3
On the Mid-Depth Circulation of the World Ocean

Joseph L. Reid

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

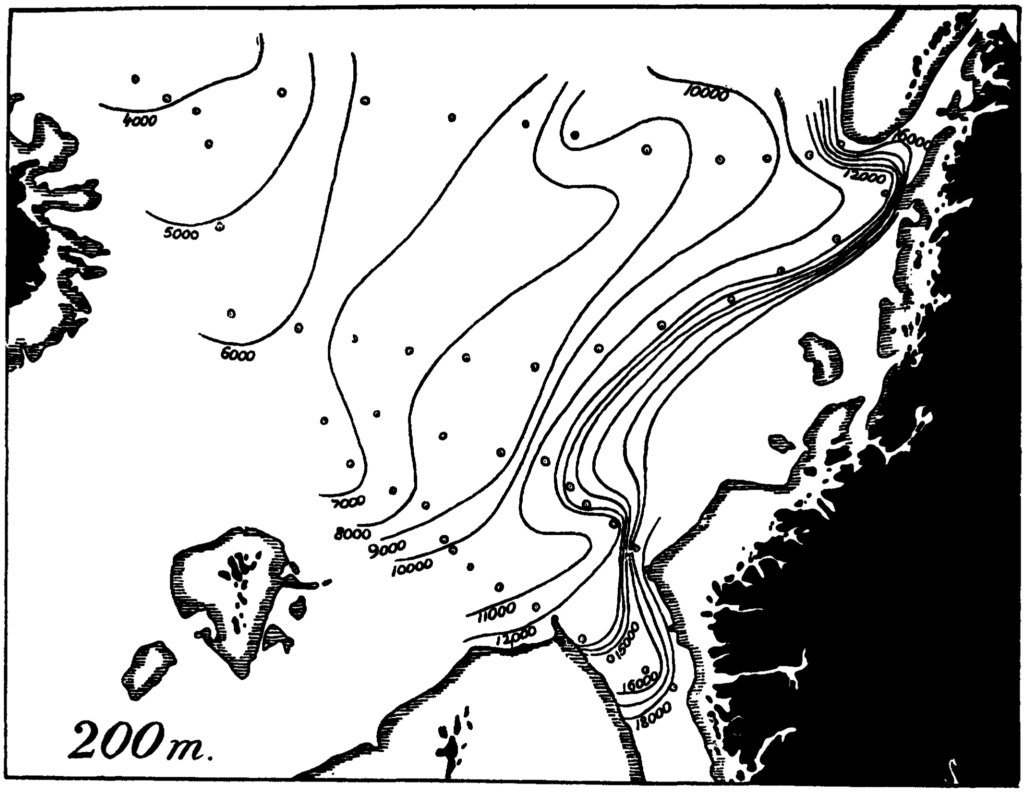

Figure 3.1 Geopotential anomaly (steric height) 0–200 db (10^{-5} dynamic m). (Helland-Hansen and Nansen, 1909.)

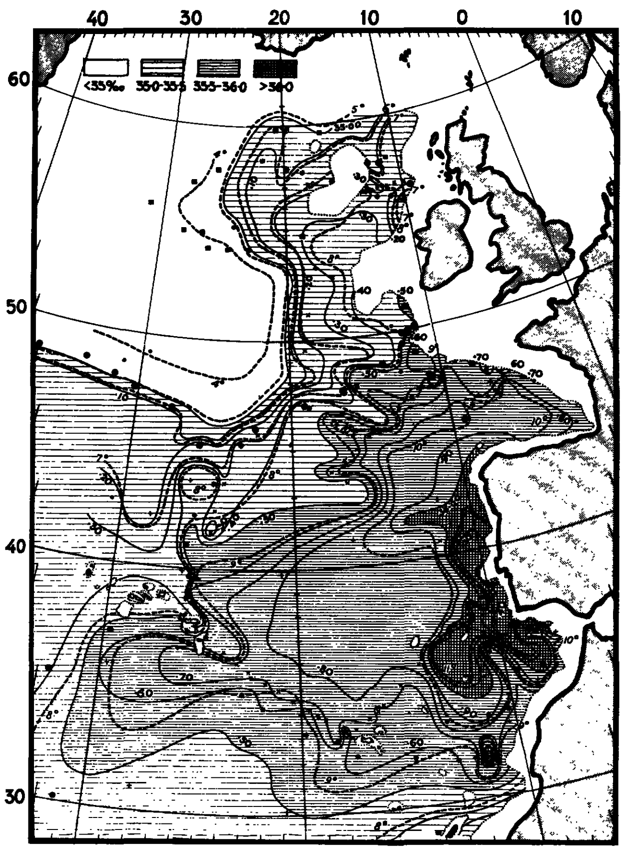

Figure 3.2 Temperature and salinity at 1000 m. (Helland-Hansen and Nansen, 1926.)

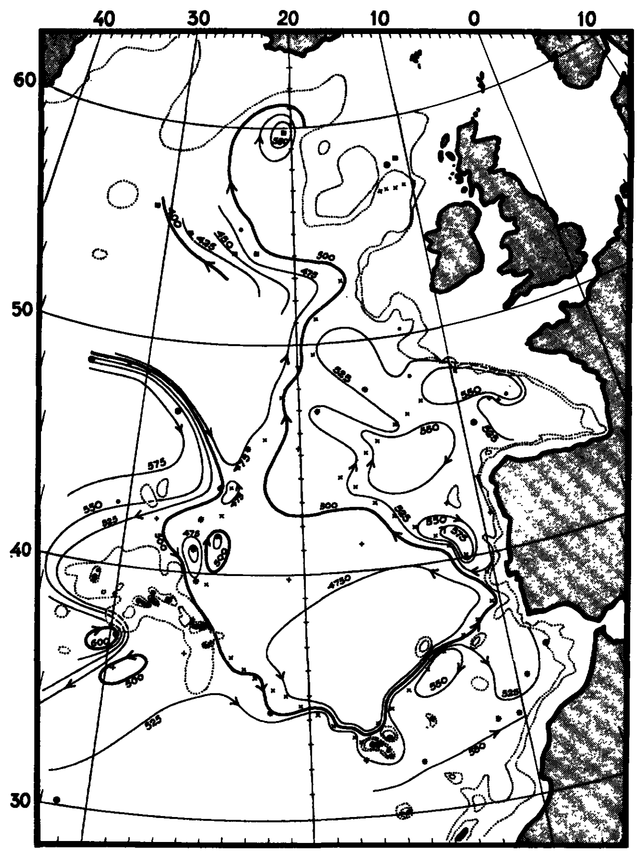

Figure 3.3 Steric height 1000–2000 db (dynamic mm). (Helland-Hansen and Nansen, 1926.)

relation of the density field to the deep southern extension of the Grand Banks (figure 3.4). Geostrophic shear was used extensively in the work of the International Ice Patrol (figure 3.5, from Smith, Soule, and Mosby, 1937) from the early 1920s and appeared to give valuable indications of surface currents when compared with the drift of icebergs. Parr (1938) reviewed various doubts about the validity of the "dynamic method" to obtain such trajectories and pointed out especially that the "method" eliminated any trajectory of a water parcel other than in the horizontal.

Jacobsen (1929) mapped the geostrophic shear between various pressure surfaces and the 1000-db surface for the central North Atlantic and the Caribbean, using data from the *Dana* expedition of 1920–1922 and adding in the northwest the results of Ekman's (1923) study of the surface flow. He found, with his limited data, quite a fair picture of the general surface circulation as supposed at present (figure 3.6A): a Gulf Stream–North Atlantic Current with a return flow of the Gulf Stream along 70°W turning toward an eastward flow north of 20°N. This, with sparse and less accurate data, is remarkably similar to the more recent work of Leetmaa, Niiler, and Stommel (1977). He showed also a map of steric height 500–1000 db (figure 3.6B). It is not detailed enough to be useful except for one interesting feature: the east-west axis of the anticylconic gyre at the sea surface appears to lie at about 25°N in midocean, but at greater depths it lies considerably farther north, past 30°N.

Koenuma (1939) examined the flow of the southwestern part of the North Pacific Ocean and found clear evidence in the density field (geostrophic shear) of a return flow just southeast of the Kuroshio, in spite of the strong eddy field.

3.4 The Mid-Depth Circulation of the Atlantic Ocean from Core Analysis and Vertical Geostrophic Shear

Apparently, the *Meteor* expedition to the South and Equatorial Atlantic was planned to study deeper circulation, which was assumed to be mostly meridional. The east-west lines were not suited for studying the gyral patterns of middle latitudes or the zonal flows in the equatorial area. Indeed, the separation of the ocean, as discussed in the *Meteor* reports, into a troposphere and stratosphere, or warm- and cold-water bodies, implies that an entirely different pattern of flow was expected below the troposphere.

Wüst's (1935) major work on the subsurface waters of the Atlantic dealt mostly with this very saline, oxygen-rich North Atlantic Deep Water (figure 3.7) and with the overlying salinity minimum, which he called Subantarctic Intermediate Water. In this subsurface

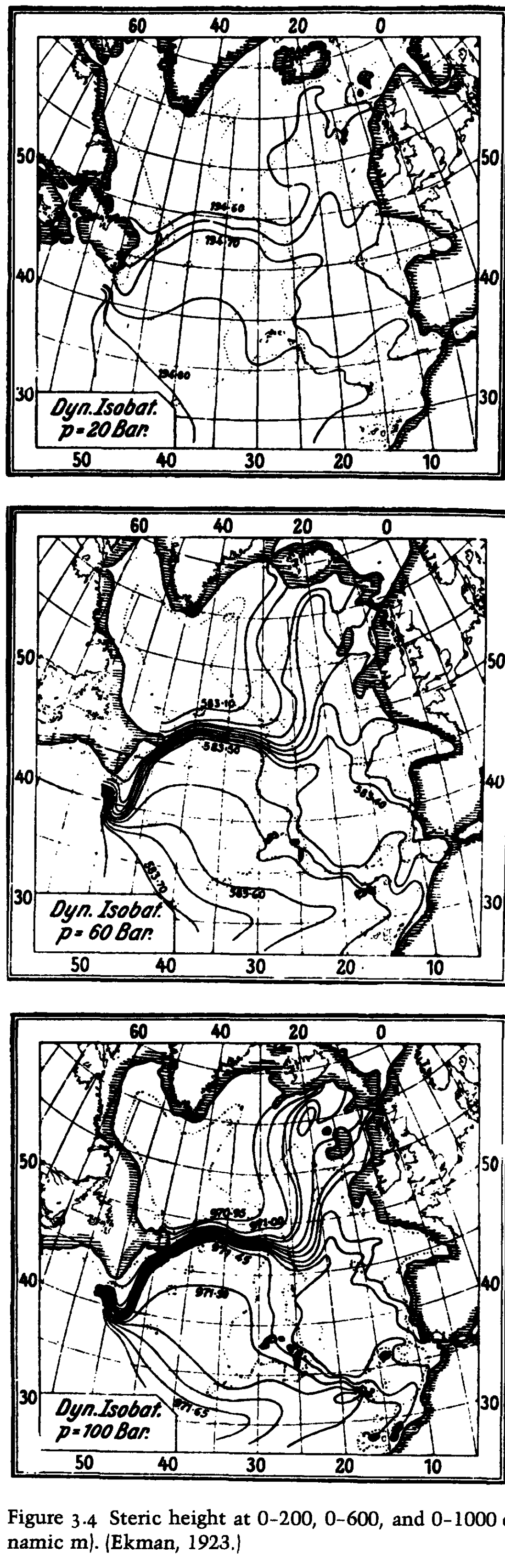

Figure 3.4 Steric height at 0–200, 0–600, and 0–1000 db (dynamic m). (Ekman, 1923.)

domain he examined maxima and minima of salinity and oxygen (the core method) under the assumption that beneath a shallow wind-driven layer the circulation was almost entirely meridional, with major flow along the western boundary except for the confluence with the Antarctic Circumpolar Current. His choice of the core-layer method limited his examination of a layer to those areas where it contained an extremum, and this was particularly limiting in the case of his Upper North Atlantic Deep Water, from the Mediterranean: where it joined other saline layers, its "core" was no longer recognizable.

His assumption of predominantly meridional, thermohaline-driven circulation was also limiting. He made no use of the density field in calculations of geostrophic shear, although the density field as mapped in the *Meteor* atlas (Wüst and Defant, 1936) clearly indicated substantial zonal patterns as well, and indeed indicated that a circulation pattern very like that recognized at the surface extended at least into the depth range of the Intermediate and Deep Water. His single consideration of the density field in any context except that of thermohaline meridional flow lies in his reference to the *Meteor* atlas map of density σ_t at 200 m in the Atlantic. He proposed that it is useful to infer the sense of flow along isopleths of σ_t at 200 m, but not below, and inferred a countercurrent on the southeastern side of the Gulf Stream that could be followed westward from the Azores to Bermuda and from there southward toward the Antilles. It is curious that he chose to limit this flow to the upper 200 m, as the density field retains that pattern to much greater depths, clearly to at least 1000 m in the *Meteor* atlas maps, and the salinity maps might have led him to propose this flow as the reason for the westward extension of the Mediterranean outflow water. The map of intermediate flow for the North Atlantic prepared by Sverdrup et al. (1942, figure 188; reproduced here as figure 3.8) makes this point quite clear. Presumably, it was the emphasis on meridional flow and his reluctance to make use of geostrophy at greater depths that caused him to consider only the upper 200 m.

The earliest portrayal of the density distribution over a large area was that of the *Meteor* atlas (Wüst and Defant, 1936). Vertical sections of σ_t as well as of temperature and salinity were prepared for all of the *Meteor* stations and, by selection of other data in the North Atlantic Ocean, maps of these quantities were prepared at selected depths from 200 m to the bottom. Wattenberg (1939) prepared corresponding maps and sections from the *Meteor* data for dissolved oxygen but did not attempt to treat the North Atlantic. It was not until 1957 that Wattenberg's phosphate atlas was published.

It was Defant (1941a,b) who first used the density field from the *Meteor* expedition and other data avail-

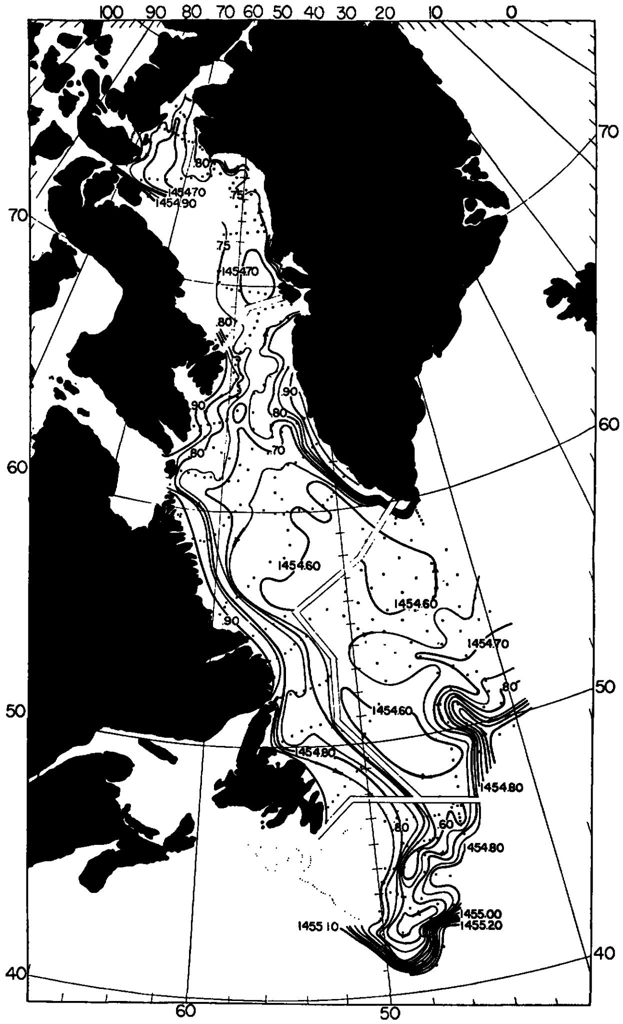

Figure 3.5 Steric height 0–1500 db (dynamic m). (Smith et al., 1937.)

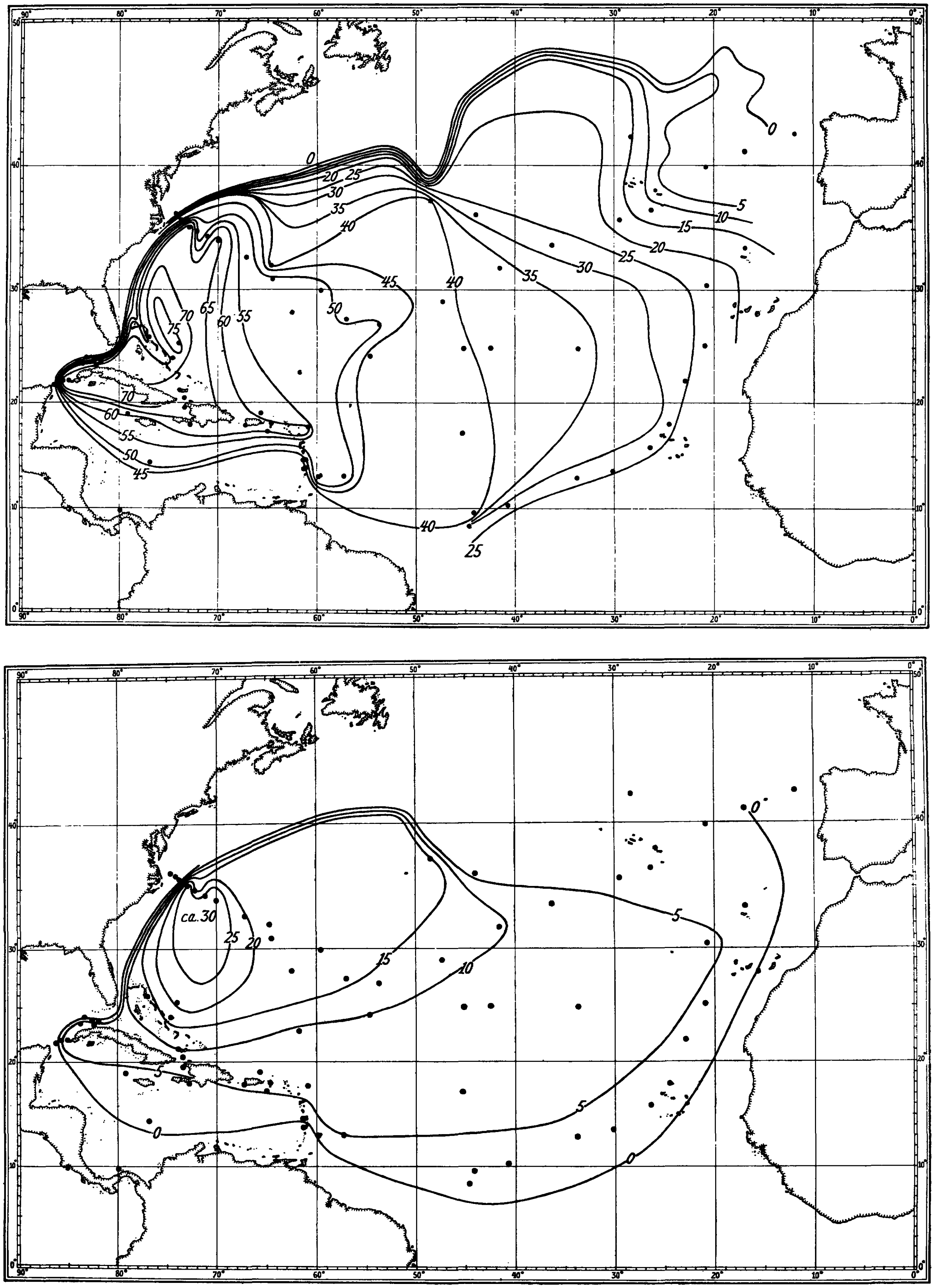

Figure 3.6 Steric height (dynamic cm): (A) 0-1000 db; (B) 500-1000 db. (Jacobsen, 1929.)

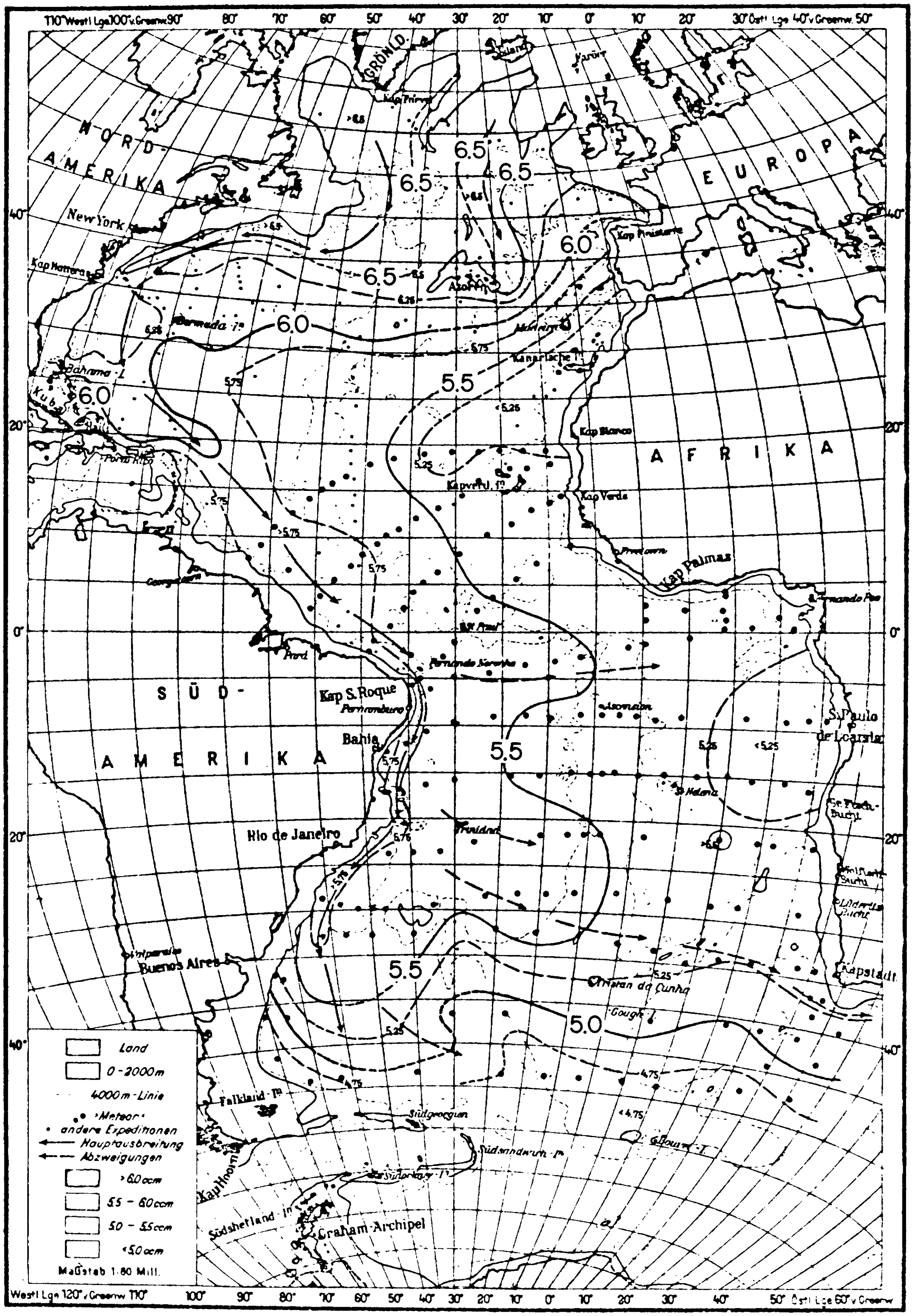

Figure 3.7 Oxygen $(ml\,l^{-1})$ of the core layer (intermediate oxygen maximum) of the Middle North Atlantic Deep Water. (Wüst, 1935.)

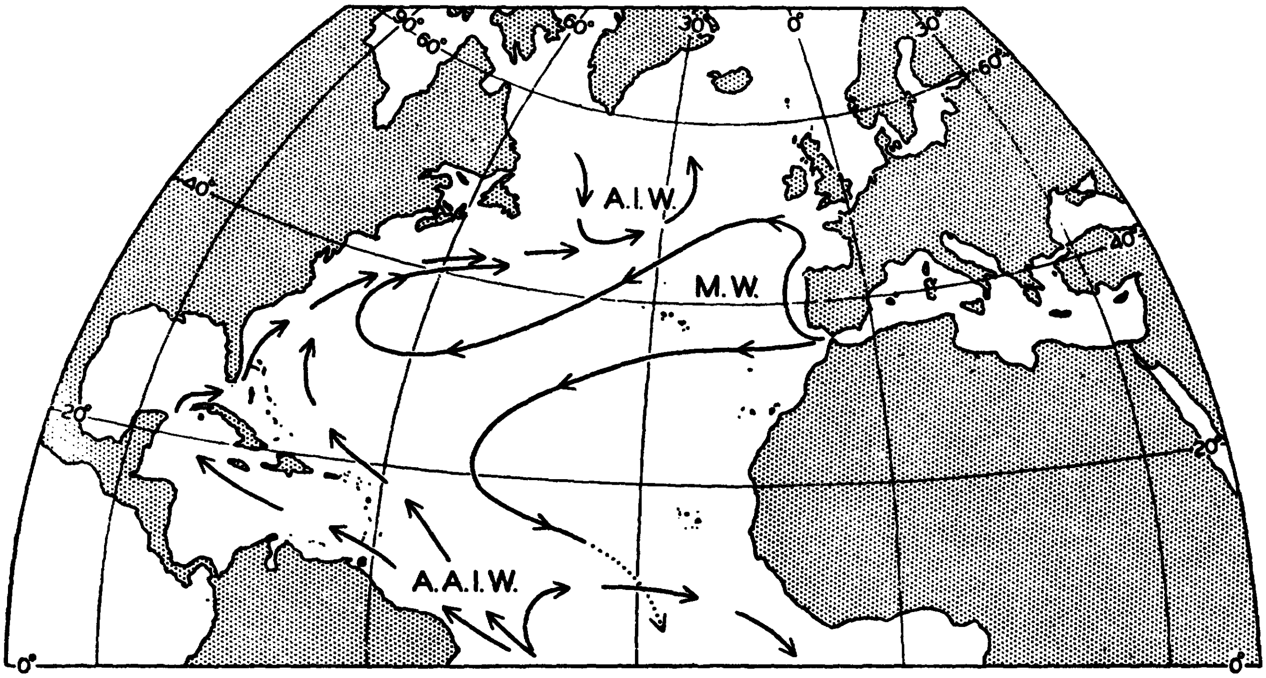

Figure 3.8 Approximate directions of flow of the intermediate water masses of the North Atlantic. A.I.W., Arctic Intermediate Water; M.W., Mediterranean Water; A.A.I.W., Antarctic Intermediate Water. (Sverdrup et al., 1942.)

able in the North Atlantic, with the geostrophic approximation, to investigate the circulation of the Atlantic Ocean at depths down to 2000 db. He prepared (1941a) maps of the steric height at the sea surface relative to various standard pressures down to 3000 db but prepared none of the steric height between two subsurface isobars. His surface maps, especially those referred to the deeper isobaric surfaces, show about the same pattern as seen in more recent data (Leetmaa et al., 1977), except for some rather severe limitations imposed by the quality and number of the data available in the North Atlantic Ocean. In particular, the curious high cell that appears on all his maps at 19–30°N along about 30–41°W stems from the *Carnegie* stations 18, 19, and 20, which he must have received before final processing, unaware of the errors. [Wüst (1935, footnote, p. 230) had noted that the *Carnegie* salinity values in the North Atlantic were too low by 0.03 to 0.04‰ on the average and had apparently either adjusted or deleted them in his work on the *Meteor* atlas, but Defant used them for his maps of steric height without adjustment. When the data were published, the error was noted (Fleming et al., 1945, p. 1).] The effect of a few errors of this sort and the general sparsity of data, and the predominantly zonal track lines in the South Atlantic, apparently tended to detract from the significance of his results. His maps of shear between the surface and 1000 or more db show clearly, however, the Gulf Stream return flow as a much sharper feature than in Iselin's (1936) map. The maps identify the major surface anticyclonic and cyclonic gyres and the North Equatorial Countercurrent, but the zonal track lines obscure the details of the equatorial circulation.

Later (1941b), in order to study subsurface flow patterns, he proposed and used a method for deriving a reference surface for the geostrophic shear. The method of derivation has not been accepted as valid by most physical oceanographers, and the resulting "absolute topography" maps at various pressures have been discounted. Indeed, one might argue that his presentations set back for some years the whole concept of geostrophy as a useful means of examining large-scale circulation through the density structure. This is unfortunate, because his maps, however referenced, are still of geostrophic shear, and provide the first evidence of the horizontal and vertical extent of the return flow just southeast of the Gulf Stream.

In his choice of a reference surface, it seems that he had hoped to satisfy continuity. His reference surface lies shallower near the equator (about 400 to 700 m) and sinks monotonically to 2500 m at 50°S. In the north, the reference extends downward to 1900 m at 50°N, but with a minor shoaling to 500 m at 12°N in mid-ocean and an abrupt rise from 1900 m to 1000 m along the western boundary in the zone from 20 to 45°N. This general shape might appear to take some account of the latitudinal variation of the Coriolis acceleration in calculations of geostrophic transport and to permit the presence of a southward flow beneath the Gulf Stream. In that area, the geostrophic shear retains the same sign to great depth, as shown by his maps of the relative flow, and any calculation of flow relative to a shallower depth would provide such a counterflow. His work with Wüst on the *Meteor* atlas provided maps at 1500 m and 2000 m (and at all depths down to 3500 m) with colder, less saline waters against the coast of North America than could be accounted for by horizontal flow from the south. On these maps, these low values connect directly to the Labrador Sea, and this may have suggested to Defant the presence of a Gulf Stream undercurrent, which would require a reference surface somewhere near 1500–2000 m. [This is remarkably consonant with the direct measurements of Swallow and Worthington (1961).] Furthermore, Wüst's (1935) maps of the spreading of the upper and middle deep water of the North Atlantic (figure 3.7), which were based upon the oxygen core as well as upon salinity and temperature, indicated such a deep return flow along the coast of the American continents.

Defant's map of "absolute" flow [figure 3.9, reproduced from Defant (1941b, Beilage XXIX)] does, indeed, show such a flow extending from the Labrador Sea southward along the western boundary to about 35 to 40°S, where it turns eastward with the West Wind Drift. This is quite like Stommel's (1965) results. This is not meant to imply that these investigators had solved conclusively, with these methods, the problem of the deep flow beneath the Gulf Stream. Defant's colder water on the west could be interpreted as another aspect of geostrophic shear, with isotherms rising to the west, rather than his interpretation of southward flow, and Wüst's core-layer method, while useful, may also yield different interpretations. The problem of the Gulf Stream Undercurrent, or deep western boundary current, has not yet been solved in a generally satisfactory manner. Richardson (1977) finds a strong southwestward flow extending past Cape Hatteras, including a coastal component as shallow as 1200 m. Worthington (1976) allows only a small southwestward component, and at the greater depths and lower temperatures. In any case, the schemes presented by Wüst and by Defant seem to have got some parts of it right by present standards.

It is noteworthy, however, that Sverdrup et al. (1942) make little reference to these studies. While recognizing the North Atlantic as the source of the deep saline waters extending into the other oceans, the undercurrent along the western boundary proposed by Wüst and by Defant was rejected, and no reference was made to a Gulf Stream return flow on its southeastern side. It is perhaps because of this that the western boundary undercurrent was not addressed again until reintroduced by Stommel (1957b), nor the Gulf Stream recirculation until the work of Worthington (1976).

3.5 Studies of Total Transport and Layers

Sverdrup et al. (1942) give little information about subsurface circulation. Aside from the meridional flow of the abyssal waters, generally northward along the western boundary, and the overlying southward flow of the deep waters that they described for all of the oceans that exchange with the Antarctic, and the poleward subsurface currents along the eastern boundary of the North and South Pacific, they provide only one other pattern of flow that is different from the surface pattern. That is the schematic pattern for the intermediate-depth circulation of the North Atlantic [figure 3.8, from Sverdrup et al. (1942, figure 188)]. This is notably different from the transport pattern they produced for the North Atlantic. It shows a westward return flow across the Atlantic just south of the Gulf Stream–North Atlantic Current, much like the pattern Wüst (1935) had proposed from the map of σ_t at 200 m in the *Meteor* atlas. It seems likely that they inferred this flow from the pattern of salinity created by the Mediterranean outflow, but this is not mentioned explicitly.

Their major flow patterns for both the North Atlantic and North Pacific are presented as calculations of transport and do not provide details of the vertical structure. Later maps (Fleming et al., 1945) of the geostrophic shear between various pressure surfaces were prepared from the *Carnegie* data in the Pacific. Though the data set was very sparse for such a presentation, the patterns clearly vary with depth. The poleward shift of the anticyclonic gyres and some return flow south of the Kuroshio are indicated.

The next major contributions on circulation, after publication of *The Oceans,* were from theory and dealt with transport rather than vertical structure. Concepts of the Sverdrup transport (Sverdrup, 1947) and westward intensification (Stommel, 1948) were followed by a study by Reid (1948) of equatorial circulation and by Munk's (1950) treatment of the large-scale wind-driven circulation. Munk's results matched the recognized circumstances of the surface flow remarkably well, accounting for the subpolar cyclonic and subtropical anticyclonic gyres and the system of zonal flows near the equator. They set in train a series of studies by several investigators [some of which were republished together by Robinson (1963)] that dealt with wind-driven circulation and western boundary currents in particular. The idealized oceans were mostly homogeneous, though some two-layer models were discussed as well, and the results were usually given as transports, without consideration of depth variations in the flow patterns other than a downward decrease of velocity.

A massive investigation of the Atlantic Ocean between about 50°N and 50°S, employing both conservative characteristics and oxygen and nutrients, relative

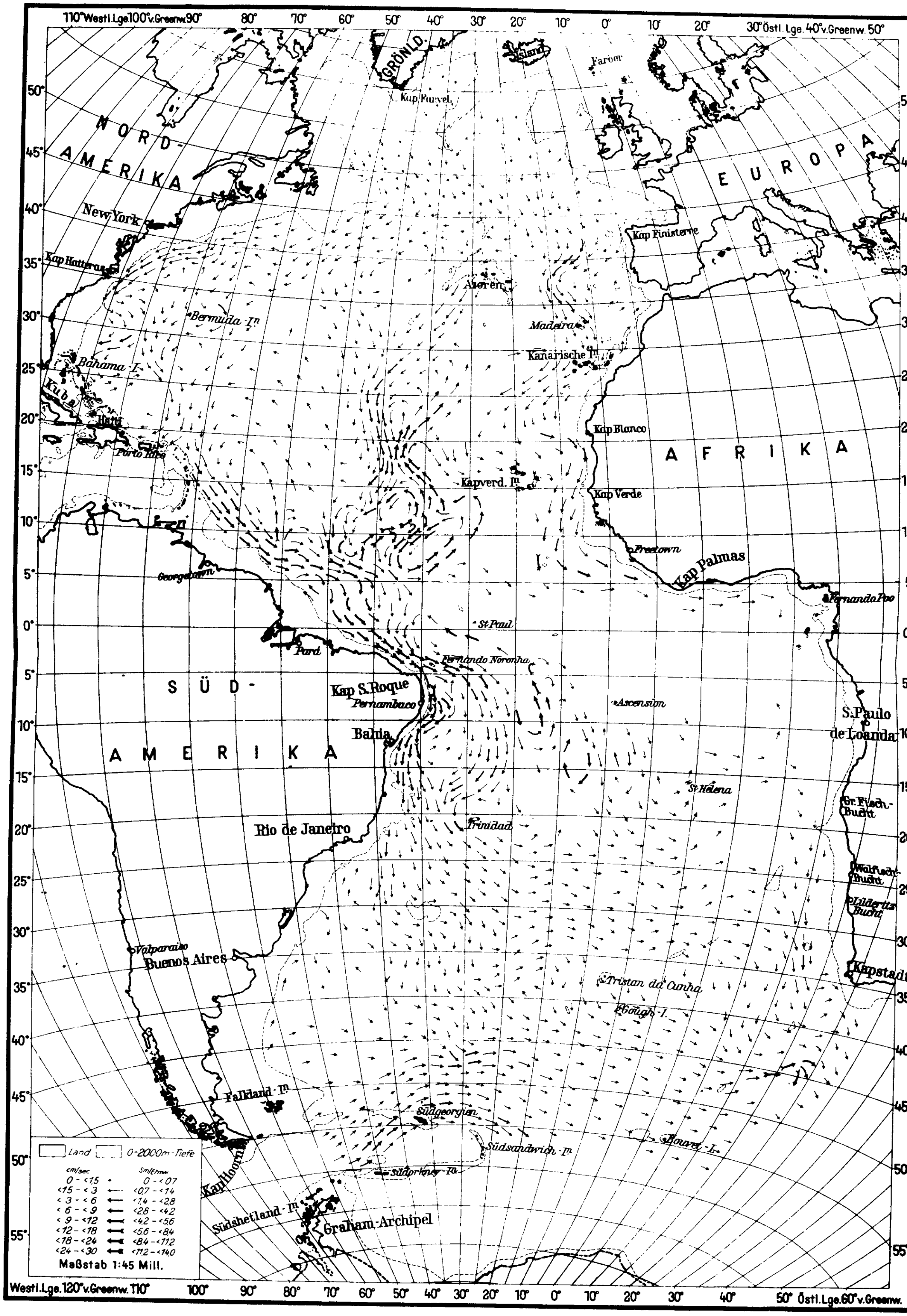

Figure 3.9 Flow field at 2000 m. (Defant, 1941b.)

geostrophic flow, and isopycnal analysis, was carried out by Riley (1951). Although his purpose was to study the nonconservative concentrations and to derive rates of oxygen utilization at various depths, he cast his study in the framework of the general circulation and provided flow patterns along various σ_t-surfaces (from 26.5 through 27.7), the deepest extending to about 2100 m in the central South Atlantic. These flow patterns, while not carried as far as they might have been had they been the principal purpose of investigation, are based upon salinity, oxygen and nutrient data (gridded by 10° intervals of latitude and longitude), as well as the density field, and show some remarkable features.

The scale of the grid he used eliminated some features, of course, and he missed the Gulf Stream return flow except in his deepest layers, and for the upper circulation in the subtropical zone he found only the large anticyclonic gyre that Sverdrup et al. (1942) had mapped. He did show that a branch of the subarctic cyclonic gyre extends southward from the Labrador Sea, forming a substantial Gulf Stream undercurrent as far south as Cape Hatteras, carrying waters of high-oxygen and low-nutrient concentration from the Labrador Sea along the western boundary. He found a poleward subsurface flow along the eastern boundary of the North Atlantic carrying northward waters of high salinity from the Mediterranean outlfow and of lower oxygen from the eastern tropical zone. He found that some part of the southward-flowing North Atlantic Deep Water turns eastward near the equator, carrying waters of higher oxygen content eastward between the two eastern tropical zones of low oxygen. Much of this, of course, was quite similar to the earlier results of Wüst and Defant. He did not attempt to carry their studies far forward, but to array them better for his particular study. His principal interests were in estimating the utilization of oxygen and the regeneration of nutrients, and the depth ranges and rates at which these processes occur. He found, using his estimated circulation patterns, that the total oxygen consumption and phosphate regeneration below the σ_t-surface 26.5 (average depth about 200 m) represent the utilization of about one-tenth of the surface production of organic matter by phytoplankton. This is consonant with later findings of Menzel and Ryther (1968), using measurements of dissolved organic carbon, that nearly all regeneration of nutrients takes place above about 500 m, and that in the deeper waters oxygen and nutrients are much more nearly conservative characteristics than in the upper levels. They are not entirely conservative, of course, even at great depth, as Fiadeiro and Craig (1978) have emphasized.

It is, perhaps, unfortunate that Riley's (1951) work came later than Munk's (1950) study. Otherwise, it might have stimulated a more thorough investigation, even with those limited data, of the variation of flow patterns with depth that might have been carried out concurrently with the studies of total transport. Both approaches merited further investigation, but it appears that the impact of Munk's very exciting paper, using one approach, had already engaged the attention of many investigators, and Riley's approach was not so quickly followed, even as more adequate data and methods became available. It has not been ignored or forgotten, of course; one very intensive continuation of his study, attempting to derive rates of deeper circulation, is the GEOSECS program.

It is also worthwhile to note that the differences in approach were not only conceptual but also practical. The Sverdrup transport concept allowed investigators to perform complex studies upon an idealized (homogeneous, steady, two-layer, flat-bottomed, etc.) ocean under an idealized or realistic wind field and to achieve important results in terms of total transport. Riley's sort of approach required the assimilation and manipulation of large quantities of data (though still perhaps too few and of uncertain quality) in order to perform the calculations, and to achieve quite different sorts of results (subsurface flow patterns, for example, instead of total transport).

Wyrtki (1961b), in a study of the thermohaline circulation and its relation to the general circulation, emphasized more clearly the density stratification of the ocean and the necessity that models should include not just surface and abyssal flow, but at least two additional layers, the intermediate and deep waters. These two layers have circulations quite different from the other layers and from each other, and their flow patterns obviously cannot be derived from the various assumptions of purely wind-driven homogeneous or two-layer oceans. And even the four layers discussed by Wyrtki (1961b) are simplifications, as he recognized.

3.6 Mid-Depth Studies Using Isopycnal Analysis

The concept that buoyancy forces in a stratified fluid may influence flow and mixing to conserve density more than other characeristics has been a topic of interest for a long time. Examination of characteristics along surfaces defined by various density-related parameters began in the 1930s, both for the atmosphere and the oceans. Various quantities ($\sigma_t, \sigma_\theta, \delta_T, \delta_\theta$, and σ_1, σ_2, σ_3, . . . , referring the density to 1000, 2000, 3000 db), . . . have been employed, and the method has been called "isentropic," "isosteric," "isanosteric," "isopycnic," and "isopycnal." (Hereafter, I shall refer to all the investigations as isopycnal and to mixing along any of the surfaces defined by these parameters as lateral mixing.) None of these quantities is entirely satisfactory because surfaces so defined can represent