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A New Look at the Role of Eddies in the General Circulation

Abstract

It has been thought (at least since Holland, 1978) that the wind-driven circulation creates a reservoir of available potential energy (sloping thermocline) which, via baroclinic instabilities, generates eddies and that these, via a turbulent cascade, lead to mechanical dissipation. In other words, the eddy field is the unique link between the forced circulation and dissipation.

Although this paradigm has stimulated abundant numerical simulations and yielded countless publications, it nonetheless suffers from two important shortcomings. First, it provides no explanation whatsoever for the amounts and properties of the observed water masses (particularly the 18-degree Sargasso Sea water or its analogue in other ocean basins called the Subtropical Mode Water). Second, it leads to models in which the western boundary current (Gulf Stream) separates too far north. The obviously missing ingredient is the thermodynamics, alias the buoyancy effects. Indeed, with heat exchanges across the surface and within the water, water masses can change their characteristics, new kinds be formed, and amounts be adjusted. Further, as Huang (1987) an Chassignet (1991) showed, the amount of water in the upper thermocline establishes the latitude of separation of the western boundary current; less water brings this latitude southward.

As we all know (and engineers are most keenly aware of), heat fluxes anywhere are set by temperature differences; they are *in response to* a state of non-equilibrium. And so it is with the ocean. Therefore, theories in which heat fluxes are prescribed (Olson, 1985; Luyten & Stommel, 1986) are contrived and suspect. They, too, fail to explain the origins and amounts of water masses. As a remedy, the P.I. proposed a theory (Cushman-Roisin, 1987) in which the magnitude of the heat flux is not specified but instead controlled by the inhomogeneities produced by the circulation itself. (We shall call this type of flux a self-regulated heat flux.) And, the theory naturally leads to several important results. Without inclusion of any eddy dynamics, it allows for a purely inertial (i.e., non-dissipative) western boundary current, accounts for surface Ekman-pumping input by an equal rate of formation of deeper waters, explains the restoration of wind-modified potential vorticity, and provides a mechanism for a recirculation southeast of the western boundary current.

Obviously, eddies do play a role in circulation dynamics; they are observed,

they spontaneously emerge in numerical simulations, and they are ultimately necessary for mechanical dissipation. But, the above theory strongly suggests that eddying is not the exclusive mechanism that lies between the large-scale wind-driven currents and small-scale dissipation. Investigations that combine eddy dynamics and a self-regulated heat flux are clearly necessary.

Questions

The combination of eddy dynamics with heat exchanges immediately brings the following questions: What is the energy pathway? And, of what consists the recirculation? Indeed, being down the temperature gradient (or, equivalently, being of a relaxing type, Cushman-Roisin, 1987), the heat flux is dissipative in nature, affecting the amount of potential energy in the stratification; also, by its vertical mass flux, cooling generates motions at greater depths, thus affecting the distribution of kinetic energy in the vertical. Further, larger near-bottom velocities imply greater energy loss to bottom-drag dissipation and a correspondingly reduced need for lateral dissipation. Interestingly enough, Weatherly (1984) estimated from observations in the western North Atlantic that bottom friction can account for the entire dissipation of the wind-energy input and that this dissipation occurs in only about 20% of the areal extent of the subtropical gyre. It is therefore clear that, in the presence of heat fluxes, eddies have a much different job to accomplish than in purely wind-driven circulation models.

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