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On the Mid-Depth Circulation of the World Ocean

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3.1 Introduction

There is a large part of the ocean circulation for which we have very little information and very vague concepts. This is the great domain of the mid-depth ocean. We have considerable information about the flow at and quite near the sea surface, and some inferences about the abyssal flow derived mostly from the traditional patterns of characteristics at the bottom. Recently, some attention has been focused on the deep western boundary currents, where the flow is strong enough to be detected both in the density field and in some cases by direct measurement. But for the greater part of the volume of the ocean—beneath the upper kilometer and away from the western boundary currents and above the abyssal waters—we have little information on, or understanding of, the circulation. Most treatments of the deep water as well as the abyssal water have dealt in terms of the western boundary flow, and a general meridional flow is all that has emerged from most of the studies. Wüst (1935), for example, assumed a principally thermohaline meridional flow to obtain from the abyssal layer up through his Subantarctic Intermediate Water, at depths above 1 km, with no recognizable pattern of gyral flow analagous to the surface circulation.

It seems worthwhile to consider what information there is for this great volume of water. This study will begin with a general discussion of the earlier ideas on this problem. It will review briefly the recent work (of the last 10 years or so), which has begun to make substantial contributions, and will display and discuss some world-wide mid-depth patterns of characteristics and of geostrophic vertical shear.

There is no simple distinction between the upper waters, the deep and abyssal waters, and what I shall call the mid-depth waters. A working definition will be that the mid-depth waters are those that are found between about 1 and 3 km in middle and low latitudes and their source waters, which are shallower in high latitudes. Warren's study (this volume, chapter 1) of the deep circulation includes some of these waters, of course, and I have tried to avoid duplication. Some duplication remains, however, in part for immediate clarity and in part for different emphasis.

3.2 The Circulation of the Upper Waters and Their Contribution to the Mid-Depths

Our first information about general ocean circulation came from the experience of mariners crossing the great oceans. They found the best routes for eastward travel to be in the zone of the west winds and for westward travel in the trades, and noted early the western boundary currents. As the information accumulated, these findings led, by the middle of the nineteenth century, to the general concept of subtropical anticyclonic gyres, subarctic gyres, and various zonal flows near the equator.

The variability of this general pattern was learned early and is most clearly presented in the sailing directions, coast pilots, and atlases prepared by the various hydrographic offices. For example, the typical atlas of surface currents of the northwestern Pacific Ocean (U.S. Navy Hydrographic Office, 1944) provides information by averages in 1° × 1° squares, but for 5° × 5° areas provides summations by octants in direction, with average speed and fractions of time for each octant. While this can give no information on the frequency of the variations (each measurement represented a mean of 12 to 24 hours or longer), the presence of variation is clearly shown everywhere, and the general findings of Fuglister (1954), Dantzler (1976) and Wyrtki, Magaard, and Hager (1976) are to some degree anticipated.

But in spite of the variability and the smoothing effects in taking its mean, certain major features of the gross field stand out. On this particular atlas the strongest of these are the Kuroshio and the North Equatorial Current. The West Wind Drift around 40°N is also clear, though weaker. But in the area between the Kuroshio–West Wind Drift and the North Equatorial Current, the return flow from the Kuroshio toward the southwest described by Sverdrup, Johnson, and Fleming (1942) is only marginally discernible. In a later compilation of the average drift (Stidd, 1974), it is somewhat clearer.

This surface circulation had been generally accepted as wind driven, but the depth to which it extended, or to which any wind-driven current extended, was not known. It is not clear what was generally believed, or why, but the impression left from reading the various papers on this subject is that it was very shallow over most of the ocean.

Information about the subsurface circulation arose from a different source. Measurements of water characteristics began in the eighteenth century. Prestwich (1875) reviewed them and the various interpretations that had been made. The measurements were mostly of temperature with some of salinity. Very few had reached abyssal depths, though there were enough to identify the Antarctic and Greenland Seas as sources of abyssal water. He concluded that all of the water, from top to bottom, is in a state of movement, and that high-latitude cold waters flow equatorward at abyssal depths from both north and south in the Atlantic, but only from the south in the Pacific and Indian Oceans, and that these sources account for the low subsurface temperatures of the central oceans.

He did not, however, consider only such a simple convection model, but worked out some more detailed parts of the system as well. His most interesting interpretations are of the details of the shallower subsurface flows. He noted that zones of maximum surface temperature and salinity in the Atlantic and Pacific are not exactly at the equator but in two zones roughly parallel to it, north and south; that the waters between 10°N and 10°S in the upper 200 m are colder than those to the north and south; and that this must result from a rising of the deeper, colder waters in that zone, where they are moved poleward as they are warmed.

He noted the excessive salinity of the Mediterranean and the very high temperature at great depth. He explained the high temperature compared to that in the Atlantic by the presence of the sill at the Straits, which excluded the colder waters of high latitudes, and winter overturn within the Mediterranean that gave the bottom waters the same temperature as the surface minimum value. He noted that the salt balance had been explained by surface inflow and subsurface outflow and noted that water with characteristics similar to those within the Mediterranean had been found at mid-depth outside the Straits.

Most important, he concluded that warmer waters are conducted into higher latitudes not by shallow surface currents alone, but by substantially thicker subsurface flows, which provide a thick, warmer subsurface layer in the polar regions. He found two channels of flow from the Arctic Ocean to the Atlantic, via Baffin Bay and the East Greenland Current, and noted that in the eastern Norwegian Sea thick layers of warmer water were found, having entered from the Atlantic. He states:

> There is every reason to believe that the open seas of the north polar regions are due, as suggested by Maury and others, to the influence of warm southern waters, though this is not, as supposed by those authors, owing to the action of the Gulf Stream, but by the surging-up of these deeper warm strata; and in the same way the open sea found by Cook, Weddell, Ross, and others, after passing the first barrier of ice in the south polar seas, may be due to a similar cause. [Prestwich (1875, p. 635).]

He concludes:

> Some of the great surface currents, which originate or acquire additional force in the equatorial and polar seas, are intimately connected with the surging-up of polar waters in the great oceans and of tropical waters in Arctic and Antarctic seas, although the ultimate course of these currents may be influenced and determined by the action of the prevailing winds and by the movement of rotation of the earth. [Prestwich (1875, p. 638).]

Further information on the mid-depth circulation was provided by Buchanan (1877), who noted the great intermediate-depth salinity minima of the North and South Pacific and of the South and Equatorial Atlantic.

He noted the generally higher salinity of the North Atlantic and ascribed it in part to the exchange with the Mediterranean.

Nansen (1902) had confirmed the presence of subsurface warmer waters from the Atlantic over a much larger area of the Arctic than that known to Prestwich, and had proposed (1906) that convection takes place to the bottom only in the Greenland Sea; but the only recognized outflow was of water of low salinity and low density through the Denmark Strait, and this outflow did not contribute directly to mid-depth circulation. Instead, the colder abyssal waters of the northern North Atlantic were attributed (Nansen, 1912; Wüst, 1935) to overturn in the Irminger and Labrador Seas. Brennecke (1921) and Defant (1938) had suggested that this overturn and formation of deep water might possibly contain a mixture of water that had overflowed from the Norwegian-Greenland Sea through the Denmark Strait or east of Iceland, but Wüst (1943) in his discussion of the subarctic bottom flow of this water apparently did not accept their conjecture, which was finally argued convincingly by Cooper (1955a).

For the Antarctic component, Brennecke's (1921), Mosby's (1934), and Deacon's (1937) work had shown the presence of a subsurface warm layer nearly everywhere throughout the Antarctic Ocean, as surmised by Prestwich, and had identified the southwestern Weddell Sea as the area where this layer was penetrated, leading to the formation of the coldest abyssal layer from the Antarctic. Deacon's (1937) study of the Southern Ocean, in particular, gave the first description of the subsurface temperature and salinity maximum, the "warm deep water," or circumpolar water extending throughout the Antarctic region. His interpretation that the meridional exchange with lower latitudes takes place in alternating directions in various strata in all oceans, which was developed further by Sverdrup et al. (1942, figure 164), was a substantial step beyond Prestwich's model. Taking as a starting point Prestwich's (1875) argument for a thick subsurface poleward flow instead of a surface flow alone, the extra layer of low salinity described very roughly by Buchanan (1877) and by Brennecke (1921) is clearly identified and accounted for, and a deep poleward flow above the equatorward abyssal flow is clearly seen and described (Sverdrup et al., 1942, figure 164).

Wüst (1933) had shown that the abyssal layer from the south extends well north of the equator in the Atlantic, with the northern component much smaller in lateral extent. He found the major product of the North Atlantic to be a thick deep-water layer of high salinity and oxygen, extending southward to the Antarctic Circumpolar Current.

3.3 The Use of Geostrophy

Sandström and Helland-Hansen (1903) provided methods for calculation of vertical shear from the density field by use of the geostrophic approximation. Helland-Hansen and Nansen (1909) used this method to calculate the shear in the upper 200 m of the Norwegian Sea in the area between Norway and Iceland and, comparing it with the information about sources of water of various characteristics, used it in their interpretation of the circulation of the Norwegian Sea.

From the data they collected they saw at once that the variability already found at the sea surface occurred also at greater depths. They noted, and discussed at length, variations in temperature, salinity, and density in the upper strata:

At any rate down to 600 m, and probably much deeper . . . such irregularities, great or small, are seen in most vertical sections where the stations are sufficiently numerous and not too far apart. The equilines . . . form bends or undulations like waves, sometimes great, sometimes small. When, in 1901, Helland-Hansen first found a great wave of this kind in the sections across the Norwegian Atlantic Current, he thought that it indicated some kind of permanent division of the current. . . . But by continued research with more stations, even several "waves" were sometimes found in the same sections, and it soon became evident that they could not indicate any such division as he had at first thought, but must have some hitherto unknown causes. [Helland-Hansen and Nansen (1909, p. 87).]

They considered the possibility of these waves in intermediate depths as pulsations in the currents, periodic variations, temporary disturbances, or cyclonic and anticyclonic vortices, and remarked upon the necessity of numerous and closely spaced observations if the density field were to be described in detail. Their map of the geopotential anomaly of the sea surface relative to the 200-db (decibar) surface (steric height 0–200 db) is reproduced as figure 3.1, illustrating one of the irregularities they encountered. Concluding that the method was good enough, in spite of the noted variability, to give useful results, they continued to use it. Later, Nansen (1913) concluded that the waters between about 200 and 1500 m off the coast of Europe and Ireland did not originate in the Gulf Stream but derived from the waters to the south and indicated a substantial mixture of highly saline water from the Mediterranean, and Helland-Hansen and Nansen (1926) mapped salinity, temperature, density σ_t, and steric height of various depths down to 2500 m, illustrating the pattern of characteristics and the geostrophic shear. Their plates 48 and 68, of temperature and salinity at 1000 m and of steric height 1000–2000 db, are reproduced as figures 3.2 and 3.3.

Ekman (1923) mapped the steric height relative to various pressures down to 1000 db and showed the