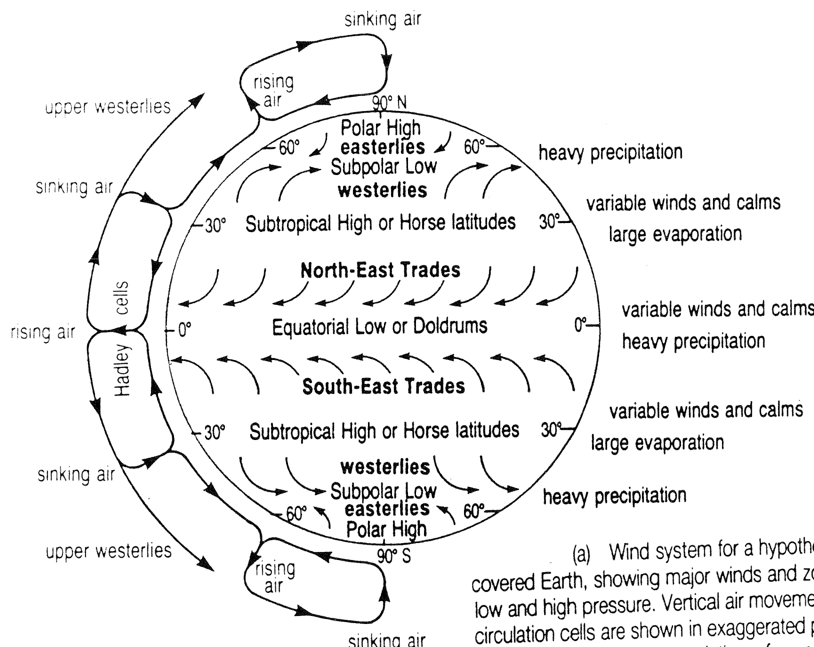
THE CORIOLIS EFFECT AND OCEANIC CIRCULATION

The Coriolis reaction has a tremendous effect on the global circulation of air and water. Here is a very brief descriprion of global circulation. The differential heating of the surface of the earth at the equator and the poles leads to a sharp temperature gradient that sets up buoyancy-driven movement of the air. For an idealized planet, the air would heat and rise at the equator, move toward the poles in the upper atmosphere, cool near the poles, dropping back toward the surface of the earth. Continuity in this cycle would ensure a continuous flow of air toward the equator near the surface of the earth (i.e., a "north wind" (pointing south) in the northern hemisphere and a south wind in the southern hemisphere). On earth, the rising equatorial air cools rapidly in the upper atmosphere (losing most of its moisture as rain over the tropics) and sinks to earth near 30° latitude. (This dry, descending air leads to a persistent band of high pressure near this latitude with the result that most continental areas near 30° (N or S) are deserts). The air below 30° moves toward the equator, the air above 30° moves poleward. Hence we would expect (in the northern hemisphere) persistent northerly wind in the tropics and a southerly at mid-latitudes. Of course, the Coriolis effect diverts all winds in the northern hemisphere to the right (*cum sole*) so the tropical winds actually blow from the northeast to the southwest (the Trade Winds) and the mid-latitude winds blow from the southwest toward the northeast (the Westerlies). In between are the relatively windless Doldrums or Horse Latitudes.



(a) Wind system for a hypothetical water-covered Earth, showing major winds and zones of low and high pressure. Vertical air movements and circulation cells are shown in exaggerated profile on the left of the diagram; characteristic surface conditions are given on the right of the diagram. The two north–south cells on either side of the Equator make up the Hadley circulation.

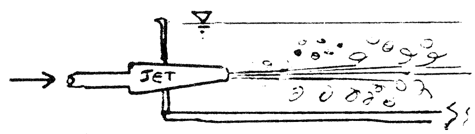
This pattern leads to generally consistent winds that profoundly affect the climate of the earth. (E.g., Oregon is so wet because of the Westerlies coming in over the Pacific Ocean). It also sets the waters of the oceans into fairly predictable motions. We will discuss two types of wind-driven flows: small scale *inertia currents* and large scale *geostrophic currents*.

Inertia Currents. If the wind sets open water into motion and the bottom and lateral boundaries exert negligible shear, as they do in deep ocean waters, it takes a long time for frictional forces to disperse the momentum. The water continues to move by its own inertia (see p.1 of this section).

The only force on the flow is the Coriolis reaction, so the fluid moves in a comparatively tight circle. In part, because the radius of motion is so small (a slow-moving mass virtually rotates on its center of mass), "pure" inertia currents are rare in the oceans and almost unknown in lakes.

However, do not discount the importance of inertial motions. Any given record of water velocities in deep, open water will contain *some* inertial components. For example, if a storm was blowing yesterday, the currents measured today will have substantial components of the residual inertia from the wind shear of the storm. Inertia greatly complicates studies of wind-induced motions, because water currents carry the inertial "memory" of many past forcings; you can never ascribe all of today's water motions to today's wind. So, while it's rare to find a coherent water mass whose motions are purely inertial, nearly all water masses embody a plethora of chaotic inertial motions as the residuum of multiple previous wind events.

Another sort of motion, which is nearly purely inertial, has been discovered in the oceans since the 1950s. Certain high-velocity, highly coherent, wind-driven currents, such as the Gulfstream and the Kuroshio, tend to "shed" large symmetric eddies known as rings. Shedding of eddies has long been known for turbulent jets, and the process of ring formation seems to be analogous:



However, at the scale of most turbulent jets, the shedded eddies (say that 10 times very fast) are chaotic and rapidly dissipated. In contrast, Gulfstream rings are often more than 100 km in diameter, have a well-defined toroid shape, and persist as distinct entities for weeks in the ocean. They form when a meander in the current kinks back on itself and pinches off.

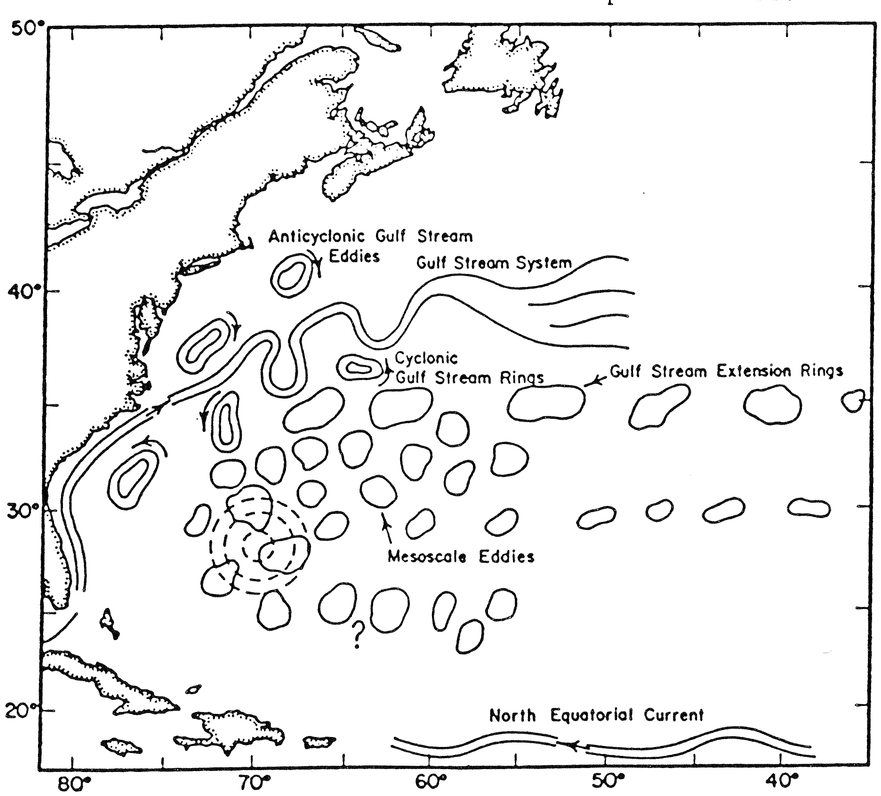
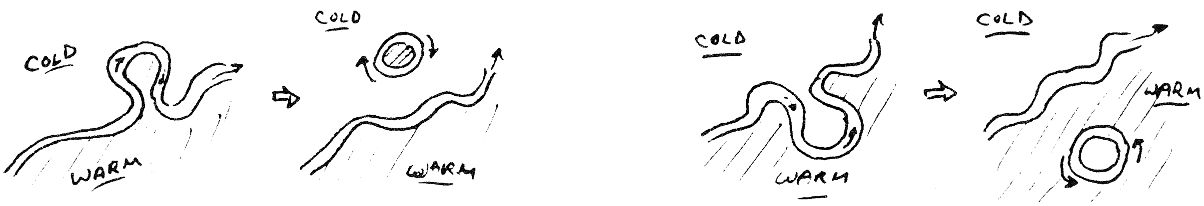


Fig. 3 The "eddy revolution" of 1960. Our view of the Atlantic circulation has changed.

Gulfstream rings are readily identified by either direct measurement of temperature, or by remote satellite sensing. The Gulfstream is a warm current, so the ring itself is warm. The water to the north of the Gulfstream is much colder than the current (due to the Labrador countercurrent), whereas the water to the south is relatively warm and is only a little colder than the Gulfstream itself. Thus, a ring that forms by pinching off on the north side will have a "core" of relatively warm water, and will be moving off into a cold environment:



These are called warm-core rings. They have anticyclonic rotation and are coherent "islands" of warm, nutrient-depleted water in the midst of cold, nutrient-rich surroundings. Rings that pinch off to the south are cold-core rings, have cyclonic rotation, and are islands of cold, nutrient-rich water in surroundings of tropical, nutrient-depleted waters.

Not surprisingly, these wholesale exportations of one sort of environment into foreign surroundings have intriguing ramifications for the physics, chemistry, and ecology of the Mid-Atlantic (and the Western Pacific in the case of the Kuroshio). For example, until about 1960, it was assumed that the Gulfstream dissipated its warmth in a gradual, continuous fashion. Now we know that the mixing occurs in a highly discretized fashion. Also, because rings persists for weeks, they carry biological populations intact into otherwise foreign domains. The coherent structure of the rings makes them ideal natural "mesocosm" for studying many phenomena: a ship can follow a warm-core piece of the tropical Sargasso Sea well up into the Grand Banks off New England. On the next page is a copy of the title page from a 1986 issue of "Deep-Sea Research" which was entirely devoted to studies of warm core rings. The titles give you some idea of the diversity of investigations.

Remember that that the momentum of the rings originates in wind-driven flow, but the rings themselves are largely inertial. However, the rings are not purely inertial because a pressure component normally is part of their momentum balance, which explains why they do not have the tiny radii of curvature expected for pure inertia currents. That is to say, rings are somewhere between inertia currents and *geostrophic currents*.

Geostrophic Currents: A geostrophic flow is governed by a balance between a pressure gradient and the Coriolis reaction. Last term we focused on geostrophic motions in the atmosphere (cyclones and anticyclones) but they are also importnat in the oceans and some lakes. Wind-driven currents in open waters tend to be pulled into large circular gyres by the action of the Coriolis effect.

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WARM-CORE RINGS—STUDIES OF THEIR PHYSICS, CHEMISTRY AND BIOLOGY

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SOME RESULTS OF THE DFG SYMPOSIUM ON PHYSICAL BASES OF CLIMATE AND CLIMATE MODELS

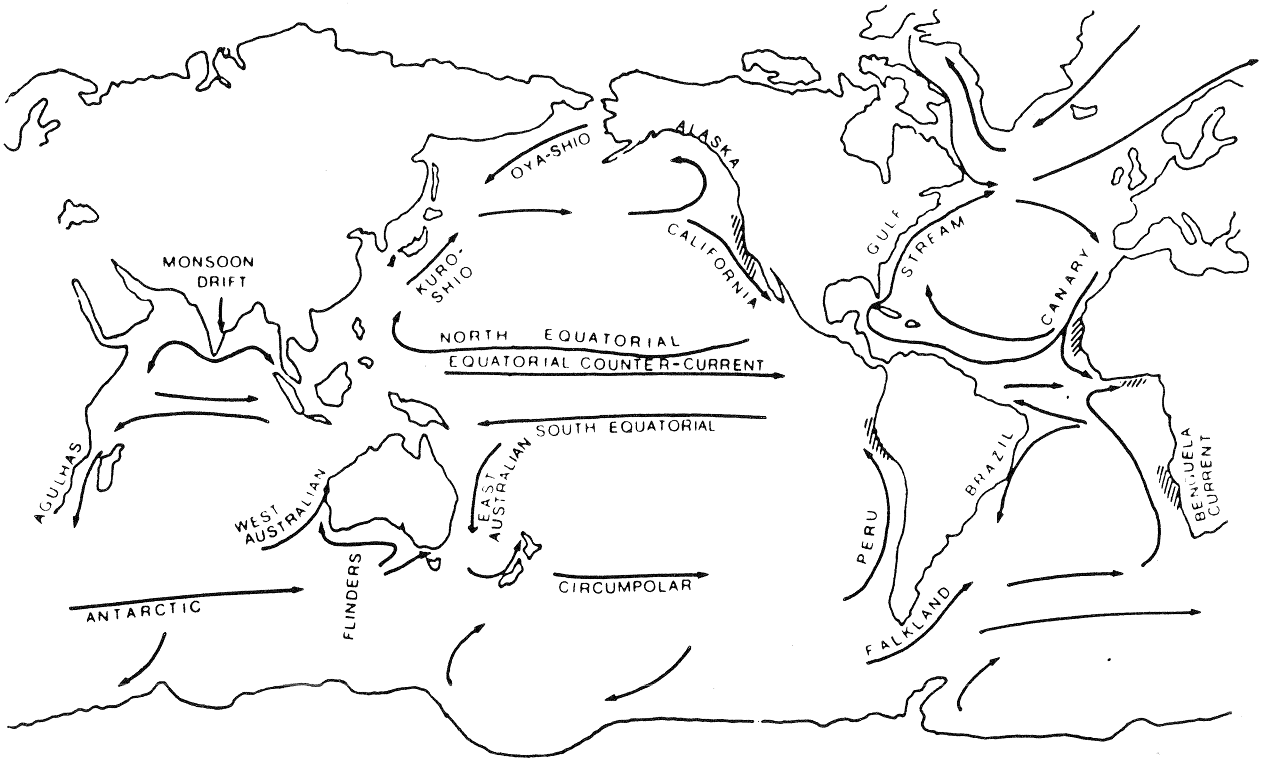


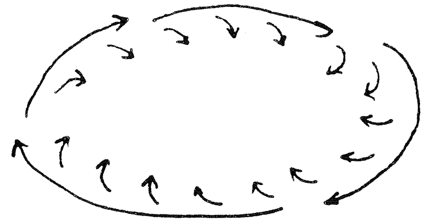
FIG. 6.1. *Major surface currents of the world oceans. The monsoon drift of the North Equatorial Current near India flows westward from November to March. Currents on the western boundaries of ocean basins are stronger than those on the eastern boundary. Currents on the eastern boundaries are weaker and upwelling may occur. Upwelling regions are shaded.*

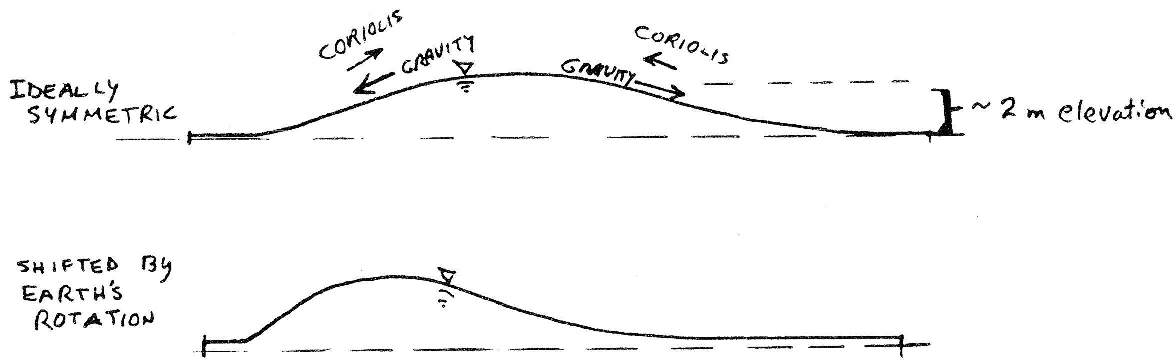
TABLE 6.1. *Flows in Major Oceanic Currents*

Current	Flow* ($m^3\ s^{-1}$)
Gulf Stream	100×10^6
Agulhas	40×10^6
Kuroshio	65×10^6
California	12×10^6
West Australian	10×10^6
East Australian	20×10^6
Antarctic Circumpolar	200×10^6
Peru	18×10^6
Benguela	15×10^6
Equatorial undercurrent	40×10^6
Brazil	10×10^6
Equatorial countercurrent	25×10^6
Pacific North Equatorial	30×10^6
Pacific South Equatorial	10×10^6
Flinders	15×10^6

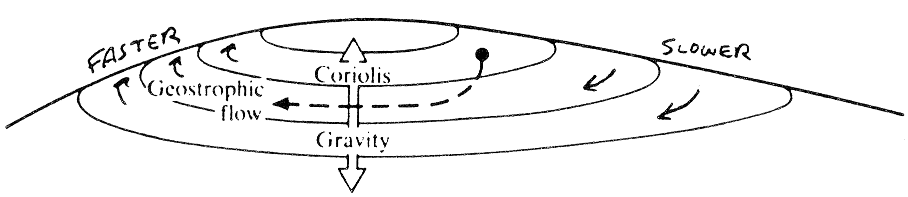
*Both hydrologists and oceanographers often use non-standard terms when referring to flows. Hydrologists call 1 $m^3\ s^{-1}$ a cumec

Within the gyre, the Coriolis force tends to pull water toward the center, where it literally "piles up". Of course as the surface of the water deforms, a graviational or hydrostatic-pressure gradient developed which tries to return the water outward. The gyres are anticyclonic, with high-pressure centers. A geostrophic balance is achieved when the hydrostatic-pressure gradient equals the Coriolis force. As a consequence, there is a slight mound of water at the center of the gyre: the water surface at the crest of the mound of the North Pacific Ocean is about 2 m higher than the water surface at the continental margins. The position of the mound is asymmetric and skewed toward the western margin because of the relative inertia of the water and the earth. The easy way to rationalize this is that the earth is moving eastward out from under the ocean, so the water tends to mound up towards the west.





This asymmetry compresses the streamlines of the gyre current on the west side and thereby increases its velocity. This is known as "western intensification" and explains why the Gulfstream and the Kuroshio currents on the western sides of their respective gyres are notably faster and more coherent than are the weaker, diffuse currents on the eastern side of the gyres.



GEOSTROPHIC CURRENT

As the earth's wind systems set ocean water in motion, circular gyres are produced. Water piles up inside the gyre with the apex of the "hill" closer to its west margin due to the earth's rotation to the east. The geostrophic current flows nearly parallel to the contour of the hill and represents an equilibrium between the Coriolis force pushing water up the slope and gravity acting to move the water down the slope. Due to the offset of the apex to the west, the current moves more rapidly along the western margin than along the more gently sloping eastern margin.