Part One

General Ocean Circulation

1
Deep Circulation of the World Ocean

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1.1 Introduction

Historically, the deep circulation of the ocean has been viewed from the perspective of property fields, mainly the distributions of temperature, salinity, density, and dissolved-oxgyen concentration. The practical reason for not considering velocity measurements as well, of course, was a technical incapacity for making them until very recently. On the whole, this was probably not a bad thing: not merely because the property distributions are as interesting in themselves as the motion field, but also because the scalar fields are so much more stable than the velocity vectors—allowing spot measurements from different areas even years apart to be combined into coherent pictures that tell a good deal about general patterns of deep flow, albeit indirectly. The slight differences between corresponding hydrographic sections in the atlases by Fuglister (1960) and by Wüst and Defant (1936), when compared with the fluctuations much larger than the means of deep velocities observed by the MODE Group (1978), for example, demonstrate how much easier it is to obtain statistically significant information pertinent to the overall global deep circulation from water-property data than from current measurements.

On the other hand, the information gained from the property fields allows only a limited view of the deep motions, at very best some kind of long-term average. Although oceanographers have usually been mindful of variability in the deep flow, even if only to accomplish eddy mixing, it seems extremely unlikely that anyone imagined the highly energetic low-frequency mesoscale motions that current records have revealed. Instead, because of the stability of the property fields, it was stationarity rather than variability that was emphasized, however implicitly, in the circulation pictures derived from them. That stability also was surely the basis for the conceptual structure of water types and masses that has been so enormously useful in summarizing and comprehending the temperature-salinity structure of the ocean and in identifying features in the property fields that can be exploited as tracers for the flow. Without velocity information, though, such descriptions of oceans have sometimes degenerated into taxonomic sterility (naming something doesn't explain it), and perhaps sometimes there has been too elemental a character ascribed to water masses (as if they were truly building blocks rather than names for features), leading to pictures of the ocean more suggestive of rigid geological strata than of the real motion field that forms the distributions.

Plainly there cannot be a satisfying description of the deep ocean circulation that does not meld station data with current records. It does not seem to me, though, that such a description is yet possible. Far too few current records have been obtained to describe the deep, low-frequency motions in a global sense; it is only in the western North Atlantic that one can even contemplate making a basin-wide description. Moreover, we simply have not learned how to combine the stable station data with the fluctuating-velocity records to tell a story that is both consistent and informative. For example, Reid, Nowlin, and Patzert (1977) reported a record (Cato 2) from a current meter moored on the South American continental slope in the core of the North Atlantic Deep Water: for 2 weeks the daily-averaged velocity vectors were directed southwestward, parallel to the isobaths, as one would have expected in this particular deep western boundary current; but then the flow abruptly changed direction and went eastward for nearly 2 weeks. Nevertheless, with due regard for different density and accuracy of observations, the high-salinity core of the current looked very much as had been depicted by Fuglister (1960) and Wüst and Defant (1936). How are we to approach these two different sets of data, to reconcile the variability of the one to the steadiness of the other, and to learn something significant from their combination about that boundary current?

Finally, it is not at all clear what effect the low-frequency velocity fluctuations have on the long-term mean flow. There is enough theoretical reason (e.g., Rhines, 1977) to suspect that their role in its dynamics may be substantial, but measurements of deep Reynolds stresses are meager. In fact, values reported by Schmitz (1977) from the Sargasso Sea well south of the Gulf Stream actually favor a negligible contribution to the vorticity balance there, but those measurements are far too few to give a general characterization of the deep open ocean.

Consequently, although I recognize its incompleteness, the following account of the deep circulation of the world ocean is undertaken mainly from the traditional perspective of hydrographic station data, with reference to current measurements only where they seem helpful in estimating velocities and transports of the prominent currents. The emphasis is on mean thermohaline circulation. What has been learned about the low-frequency motions is described in detail by Wunsch in chapter 11 of this volume.

In section 1.2, I have attempted a historical review of what seem to me to be the important events and dates in the development of ideas about the deep circulation, from the first deep temperature measurements through Sverdrup's comprehensive synthesis in chapter XV of *The Oceans* (Sverdrup, Johnson, and Fleming, 1942). In section 1.3, I have discussed the dynamical ideas of Stommel and his colleagues that led to the overthrow of a substantial part of Sverdrup's picture, and its revision in contemporary thinking with dynamically consistent models of circulation. Section 1.4 is an account of the sinking processes that supply water to the deep ocean from the surface layer. Section 1.5 is a consideration of how well the kinds of deep-circulation patterns envisioned in dynamical theory stand up to observation; it is necessarily mainly a digest of the evidence for deep western boundary currents in the world ocean. Finally, in section 1.6, I have speculated about some fundamental aspects of the deep circulation that seem to me to be not very well understood at this time.

The focus throughout is more on the circulation of deep water than on the complementary problem of its properties, because the subject of deep-water characteristics has been treated in detail by Worthington in chapter 2 of this volume. There is, of course, some overlap with that chapter, as well as with Reid's general discussion of the mid-depth circulation (chapter 3). To the extent that our opinions are in conflict, we hope that readers will recognize subjects for further observation and thought.

1.2 Historical Development of Ideas about the Deep Circulation

In 1751 Henry Ellis, captain of the British slavetrader *Earl of Halifax*, wrote to the Reverend Stephen Hales to describe some deep temperature measurements that he had made at lat. 25°13′N, long. 25°12′W, with a "bucket sea-gage" devised and provided for him by Hales. This instrument, to be attached to a sounding line, was a "common houshold pail" covered at top and bottom by valves that would be forced open during descent and pushed shut by drawing the bucket back to the surface; it was furnished with a thermometer so that the temperature of the water sample thus trapped could be read when the bucket was returned to the ship. In his letter, which Hales transmitted to the Royal Society of London, Ellis (1751) reported:

> Upon the passage, I made several trials with the bucket sea-gage, in latitude 25′-13″ north; longitude 25′-12″ west. I charged it and let it down to different depths, from 360 feet to 5346 feet; when I discovered, by a small thermometer of Fahrenheit's, made by Mr. Bird, which went down in it, that the cold increased regularly, in proportion to the depths, till it descended to 3900 feet: from whence the mercury in the thermometer came up at 53 degrees; and tho' I afterwards sunk it to the depth of 5346 feet, that is a mile and 66 feet, it came up no lower. The warmth of the water upon the surface, and that of the air, was at that time by the thermometer 84 degrees. I doubt not but that the water was a degree or two colder, when it enter'd the bucket, at the greatest depth, but in coming up had acquired some warmth.

Ellis's guess of one or two degrees warming during the ascent was based on changes observed in the temperature of the sample while on deck. Modern data, however, indicate that Ellis's values were some 10–