

high-flying aircraft and Earth satellites are referred to collectively as remote sensing. This comprises both the observation of natural radiation in various spectral bands, including both visible and infrared radiation, and measurements of the reflectivity of infrared and radar radiation. See REMOTE SENSING.

Well logging. A variety of types of geophysical measurements are made in boreholes, including self-potential, electrical conductivity, velocity of seismic waves, natural and induced radioactivity, and temperature variations. Borehole logging is used extensively in petroleum exploration to determine the characteristics of the rocks that the borehole has penetrated, and to a lesser extent in mineral exploration.

Measurements in boreholes are sometimes used in combination with surface methods, as by putting some electrodes in the borehole and some on the surface in electrical exploration, or by putting a seismic detector in the borehole and the energy source on the surface. See WELL LOGGING. R. E. Sheriff

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Geophysical fluid dynamics

The branch of physics that studies the dynamics of naturally occurring large-scale flows in both the atmosphere and oceans. Examples of such flows are weather patterns, atmospheric fronts, the Gulf Stream, coastal upwelling, and El Niño. The fluids are either air or water in a moderate range of temperatures and pressures. See EL NIÑO; GULF STREAM.

Because of their large scale (from tens of kilometers up to the size of the planet), geophysical flows are strongly influenced by the diurnal rotation of the Earth, which is manifested in the equations of motion as the Coriolis force. Another fundamental characteristic is stratification, that is, density heterogeneity within the fluid in the presence of the Earth's gravitational field, which is responsible for buoyancy forces. Thus, geophysical fluid dynamics may be considered to be the study of rotating and stratified fluids. It is the common denominator of dynamical meteorology and physical oceanography. See CORIOLIS ACCELERATION; EARTH; METEOROLOGY; OCEANOGRAPHY.

Historical development. Although geophysical fluid dynamics first became recognized as a scientific discipline in the late 1950s, its foundations can be traced to developments in fluid mechanics over a much longer period of time. During the nineteenth and early twentieth centuries, a number of mathematicians (for example, P. S. de Laplace), fluid dynamicists

(Lord Kelvin, H. von Helmholtz, G. I. Taylor), meteorologists (L. F. Richardson, V. Bjerknes, C. G. Rossby), and oceanographers (A. Defant, V. W. Ekman) made significant contributions to the study of large-scale flows that later became incorporated in the discipline of geophysical fluid dynamics. See FLUID MECHANICS.

During World War II the demand for improved forecasts of the weather and sea state provided a major impetus and resulted in a new generation of dynamical meteorologists and physical oceanographers who continued to make contributions long after the war ended. The main catalyst, however, was the launching of the geophysical fluid dynamics Summer Program at the Woods Hole Oceanographic Institution, in Massachusetts, which began in 1959.

Dynamics of rotating flows. The first of the two distinguishing attributes of geophysical fluid dynamics is the effect of the Earth's rotation. Because geophysical flows are relatively slow and spread over long distances, the time taken by a fluid particle (be it a parcel of air in the atmosphere or water in the ocean) to traverse the region occupied by a certain flow structure is comparable to, and often longer than, a day. Thus, the Earth rotates significantly during the travel time of the fluid, and rotational effects enter the dynamics. Fluid flows viewed in a rotating framework of reference are subject to two additional types of forces, namely the centrifugal force and the Coriolis force. (Properly speaking, these originate not as actual forces but as acceleration terms to correct for the fact that viewing the flow from a rotating frame—the rotating Earth in the case of geophysical fluid dynamics—demands a special transformation of coordinates.) Contrary to intuition, the centrifugal force plays no role on fluid motion because it is statically compensated by the tilting of the gravitational force caused by the departure of the Earth's shape from sphericity. Thus, of the two, only the Coriolis force acts on fluid parcels. History reveals that Laplace wrote the correct equations of fluid flow in a rotating frame for a study of ocean tides some decades before G. G. de Coriolis, but somehow the name of the latter has remained attached to the terms representing the rotational effect in the equations of motion. See EARTH ROTATION AND ORBITAL MOTION.

The importance of the Coriolis force in the dynamics is measured by the Rossby number, Ro [Eq. (1)], where U is a typical velocity value within

$$\text{Ro} = \frac{U}{fL} \quad (1)$$

the flow, $f = 2\Omega \sin(\text{latitude})$ the Coriolis parameter [the Earth's angular rotation rate $\Omega = 7.29 \cdot 10^{-5}/\text{s}$], and L a representative distance along the flow. The smaller this number, the stronger the effect of rotation on the flow.

At low speeds or long length scales, not atypical of geophysical flows, the Rossby number may fall far below unity. In such case, the rotating effects

become dominant, and the balance of horizontal forces is primarily an equilibrium between the pressure-gradient force and the Coriolis force [Eqs. (2) and (3)]. Here ρ is the density, f the Coriolis

$$-\rho f v = -\frac{\partial p}{\partial x} \quad (2)$$

$$+\rho f u = -\frac{\partial p}{\partial y} \quad (3)$$

parameter, u and v the eastward and northward velocity components respectively, p the pressure, and x and y the eastward and northward coordinates respectively. This balance is called geostrophy. *See* GEOSTROPHIC WIND.

One remarkable property of geostrophic flows is their vertical rigidity: All fluid parcels on the same vertical share the same velocity and therefore move as one rigid column. This is known as the Taylor-Proudman theorem. A corollary is another property: If there is any vertical velocity, fluid columns must go up and down without shrinking or stretching, occasionally forcing isolation of entire fluid columns above bottom bumps or dips, called Taylor columns. In the atmosphere and oceans, this property is manifested by the tendency of slow flows to follow topographic contours.

When the Rossby number is less than unity but not extremely small, the dynamics are less degenerate, and flow fields can exhibit a number of time-dependent behaviors, including inertia-gravity waves and vorticity waves. Inertia-gravity waves are the classical surface gravity waves with a modification due to the Coriolis effect. Their frequency-wavenumber relationship is shown in Eq. (4). Here g is the Earth's

$$\omega = \sqrt{g b k^2 + f^2} \quad (4)$$

gravitational acceleration, b the fluid's resting depth, f the Coriolis parameter, and k the wavenumber (2π divided by the wavelength). One property of these waves is that, unlike their purely gravitational counterparts, their frequency cannot fall below a minimum (f), lest they become evanescent (exponential instead of periodic behavior in one of the spatial directions). The Kelvin wave is the special case of a wave that is propagating along a boundary (shoreline) and evanescent away from it. This wave also has the property of having no velocity component transverse to the direction of propagation.

The other kind of waves is specific to rotating fluids. Instead of gravity, their restoring force is a vorticity gradient, which is created either by the Earth's curvature or by a bottom slope. There are thus two kinds of vorticity waves: planetary and topographic waves. Synoptic weather formations at midlatitudes share characteristics with planetary waves, whereas topographic waves tend to be associated with air-flow over mountain ranges and ocean currents along the continental slope. A third source of vorticity gradient is a gradient in the horizontal shear of a horizontal flow. In this case, however, a portion of

the kinetic energy stored in the flow is easily transferred to the wave, and the result is a growing wave that greatly distorts the original flow field. This is called barotropic instability. *See* WAVE MOTION; SURFACE WAVES.

In the vicinity of a top or bottom boundary, friction can become important, and the combination of rotation with friction leads to the development of Ekman layers. These layers differ from their cousins in classical fluid mechanics by having a well-defined thickness and a helicoidal flow field. An unexpected result is the existence of a significant angle between the frictional stress causing the boundary layer and the direction of the fluid transport within it. *See* FRICTION.

Dynamics of stratified flows. Variations of moisture in the atmosphere, of salinity in the ocean, and of temperature in either can modify the density of the fluid to such an extent that buoyancy forces become comparable to other existing forces. The fluid then has a strong tendency to arrange itself vertically so that the denser fluid sinks under the lighter fluid. The resulting arrangement is called stratification, the second distinguishing attribute of geophysical fluid dynamics. The greater the stratification in the fluid, the greater the resistance to vertical motions, and the more potential energy can affect the amount of kinetic energy available to the horizontal flow. A practical measure of stratification is the Brunt-Vaisala frequency, N , defined from its square according to Eq. (5), where $\rho(z)$ is the density function of the

$$N^2 = -\frac{g}{\rho} \frac{d\rho}{dz} \quad (5)$$

vertical z and decreasing upward ($d\rho/dz < 0$). In many ways, the Brunt-Vaisala frequency N is to stratified fluids what the Coriolis parameter f is to rotating fluids, and a close analogy can be developed between stratified and rotating fluids—namely, vertical properties of the latter are similar to horizontal properties of the former. The dimensionless number of stratified flows corresponding to the Rossby number of rotating flows is the internal Froude number, Fr [Eq. (6)], where H is the height of the fluid region

$$Fr = \frac{U}{NH} \quad (6)$$

under consideration. *See* DENSITY.

Just as the water-air density discontinuity can support gravity waves, the gradual density variation of a stratified fluid can support gravitational waves, called internal waves. Like their surface counterparts, internal waves can be affected by the Earth's rotation, and unlike them, they can propagate not only horizontally but also vertically. Internal waves are ubiquitous in the ocean, where their frequency spectrum very often displays a standard structure suggesting saturation. In the atmosphere, mountain waves and cloud rolls are manifestations of internal waves.

On occasion, a source of energy is sufficiently intense to create vertical motions that overcome the

stratification, and the result is vertical mixing over a partial extent of the fluid system. A common situation is one where turbulence induced by a shear stress in the proximity of a boundary generates a mixed boundary layer. In the ocean, a mixed layer is created almost daily in the top few meters under the action of surface winds, and it also exists at the bottom of the ocean wherever near-bottom currents can generate enough turbulence to overcome the stratification. *See* TURBULENT FLOW.

Another mechanism capable of erasing an existing stratification is thermal convection. Whenever a fluid is heated from below or cooled from above, it becomes top heavy, and negative buoyancy forces generate velocities that rearrange the fluid toward a more stable state. During daytime, the ground is warmed by the Sun and effectively heats the atmosphere from below. The result is a state of convection that gradually erases the previous nocturnal stratification and creates a well-ventilated layer called the atmospheric boundary layer. The turbulence accompanying this state of convection greatly facilitates the dispersal of pollution. In lakes and oceans, heat loss at the surface during winter generates convection that can mix the water over several tens or hundreds of meters, depending on the intensity of the cooling and on the strength of the stratification created during the previous summer. *See* CONVECTION (HEAT).

Dynamics of rotating and stratified flows. A quantity central to the understanding of geophysical flows, which are simultaneously rotating and stratified, is the potential vorticity, q . This quantity incorporates both rotation and stratification [Eq. (7)] and has the

$$q = \left(f + \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) \frac{\partial \rho}{\partial z} + \left(\frac{\partial u}{\partial z} \frac{\partial \rho}{\partial y} - \frac{\partial v}{\partial z} \frac{\partial \rho}{\partial x} \right) \quad (7)$$

property of being nearly conserved by fluid parcels as they travel with the flow. One situation in which potential-vorticity conservation rules the fate of the fluid is geostrophic adjustment. This occurs whenever a heterogeneous fluid initially away from equilibrium seeks a lower level of energy; potential-vorticity conservation then limits the amount of vertical stretching or squeezing that every parcel can undergo, and the result is a final state with a residual motion in geostrophic balance. Many atmospheric and oceanic density fronts exhibit attributes of geostrophic adjustment.

The interplay between rotation and stratification effects creates a preferential length scale at which a large portion of the energy available in geophysical flows tends to be concentrated. This privileged length, L , called the radius of deformation, arises when the Rossby and Froude numbers are equal [Eq. (8)]. Numerous structures such as jets, vortices,

$$L = \frac{NH}{f} \quad (8)$$

and fronts have horizontal dimensions that are comparable to the radius of deformation. In the atmosphere, the radius of deformation sets the size of syn-

optic weather patterns (500–1000 km; 310–620 mi), whereas in the ocean it is usually smaller (10–50 km; 6–30 mi) and related to the width of currents such as the Gulf Stream.

Because they do not correspond to a state of absolute minimal energy, geostrophically adjusted states retain a certain amount of energy that can still be made available for subsequent motions. The process by which a geostrophic state relaxes toward a yet lower energy level is called baroclinic instability. The instability begins with a horizontal meandering of the flow that has a vertical phase shift creating a mutual reinforcement of the meanders at the different vertical levels of the fluid. Growing meanders eventually detach as vortices, and the ultimate situation is a complex pattern of a wavering flow embedded in an assortment of interacting vortices. The preferential length scale of the meanders and vortices is again the radius of deformation.

Geophysical flows are replete with vortices, resulting from baroclinic instability. Their interactions generate highly complex flows not unlike those commonly associated with turbulence. Unlike classical fluid turbulence, however, geophysical flows are wide and thin (with, furthermore, a high degree of vertical rigidity as a result of rotational effects), and their turbulence is nearly two-dimensional.

Applications. Geophysical fluid dynamics finds much of its use in dynamical meteorology and physical oceanography. In meteorology, geophysical fluid dynamics has been the key to understanding the essential properties of midlatitude weather systems, including the formation of cyclones and fronts. Geophysical fluid dynamics also explains the dynamical features of hurricanes and tornadoes, sea and land breezes, the seasonal formation and break-up of the polar vortex that is associated with high-latitude stratospheric ozone holes, and a host of other wind-related phenomena in the lower atmosphere. *See* CYCLONE; HURRICANE; TORNADO.

In oceanography, successes of geophysical fluid dynamics include the explanation of major oceanic currents, such as the Gulf Stream. Coastal river plumes, coastal upwelling, shelf-break fronts, and open-ocean variability on scales ranging from tens of kilometers to the size of the basin are among the many other marine applications. The El Niño phenomenon in the tropical Pacific is rooted in processes that fall under the scope of geophysical fluid dynamics. *See* EL NIÑO; GULF STREAM.

Highly successful applications of geophysical fluid dynamics have also been made to other planetary-scale fluids, such as the molten rock in the Earth's outer core, Jupiter's Great Red Spot, and convective gases in stars, including the Sun. *See* JUPITER; SUN.

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