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An Elementary Explanation of Why Ocean Currents are Strongest in the West *

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DURING the last three years a series of papers has been published on the detailed nature of the ocean currents set up by broad steady wind currents. These have culminated in the research of Munk [1950] who has succeeded in showing that the major features of the observed surface ocean currents may be quantitatively attributed to the mean wind stress. The history of the speculations leading to this new ocean current theory has been summarized by the author in another place [Stommel 1950]. Because the details of the theory are necessarily mathematical its basic physical plausibility may escape the general reader. It is the purpose of this article to explain the physical reason for the westward intensification of ocean currents in ordinary words. In so doing we are only doing qualitatively what has already been done quantitatively [Stommel 1948, Munk 1950].

That there really is an observed intensification of most ocean currents toward the west, regardless of hemisphere, seems to be an established fact. In the North Atlantic Ocean the Gulf Stream is an outstanding example, the Kuroshio is the counterpart in the North Pacific. In the Indian Ocean the Agulhas Current hugs the coast of Africa. In the South Atlantic there is the Brazil Current. The coastlines and areas of these oceans are quite different, so we are tempted to think that local bathygraphic peculiarities are not an essential influence in the western intensification of ocean currents; thus the existence of the Straits of Florida is not essential to the formation of the Gulf Stream. If the Antilles were excavated the Gulf Stream would still exist. However, the South Pacific Ocean offers a somewhat embarrassing exception. There does not appear to be any current of great intensity off Australia; in fact the Humboldt Current off Peru is the strongest South Pacific Current, and it lies in the eastern portion of the South Pacific. With this important exception the following rule does seem to hold: on the western edge of most of the world's oceans there is a system of strong currents. Now we may ask ourselves, why is this so? If the wind system, a broad wide-spread phenomenon, drives the ocean currents, how is it that the resulting ocean current system should be so asymmetrical; in particular, why should the strongest currents be squeezed into a narrow belt on the western edge of the oceans? It is this question to which the present theory purports to supply the answer.

The physical picture is as follows: Suppose we consider a large ocean basin such as shown in FIGURE 1 with an anticyclonic wind circulating over it. Our intuition tells us that this wind will produce an ocean surface current in an anticyclonic sense. From what little we know about the distribution of properties in the deeper portions of the ocean it seems reasonable to suppose that the current which the wind induces does not extend to the bottom. Our intuition also tells us that if the ocean current system has arrived at a state of steady motion under the stress of the wind, the free surface and isopleths of density in the ocean will have adjusted themselves so as to produce the horizontal pressure gradients necessary to balance the Coriolis forces acting upon the moving water; also, that frictional dissipation of the energy added to the sea by the wind is necessary. But that is about as far as our intuition takes us, and it gives no hint of the necessary asymmetry in the current system. To progress further it is necessary to consider the processes tending to increase or decrease the vorticity of the ocean water.

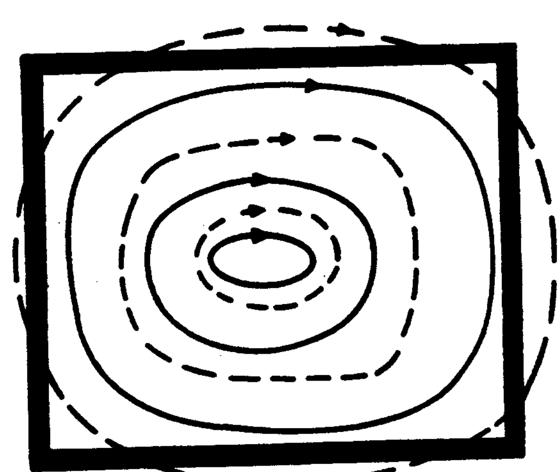

FIG. 1. Symmetric circulation of water (solid lines) under an anticyclonic wind (dashed lines). The coastline is drawn schematically as rectangular.

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The vorticity of a vertical column of water † is taken as positive if counterclockwise, and negative if clockwise. If the spin is measured relative to the earth, we speak of relative vorticity; by adding the Coriolis parameter to the relative vorticity we obtain the absolute vorticity of the column. Unlike the velocity distribution, the vorticity distribution in the ocean may be discussed without reference to the pressure field (formally the vorticity equation is obtained by elimination of the pressure from the equations of motion by cross-differentiation), a fact which greatly simplifies qualitative discussions. The wind system of FIGURE 1 is chosen so that it tends to decrease (make negative) the relative vorticity of all the water columns in the ocean. In the steady state of motion which must exist under a prolonged exposure of the ocean to this wind system, the relative vorticity has a fixed value at each point of the ocean independent of time. This means that other influences must act to counteract the negative vorticity tendency due to the wind alone. Horizontal convergence and divergence are ruled out on account of the steady state condition; advection of vorticity from one region to another seems to be, for the most part, negligible. This leaves two processes by which the negative vorticity tendency due to the wind may be counteracted.

The first of these is friction, but since, as we have already seen, the ocean surface circulation does not seem to be frictionally bound to the bottom, it must be frictionally bound to the ocean shores by horizontal eddies. Moreover, this horizontal viscosity would provide a positive vorticity tendency over the ocean of FIGURE 1. A numerical check, using values of lateral eddy viscosity inferred from the distribution of conservative properties and a horizontal oceanic circulation which looks like the wind system, without any evidence of asymmetry, requires a circulation many times faster than the real ocean circulation to produce enough positive vorticity tendency to balance the wind stress vorticity tendency.

The second process is the planetary vorticity tendency. Columns of water moving northward without convergence or divergence have a negative vorticity tendency, and those moving southward a positive vorticity tendency regardless of hemisphere. This follows from the conservation of angular momentum or, putting it in other words, the variation of the Coriolis parameter with latitude. Since the net meridional transport of water across a parallel of latitude is zero (as much water moves north as south), the planetary vorticity tendency is positive for water in the eastern part of the ocean of FIGURE 1, and negative in the western part. Therefore the planetary vorticity tendency alone is incapable of balancing the wind stress vorticity tendency. In the steady state we must have a zero over-all vorticity tendency, by definition. That is, at every point in the ocean the wind-stress-, frictional-, and planetary-vorticity tendencies must add up to zero.

TABLE 1. VORTICITY TENDENCIES IN A SYMMETRIC CIRCULATION

	North flowing currents in the western ocean	South flowing currents in the eastern ocean
Wind stress	−1	−1
Frictional	+0.1	+0.1
Planetary	−1.0	+1.0
Total	−1.9	+0.1

The distribution of the wind stress vorticity tendency may be regarded as fixed, let us say of an order of magnitude − 1. If there were only a broad current system without the asymmetry that is actually observed, but with a transport of water similar to the observed transport, the frictional vorticity tendency would be an order of magnitude too small, say + 0.1, and the planetary vorticity tendency would be of the order − 1 in the western and + 1 in the eastern part of the ocean of FIGURE 1. Thus there would be an approximate balance of tendencies in the eastern portion of the ocean, but the western part would not be equilibrium, so

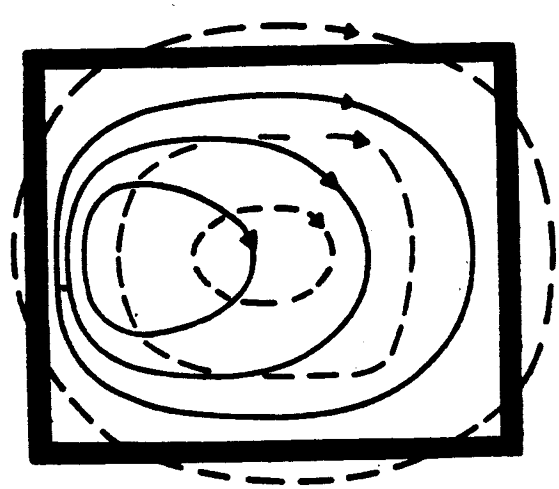

FIG. 2. Asymmetric circulation.

† The vorticity of an element of fluid is twice its angular velocity. An element of fluid in a shearing motion is subjected to an instantaneous spin. In this article the qualitative reasoning is done entirely in terms of the vorticity of a vertical water column, that is, the sum of the vertical components of vorticity of all the elements of a vertical water column.

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that a symmetrical current system is not physically possible in the steady state. The state of affairs is summarized in TABLE 1.

However, if we let the current system be strongly asymmetrical, as shown in FIGURE 2, we do not affect seriously the balance between the wind stress and planetary vorticity tendencies in the eastern portion of the ocean where frictional vorticity tendency is very small. However, on the western side where the velocity and shear are great because of the narrowness of the western meridional current, the frictional and planetary vorticity tendencies are greatly enhanced, to orders of magnitude greater than the wind stress, say + 10 and − 10, respectively. In this way we may achieve a balance between the tendencies in the western side of the ocean as well, and so obtain a steady state. TABLE 2 shows the balance of terms in an asymmetric circulation.

TABLE 2. VORTICITY TENDENCIES IN AN ASYMMETRIC CIRCULATION

	Strong north currents in the western edge	South flowing current over rest of ocean
Wind stress	− 1.0	−1.0
Frictional	+10.0	+0.1
Planetary	− 9.0	+0.9
Total	0.0	0.0

If one analyzes ocean currents in this qualitative manner for anticyclonic and cyclonic wind systems in both hemispheres he will find that the necessary intensification of the ocean circulation is always on the western side of the ocean.

Among the interesting consequences of this theory are: (*1*) the fact that although energy is added to the oceans by the work of the wind over the entire surface, it is dissipated chiefly in the strong western currents; (*2*) that a good representation of the circulation outside of the western currents can be obtained from a knowledge of the field of the wind stress alone, independent of friction, as was shown by Sverdrup [1947].

In view of the fact that the theory gives an adequate schematic picture of the oceanic surface circulation, one is tempted to suppose that it is physically sound. The transports computed by Munk are about one-half the observed values. This discrepancy may arise simply from the very crude estimates of the wind stress that were available, or it may be due to some physical factor which has not yet been considered.

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