different dynamics follow.

The vertical Ekman number giving the ratio of vertical momentum diffusion terms to the Coriolis term is

$$E = v_z/fH\delta$$

Thus E may be interpreted as a ratio indicating relative importance of bottom frictional effects and those due to the Earth's rotation. High E values are indicative of flows in which bottom friction dominates the flow (very shallow flows or flows with high vertical eddy viscosity), whereas $E \ll 1$ is indicative of deeper flows, or flows where bottom friction is less effective.

The importance of an island wake parameter P (or its square root) defined by

$$P = UD^2/v_zL$$

is discussed by several authors as being the relevant parameter (*see* **Island Wakes**) to describe a wake some distance downstream; it is essentially a Reynolds number based on vertical eddy diffusivity rather than horizontal. A survey of data from a range of island wakes indicates that for $P \ll 1$ the current simply flows around the headland with no recirculating eddies, for $P \sim 1$ the wake is steady and stable, and for $P \gg 1$ eddy shedding is observed.

For very shallow water flows where bottom stress is dominant, a summary of data show that a ratio of Rossby to Ekman numbers defined by

$$R_o/E_k = UD\delta/v_zL$$

is perhaps a better parameter than P with eddy shedding for large numbers ($R_o/E_k > 500$), steady eddy formation for $R_o/E_k \sim 100$ and fully attached eddies for $R_o/E_k < 10$. In shallow waters where $D \sim \delta$, these parameters (P and R_o/E_k) are essentially the same.

The use of dimensionless numbers to characterize flows is based on the assumptions that the essential processes are characterized by simple dynamical balances which will hold essentially throughout the domain of interest. However, for unsteady, non-linear flows the balances are dependent on both location and time. Thus the Reynolds and Rossby numbers above are a measure of the flow balance in the upstream region. Reynolds numbers higher than some critical value imply that the resultant downstream flow is unsteady and chaotic, and is fundamentally different from the steady flow which occurs at lower Reynolds numbers. By contrast, the island wake parameters P and the R_o/E_k represent physical balances of the wake downstream of the headland. The bottom boundary layer thickness and Ekman numbers are properties of the vertical profile of the flow at any location.

A major feature, recognized in the early laboratory experiments was that flow stability at low Reynolds numbers was dependent on the absence of small-scale, rapidly changing background variability (referred to here as stochastic noise) occurring in the incident or upstream flow. However, it has been demonstrated theoretically that transition of the larger-scale flow to an unsteady chaotic system can be linked to the system's amplification of background stochastic noise. In the case of recirculating headland eddies, such stochastic noise might be due to variations in wind stress, wave activity (internal and surface), and nonlinear small-scale high-frequency turbulence caused by flow over or around bottom topography such as submerged or semisubmerged reefs.

Support for these ideas is provided by analyses of data from Bass Point. It is hypothesized that the turbulence generated by the smaller-scale reefs at the tip of Bass Point creates a turbulent horizontal shear layer. This pushes the flow separation point downstream, inhibiting the formation of a larger-scale attached eddy except under strong incident current conditions. Thus the smaller-scale turbulence at the tip of the Point has a substantial effect on the larger-scale wake flow. The small-scale turbulence is characterized in strength by a horizontal eddy diffusivity ν_x, and since ν_x is absent from the above wake parameters, the wake parameters cannot be definitive in terms of flow description. Thus it can be concluded that simulations or predictions of flow behavior based on dimensionless numbers alone, traditional stability analyses, or direct (nonlinear) numerical simulation may fail without exact knowledge of the background environmental stochastic noise.

The above description of flows is essentially applicable to cases of steady upstream inflows, however, in many coastal regions the tidal flood and ebb creates an alongshore current which floods and ebbs in opposite directions alongshore. In this case, there may be transient eddies generated at each half tidal cycle at every headland. The schematic diagram given here in **Figure 3** illustrates the point.

Eddies are generated on each cycle, and sit either side of the headland, with a residual flow always directed offshore at the tip of the point (**Figure 3A**); depth variability offshore ensures that rotational motions are generated by differential bottom friction (**Figure 3B**). A simple headland eddy is shown in **Figure 3C**, and a vortex street in **Figure 3D**.

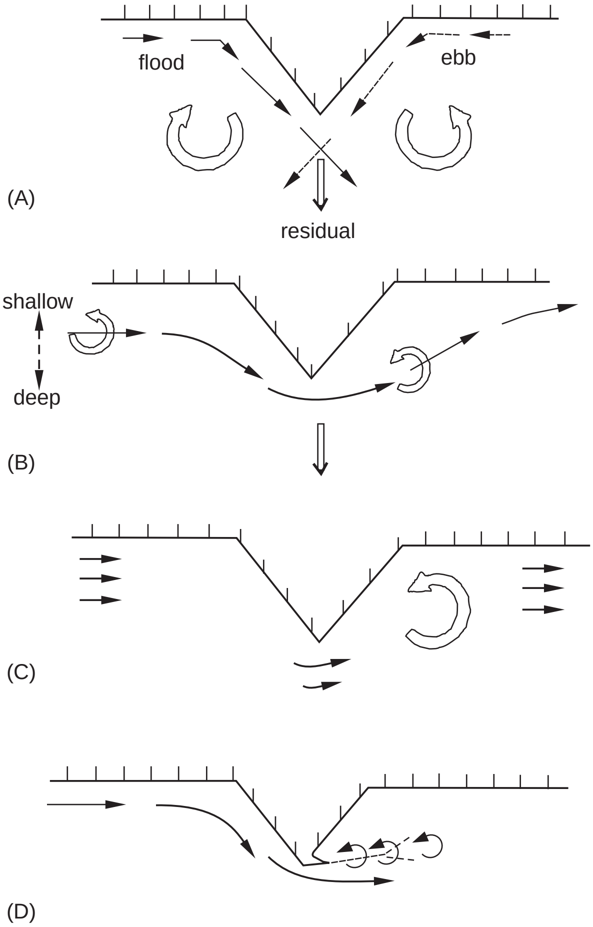

Figure 3 The possible mechanisms for the generation of headland eddies in a tidally cyclic flow (A), a steady flow where the depth increases offshore (B), and cases where a steady flow induces a simple attached eddy (C) or a train of separated eddies (D). (Reproduced from (Robinson 1975.)

The dynamics that allow generation of topographic eddies do not necessarily control their subsequent motion, the turbulent energy cascades (*see* **Three-dimensional (3D) Turbulence, Mesoscale Eddies**) or their ultimate dissipation. For topographic eddies in coastal waters, the presence of bottom boundary layers renders the flow partly three-dimensional, and so energy cascades to smaller and smaller scales as eddies break up. Vertical eddy viscosity in the bottom boundary layer, caused by friction at the seabed, also extracts energy from the system, creating a form drag on coastal currents.

Topographic Eddies Due To Bottom Topography in Stratified Flows

A dimensionless number which directly gives the ratio of current velocity U to the velocity of gravity waves in a current of depth D is known as the Froude number and is defined by

$$F_r = U/(gD)^{1/2}$$

The Froude number is the definitive number which divides a physical process where a disturbance may propagate upstream (called subcritical and denoted by $F_r < 1$), or a disturbance is swept downstream (called supercritical and denoted by $F_r > 1$). Flows over shallow sills, or coral reefs, in areas of strong tidal flow (e.g., north-western Australia) may sometimes be so rapid as to be supercritical. Hydraulic jumps, caused by a flow transition from rapid smooth flow upstream with $F_r > 1$ to slow turbulent flow downstream with $F_r < 1$, are also known to occur in strongly flowing rivers.

Flows which are density stratified are characterized by the flow speed U and the buoyancy frequency N, where N is defined by

$$N^2 = \frac{g d\rho}{\rho dz}$$

In flows of depth D, the dimensionless number which reflects the ratio of current speed to wave speed is

$$F_r = U/ND$$

Flows over and around obstacles depend not only on this internal Froude number, but also on the height H of the obstacle, its horizontal size and the steepness of the topography. Internal hydraulic jumps are also known to exist in the ocean where very strong tidal currents flow over steep topography, such as the Mediterranean outflow, or off the British Columbia coast (**Figure 4**). The subsequent turbulence is confined downstream causing a high level of mixing and turbidity, while upstream waters remain relatively placid and clear. Since such hydraulic jumps usually occur in irregularly shaped channels, they are often also the source of small topographic eddies.

Consideration of stratified flow around obstacles having an infinite value R_o (zero Coriolis parameter) provides many examples of the generation of topographic eddies. These include hydraulic jumps, exchange flows, waves and recirculating flows over two and three-dimensional obstacles in finite depth and infinitely deep stratified flows. In water much deeper than the obstacle height H, the relevant height scale is H, and the relevant dimensionless parameter is NH/U, an inverse Froude number based on the obstacle height. An interesting case study is depicted in **Figure 5**, for stratified flow with parameter $NH/U = 5$. In this case the stratification

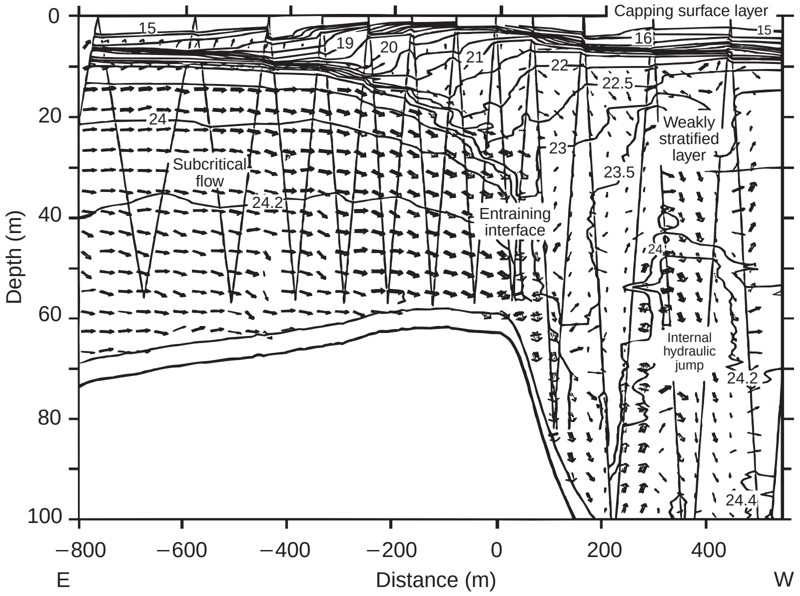

Figure 4 Schematic diagram of an internal hydraulic jump, in which the upstream flow (at left) is slow (with $F_r < 1$) accelerates rapidly down a steep slope (with $F_r > 1$), and flows into a turbulent hydraulic jump (with $F_r < 1$). (Reproduced from Farmer and Armi, 1999.) The downstream turbulence cannot propagate up the steep slope as the stratification N is not sufficiently large for the internal wave speed ND to exceed U, and so the turbulent flow is confined downstream of the topographic slope.

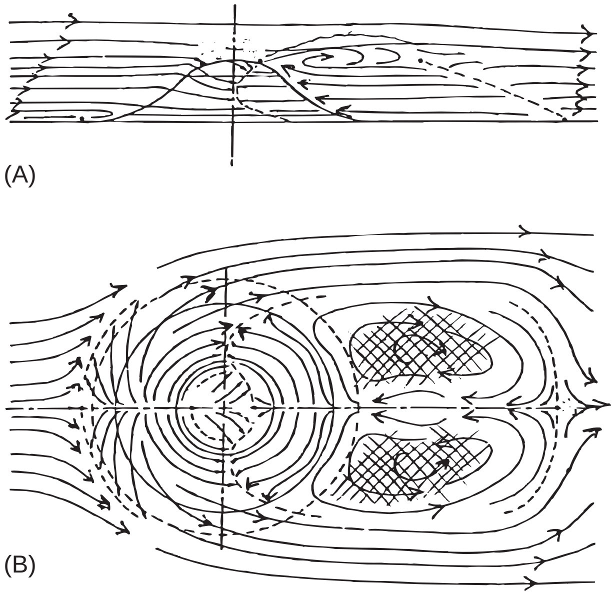

Figure 5 Topographic eddy in stratified flow over a three-dimensional obstacle with $NH/U = 5$ (reproduced from Baines, 1995), showing the side view through a cross-section along the line of symmetry (A), and the plan view showing the horizontal current components at a depth below the top of the obstacle (B). Also shown in (B) is the zone in which upwelling occurs at that same level (hatched).

is sufficiently strong to confine recirculation patterns to within about two obstacle heights of the seabed, with flow going both over and around the obstacle, and generating a pair of steady attached eddies. The dynamics are extremely complex, and consist of nodes where the flow separates, and stagnation points where the flow has zero current.

The flows described have zero background rotation (i.e., $f = 0$), and thus cannot describe a range of eddy-like flows, trapped above an obstacle in a current flow in a rotating reference frame and known as Taylor columns. For stratified flows over typical ocean seamounts in which the earth's rotation plays a role, the relevant scale of vertical disturbance above the seamount is fL/N, where L is the horizontal scale of the seamount. The ratio of the vertical scale of the obstacle H to this scale height is thus NH/fL, which in the form

$$B_{\mathrm{u}} = (NH/fL)^2 = (R_{\mathrm{o}}/F_{\mathrm{r}})^2$$

is known as the Burger number. B_{u} is also the ratio of Rossby number to Froude number squared. The Burger number is thus an indication of the balance of effects of stratification and earth's rotation, adjusted for the vertical aspect ratio of the seamount. High values of B_{u} tend to keep topographic disturbances more confined vertically, whereas low values permit taller Taylor columns, in which the effects of the obstacle extend higher in the water column. A full description of Taylor columns above seamounts in stratified flows is beyond the scope of this article.

Turbulence Due to Small-scale Bottom Topography and Reefs

For topography whose roughness scales are much smaller than the depth, and timescales are short, then the R_{o} number is high and Coriolis effects are negligible. Flow around such topography then has properties typical of those found in laboratory experiments, allowing for even smaller-scale turbulence to act as a stochastic noise at the inflow region. A number of topographic eddies may then be formed at different times and/or places, sometimes creating a wholly turbulent flow field over a limited region of the coastal ocean.

Such turbulence may be caused by strongly flowing tidal currents over a rough seabed or over and through coral reefs, for example, where the roughness scales may be as small as a few centimeters. These flows may scour the seabed, raising sediments off the seafloor and transporting them elsewhere. Such turbulence can also act to thoroughly mix the water column in areas where strong tidal currents flow over significant bottom topography. This occurs, for example, over submerged coral reefs at 80 m of water depth offshore from Hydrographers Passage in the Great Barrier Reef where phytoplankton multiply rapidly as a consequence of the combination of nutrient supply and light (*see* **Small-scale Physical Processes and Plankton Biology**). Turbulence on these scales is still subject to the energy cascade phenomenon, whereby eddies continually break down to smaller and smaller eddies until fluid viscosity damps out the motions.

Biological Implications of Topographic Eddies

As depicted in **Figure 1**, there is clearly a relationship between the wake of Tobi Island and the fish concentrations, as described by the local fishermen. However, there are also some much more subtle responses. These are related to the vertical circulation which is necessarily part of a horizontally circulating eddy.

The physics is relatively straightforward. In a horizontal eddy, the eddy can only maintain its structure if the eddy center has low pressure, which exists by virtue of a reduced sea level in the eddy center. Throughout the main part of the water

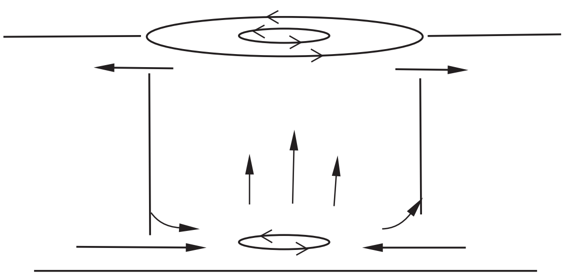

Figure 6 Topographic eddy in the coastal ocean showing inflow in the bottom boundary layer, upwelling in the eddy center, and outflow at the surface.

column (away from the seabed) the horizontal pressure gradient balances the centripetal force. However, in coastal waters the pressure gradient has an effect right down through the bottom boundary layer to the seabed. In this bottom boundary layer, the centripetal force is reduced because the velocity is reduced, and so the pressure gradient drives a flow toward the center along the seabed. This flow then upwells in the eddy center (**Figure 6**), and outflows on the surface.

The upwelling brings with it fine sediments, nutrients, plankton, and perhaps larval fish. The combination of nutrients, plankton and greater light can enhance plankton growth. Thus eddies in shallow waters are intrinsically places of enhanced plankton growth, and perhaps enhanced concentrations of other elements of the marine food chain.

In deeper waters, where the ocean is stratified, the lower pressure at the eddy center also results in a general uplift of deeper nutrient-rich waters, creating the same effect as in shallower waters. Observations in the wake of Cato Reef off eastern Australia showed higher concentrations of nutrients, phytoplankton, and larval fish of better condition, and the principal effects of this increased productivity were attributed to the uplift in the wake.

Referring back finally to **Figure 1**, the diagram can now be interpreted. The arms along which the flying fish and tuna concentrate are zones in which upwelled nutrient-rich waters, now outflowing from the eddy centers, meet the nutrient poor free-stream currents. This is likely to be a zone where plankton in the free stream now have an opportunity to grow, and the larger fish are perhaps benefiting from the enhanced primary productivity.

See also

Coastal Trapped Waves. Island Wakes. Mediterranean Sea Circulation. Mesoscale Eddies. Small-scale Physical Processes and Plankton Biology. Three-dimensional (3D) Turbulence. Wind Driven Circulation.

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