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## 2 The Water Masses of the World Ocean: Some Results of a Fine-Scale Census

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### 2.1 Introduction

In his original brief monograph, Helland-Hansen (1916) introduced the concept of a water mass as being defined by a temperature-salinity ( $T$ - $S$ ) curve. He found that over a large area of the eastern North Atlantic a "normal"  $T$ - $S$  curve could be drawn. He showed that variations from this curve could be attributed to the intrusion of alien water masses that had originated elsewhere. The use of the  $T$ - $S$  diagram has been almost universal in physical oceanography since Helland-Hansen introduced it. It is not only a powerful descriptive tool, but observers at sea routinely plot  $T$ - $S$  diagrams and use them as a check on the tightness of their sampling bottles and the correct function of their thermometers.

The term "water mass" has been very loosely used by numerous authors. According to Sverdrup, Johnson, and Fleming (1942), a water mass is defined by a segment of a  $T$ - $S$  curve, and a "water type" by a single value of temperature and salinity that usually falls on a  $T$ - $S$  curve. Thus a  $T$ - $S$  curve is made up of an infinite number of "water types." These definitions will be adhered to in this chapter as far as is possible. Oceanographers have used other methods to describe the ocean, both before and after Helland-Hansen's introduction of the  $T$ - $S$  diagram, and these methods will be briefly discussed below, but I will deal primarily with the world water masses as defined by  $T$ - $S$  diagrams.

The most important advance in water-mass analysis since Helland-Hansen came with the introduction by Montgomery (1958), Cochrane (1958), and Pollak (1958) of the *volumetric*  $T$ - $S$  diagram, in which the volumes of all the world water masses were estimated. The volume of the world ocean, including adjacent seas, is  $1369 \times 10^6$  km<sup>3</sup>. Montgomery, Cochrane, and Pollak were able to divide the individual and world oceans into bivariate classes of temperature and salinity, each of which contained an assigned volume. For example, the most abundant class found by Montgomery (1958) in the world ocean was  $T = 1.0$ - $1.5^\circ\text{C}$ ,  $S = 34.7$ - $34.8\text{‰}$ ; he calculated that this relatively small class contained  $121 \times 10^6$  km<sup>3</sup>, or 9% of the water in the ocean.

Wright and Worthington (1970) produced a volumetric census of the North Atlantic that was a direct descendant of Montgomery's (1958) work. This later census was motivated by the introduction, pioneered by Schleicher and Bradshaw (1956), of the very accurate salinometers based on the measurement of electrical conductivity. The precision of data obtained with these salinometers enabled Wright and Worthington (1970) to divide the North Atlantic into much smaller classes than Montgomery and his colleagues had used: Wright and Worthington's smallest class (below  $2^\circ\text{C}$ ) was  $0.1^\circ\text{C} \times 0.01\text{‰}$ . Fifty of these classes make up one of

Montgomery's classes ( $0.5^{\circ}\text{C} \times 0.1\text{‰}$ ). This fine-scale census had clear advantages over the coarser-scale census that inspired it, and in consequence I undertook a census of the world-ocean water masses using the fine-scale classes that Wright and Worthington (1970) introduced. The greater part of this paper will be devoted to the presentation of the results of this census, with some discussion of the formation of these water masses.

## 2.2 Methods of Describing the Oceans

The simplest and the most universally used method of describing the oceans has been the preparation of vertical profiles of temperature, salinity, dissolved oxygen, or some other variables, constructed from oceanographic sections made across an ocean, or part of an ocean, from a ship or a number of ships. Ocean-wide temperature profiles have been drawn by oceanographers since Thomson's (1877) treatment of the *Challenger* sections, but the standard of excellence for this kind of presentation was set by Wüst and Defant (1936) in their atlas of the temperature, salinity, and density profiles from the Atlantic *Meteor* expedition of 1925–1927 and by Wattenberg (1939), who prepared the oxygen profiles. These vertical profiles were drawn in color, with detailed bottom topography provided. The atlas by Wüst and Defant (1936) provided the model for Fuglister's (1960) atlas of vertical profiles of temperature and salinity from the transatlantic sections made by various ships and observers during the International Geophysical Year. Later, Worthington and Wright (1970) drew similar profiles, for sections made by the *Erika Dan* in the northern North Atlantic in 1962. They also included dissolved-oxygen profiles modeled on those of Wattenberg, which Fuglister had been unable to do because of the poor quality of oxygen analyses made from Woods Hole ships during the International Geophysical Year.

Probably the finest example in this form is that of the vertical profiles by Stommel, Stroup, Reid, and Warren (1973) for the transpacific sections at  $28^{\circ}\text{S}$  and  $43^{\circ}\text{S}$  from *Eltanin* in 1967. These profiles are shown in six color plates; the variables are temperature, salinity, oxygen, phosphate, nitrate, and silicate. The station and sample-bottle spacing for these sections were carefully planned so as not to miss any important baroclinic gradient or variation in nutrient concentration.

Composite vertical profiles are often drawn from data provided by a number of ships from different years or even different decades. Such sections are, of course, less useful for dynamical studies, but sometimes provide an excellent description of the water. A fine example is that of Wüst's much cited north–south temperature, salinity, and oxygen profiles in the Atlantic (Wüst, 1935, plate XXIII). Reid (1965) used the same

method to construct zonal and meridional profiles of temperature, salinity, oxygen, and phosphate across the Pacific.

Helland-Hansen and Nansen (1926) drew vertical profiles of temperature and salinity superimposed on each other in their work on the eastern North Atlantic. This method has been followed by others, notably Tait (1957). I find such profiles difficult to read, but that may be idiosyncratic. Helland-Hansen and Nansen (1926) also introduced vertical profiles of the anomaly of salinity—in this, they were followed by Iselin (1936). My own preference (Worthington, 1976, figures 18, 19, and 20) is to draw vertical salinity anomaly charts, preferably in color, with selected isotherms included. I feel that this method illustrates most clearly the vertical juxtaposition of different water masses.

As Wüst (1935) remarked, horizontal charts of variables are of limited use in water-mass analysis because the various layers rise and sink above and below a fixed level. Nevertheless, the best early example of such horizontal charts is their own atlas (Wüst and Defant, 1936). Such charts have other uses, however, and are of particular value in satisfying the queries of laymen about the ocean.

The use of the "core layer" (*"Kernschicht"*) method to describe ocean waters is almost wholly due to Wüst (1935), his students, and, to a lesser extent, Defant (1936). In his classic description of the Atlantic, Wüst (1935) identified seven such core layers, characterized by maxima or minima of oxygen, salinity, or temperature. While the study of the spreading of these layers is of unquestionable value in descriptive oceanography, they have a drawback, pointed out by Montgomery (1938a), in that these layers are few in number, whereas the number of potential-density surfaces (which Montgomery prefers to core layers) is infinite. A further drawback, noted by Worthington (1976), is that core layers are often uncritically assumed to be the main paths of ocean circulation. He was struck by the paradox that most observers who had made hydrographic stations combined with direct current measurements in the northern North Atlantic (Steele, Barrett, and Worthington, 1962; Worthington and Volkmann, 1965; Swallow and Worthington, 1969) had been constrained by these measurements to place a level of zero motion in the salinity-minimum core layer of the Labrador Sea Water, which can be identified as Wüst's (1935) Middle North Atlantic Deep Water. The reasons for this seemed clear; the volume of Labrador Sea Water in the North Atlantic is about  $6 \times 10^6 \text{ km}^3$  (Wright and Worthington, 1970) and the formation rate was thought to be between 2 and  $4 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ . This gives a mean residence time for Labrador Sea Water of between 50 and 100 years. Accordingly, a particle of Labrador Sea Water should move from its formation area to its geo-

graphical limit between Iceland and Scotland at a speed of only a fraction of a centimeter per second.

Montgomery (1938a) made the first really effective use of the examination of variable properties on surfaces of constant potential density in the ocean. He credits Shaw (1930) with the development of this method in the atmosphere. It was used by Montgomery (and others who followed) mainly in the study of ocean circulation; the *depth* of a potential-density surface can be used as a diagnostic tool for locating geostrophic currents since rapid changes in the depth of these surfaces occur where such currents are found. It has also been a useful qualitative tool for describing water masses, since waters of different origin on the same potential-density surface usually contain widely different concentrations of variables, such as salinity, dissolved oxygen, and nutrients. Montgomery's (1938a) study of the tropical North Atlantic illustrated (among other things) the strong contrast in most upper layers between the low-salinity waters of the South Atlantic and the high-salinity waters of the North Atlantic.

Taft (1963) used this method to describe the shallower circumpolar water masses (and their circulation), and Callahan (1972) the deeper circumpolar water masses. Reid (1965) prepared charts of salinity, oxygen, and phosphate on two potential-density surfaces in the upper Pacific. These charts provide the best qualitative description of the thermocline waters of the Pacific, and the accompanying charts of the depths and acceleration potential at these surfaces give an equally broad qualitative description of the circulation for the upper layers of that ocean.

Perhaps the finest use of this method was Tsuchiya's (1968) description of the upper Equatorial Pacific. He displayed (in color) the depth, acceleration potential, potential temperature, salinity, and dissolved-oxygen concentration on four potential-density surfaces. The effect of such features as the Pacific Equatorial Undercurrent on the water-mass distribution is seen very clearly (this current being characterized by high salinity and high oxygen). The spreading of the oxygen minimum on both sides of the equator is also shown. One could wish (in hindsight) that Tsuchiya had extended his work to greater depths in the light of the recent discovery (C. Eriksen, personal communication) of deep equatorial jet currents in the Pacific.

In his monumental atlas of the Indian Ocean, Wyrski (1971) used *all* of the techniques listed (and more) to delineate the water masses of that ocean, including volumetric *T-S* diagrams of the kind introduced by Montgomery (1958), Cochrane (1958), and Pollak (1958). This atlas represents by far the most complete description we have of any ocean. It is marred by only one minor flaw; because of the international character of the atlas, Wyrski (1971) included slightly inferior data from some ships that participated in the Indian

Ocean expedition. This, however, does not present a problem to professional oceanographers, who can usually recognize and reject spurious data.

Readers who are interested in descriptive oceanography in general will find the atlas compendium of Stommel and Fieux (1978) an invaluable guide.

### 2.3 The World Water Masses As They Exist in the Second Half of This Century

The use of the conductivity properties of sea water to measure salinity was introduced in 1922 by Wenner (Wenner, Smith, and Soule, 1930; see chapter 14). The Wenner instrument was always calibrated by chemical titration using the Knudsen method, however, so that its full precision was never realized. In practical terms, the ocean-wide use of the conductivity method dates from 1954, when Schleicher and Bradshaw (1956) introduced their salinometer. The availability of this instrument was in large part responsible for the recommendation by Iselin in 1954 to reexamine the physical structure of the Atlantic Ocean using deep sections modeled on those of Wüst and Defant (1936). Subsequently, other oceanographic laboratories followed the lead of Schleicher and Bradshaw (1956), and a body of high-quality physical data began to appear on the world ocean; in 1973, this work on an ocean-wide census was undertaken at Woods Hole.

The coverage chart for this world-ocean water-mass census is shown in figure 2.1; it clearly requires some explanation. As in the North Atlantic census of Wright and Worthington (1970), the basic area unit used was 5° of latitude by 5° of longitude. For convenience this unit will be called a 5°-square.

If no high-quality, deep hydrographic station can be found in a 5°-square, that square is shown in black. There were certain standards that had to be met for a station to be considered of high quality. The most important of these was that salinity should have been recorded to three decimal places and that such recording should have been justified. A great deal of tiresome work went into deciding whether each station met this standard. All hydrographic stations in which salinity was recorded to three places were obtained from the National Oceanographic Data Center. Potential temperature-salinity diagrams were drawn for these deep stations, and if the scatter of points on any station in the deep water was more than about  $\pm 0.01\text{‰}$ , the station clearly did not qualify. Experience has taught us that *all* the deep water masses of the world have a very tight potential temperature-salinity correlation and that variations from a mean curve are due to genuine geographic differences in the water masses. (Hereafter, all temperatures referred to in the text will be *potential* temperatures unless *in situ* temperature is specified. The symbol  $\theta$ , for potential temperature, is

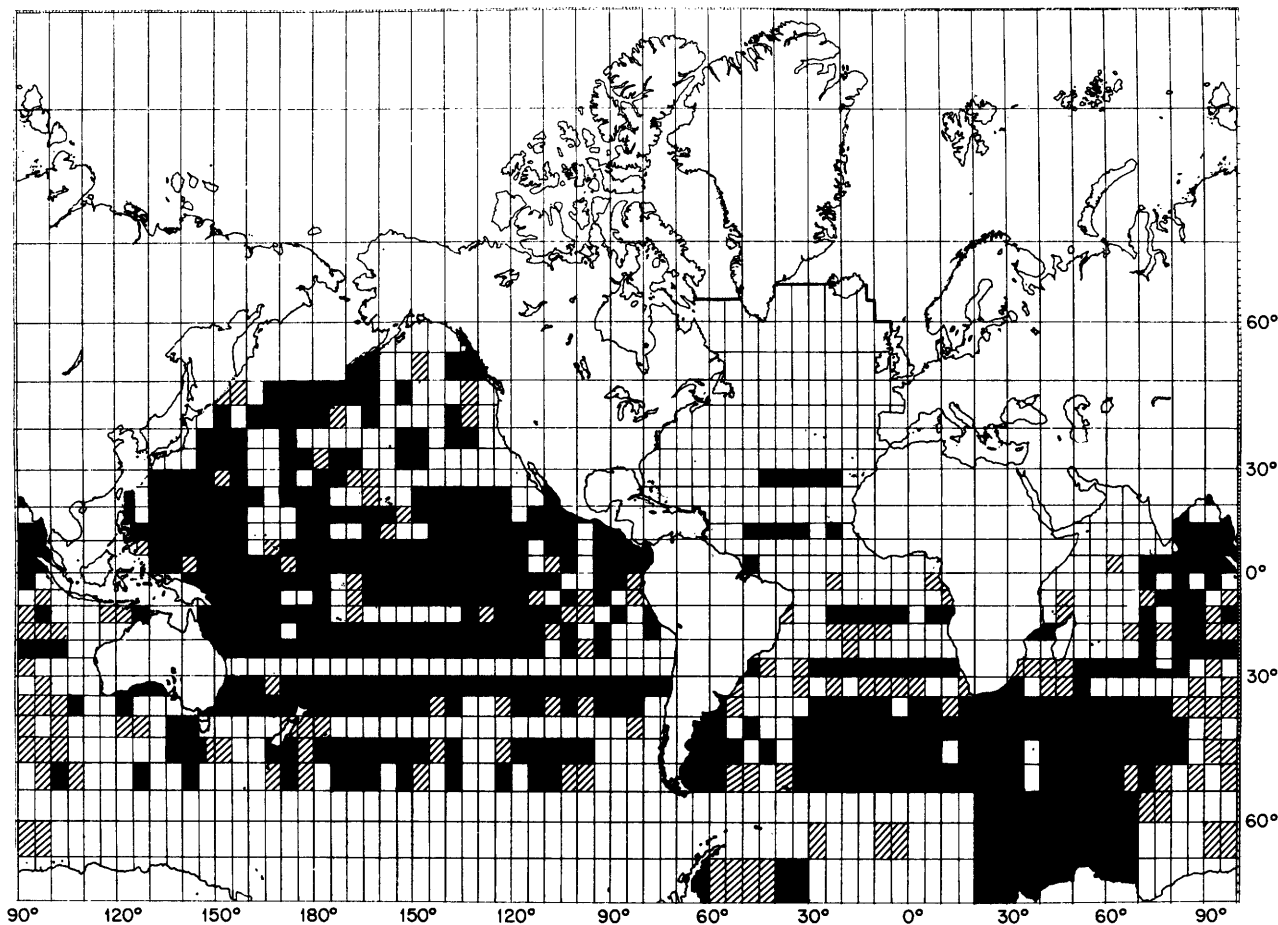


Figure 2.1 Coverage chart showing where high-quality deep stations are available (up to June 1977) in the world ocean. Unshaded 5°-squares contain at least one high-quality deep

station. Crosshatched 5°-squares contain at least one high-quality station but in a shallow area of the square. Black 5°-squares contain no high-quality deep stations.

used in tables in case these should be reproduced elsewhere.) Occasionally, it appeared that a single ship, on a single cruise, had measured salinity incorrectly. This was determined by comparing the values obtained by this ship with those obtained by other ships where the data were plentiful. Usually, these systematic errors were of the order of 0.01‰. This was the most vexing determination in the census because the ship in question often traveled into virgin territory as well, but no empirical corrections were made to adjust the data from that ship to those from its fellow ships. Such data were simply omitted from the census.

Another, easier standard to be met was that the bottle spacing be sufficiently close that an unambiguous *T-S* curve could be drawn. Again, comparison with other stations in the same area was used to determine, for example, that no maxima or minima had been missed. The final standard involved the meaning of the word "deep." Generally, if a station extended to 90% of the water depth, it could be used in the census by extrapolation, but there are areas in the ocean where the temperature and salinity change rapidly near the bottom and extrapolation was not justified. Stations in

such areas were also omitted from the census.

Accordingly, for a 5°-square to be unshaded in this coverage chart (figure 2.1), the square must contain at least one station of high quality that extended close enough to the bottom so that virtually no fictitious water could be assigned to it. Another qualification was that this station should be at, or close to, the greatest ocean depth in that 5°-square. If a 5°-square contained water somewhere that was, say, 5000 m deep, and the only station in that square did reach the bottom but only to some lesser depth (such as 3000 m) because it was taken over a seamount or on the continental slope, the 5°-square was not used in the census. Such 5°-squares are designated in figure 2.1 as crosshatched rather than black, to indicate that one or more high-quality stations exist in that square, but that they do not permit classification of all the water in that square.

It is possible that some fictitious water may exist in the census owing to systematic errors in thermometer calibration, but such volumes of water are thought to be small. Certainly no evidence for such errors was detected.

The census includes all high-quality data that were available from the National Oceanographic Data Center before June 1977. The North Atlantic census of Wright and Worthington (1970) was included unchanged. It can be seen (figure 2.1) that the North Atlantic is by far the best covered of the oceans, but as J. L. Reid (personal communication) has pointed out to me, nutrient data from the North Atlantic are sadly lacking.

The coverage chart (figure 2.1) is disappointing, coming as it does from the second half of a decade supposedly devoted to ocean exploration. In fact, by far the greater number of stations used in this census was made before this decade began. It is additionally disappointing that in spite of the large number of ocean-wide cruises made by ships of the Soviet Union before and during this decade, not a single station of theirs could be used in this census because the precision of their salinity data was not sufficient.

Certain features of this chart are worth mentioning. The North Atlantic was well covered, as we have seen, by purely physical data. Virtually all of the North Atlantic stations were made during the years 1954–1962. The excellent coverage of the Southern Ocean is almost entirely due to the work sponsored by the United States Antarctic Research Program aboard the U.S.N.S. *Eltanin*, under the leadership of Arnold Gordon. The lack of coverage in the southwest Indian Ocean and the southeast Atlantic Ocean is the result of a decision, made for financial reasons, to suspend temporarily the circumnavigation of Antarctica, combined with the cutoff date (June 1977) used for this census. The excellent coverage of the northwest Indian Ocean is due to the many participants in the International Indian Ocean Expedition whose interests lay chiefly in the glamorous monsoonal regions. Coverage in other parts of the Indian Ocean was poor except for the efforts of the Australians in the eastern part. In the South Pacific, the sections made by Stommel et al. (1973) at 28°S and 43°S are the most outstanding feature. In the North Pacific, one might deduce that there have been oceanographers working out of California and Japan, but deep coverage is generally poor.

None of these strictures applies to the upper layers of the oceans, where data are plentiful in nearly all oceans, and high precision of salinity analysis is, for the most part, not necessary to describe their broad features. However, only *precise* data have been used in this census at all depths. There are high-quality data in a number of the inland seas that connect to these oceans, but since not *all* these seas have been covered, it was decided to include none of them and deal only with the open ocean.

The volume of the oceans, excluding the adjacent seas, was found to be  $1320 \times 10^6$  km<sup>3</sup>. This figure was calculated from the following: the sounding (corrected

for the speed of sound) at each deep station for the 1°-square in which that station fell; in 1°-squares where no station fell (the vast majority), the tables of Menard and Smith (1966). These tables give the mean elevation (above or below sea level) for each 1°-square from the equator to lat. 50°, for each area of 1° of latitude by 2° of longitude from lat. 50° to lat. 70°, and for each area of 1° of latitude by 5° of longitude above lat. 70°. These tables are, of course, useless near islands and land masses where a given 1°-square may contain a considerable volume of water while its *mean* elevation is above sea level.

A rough description of how this  $1320 \times 10^6$  km<sup>3</sup> of water is distributed is shown in figure 2.2. This is a computer-simulated three-dimensional sketch of the world water masses. The apparent elevation in this diagram is proportional to the abundance of water that exists in the ocean in each class  $0.1^\circ\text{C} \times 0.01\text{‰}$ . In the warmer parts of the ocean, where coarser classes were used, each class was prorated on the basis of this smallest class, as Wright and Worthington (1970) have described. For example, the classes in the temperature range 3–4°C have dimensions  $0.2^\circ\text{C} \times 0.02\text{‰}$ . If such a class contained  $4800 \times 10^3$  km<sup>3</sup>, it would be prorated at  $1200 \times 10^3$  km<sup>3</sup>. In all important respects, the methods of Wright and Worthington (1970) have been followed in this work, except that a computer program has done most of the drudgery involved in separating the water at each station into the appropriate classes.

This diagram must be viewed with a certain amount of skepticism because the data on which it was based are so sparse. For example (by the standard shown in figure 2.1), only 28.7% of the North Pacific has been surveyed. For purposes of this diagram (figure 2.2), and the subsequent figures and tables, it has been assumed that the remaining 71.3% of the North Pacific is divided into the same *T-S* classes. The class that contains the largest volume of water, shown by the tallest peak in figure 2.2, is found in the North Pacific. This class is defined by  $T = 1.1\text{--}1.2^\circ\text{C}$ ,  $S = 34.68\text{--}34.69\text{‰}$ . According to this census, there are  $26 \times 10^6$  km<sup>3</sup> of water in this class, but only  $7.3 \times 10^6$  km<sup>3</sup> were actually observed in the white areas of the North Pacific (figure 2.1) in which reliable data were available.

Nevertheless, I feel that an image of the real ocean would not differ too greatly from that shown in figure 2.2. The most serious gap in the census is in the southeastern Atlantic and the southwestern Indian Ocean, where the transition between Atlantic and Indian Ocean water masses has not been properly observed. This diagram (figure 2.2) makes graphically clear what was already numerically clear from the work of Montgomery (1958), Cochrane (1958), and Pollak (1958), namely, that nearly all the water in the oceans is cold. The most abundant fine-scale class, occupying the bottom of the North Pacific, contains more water ( $26 \times$

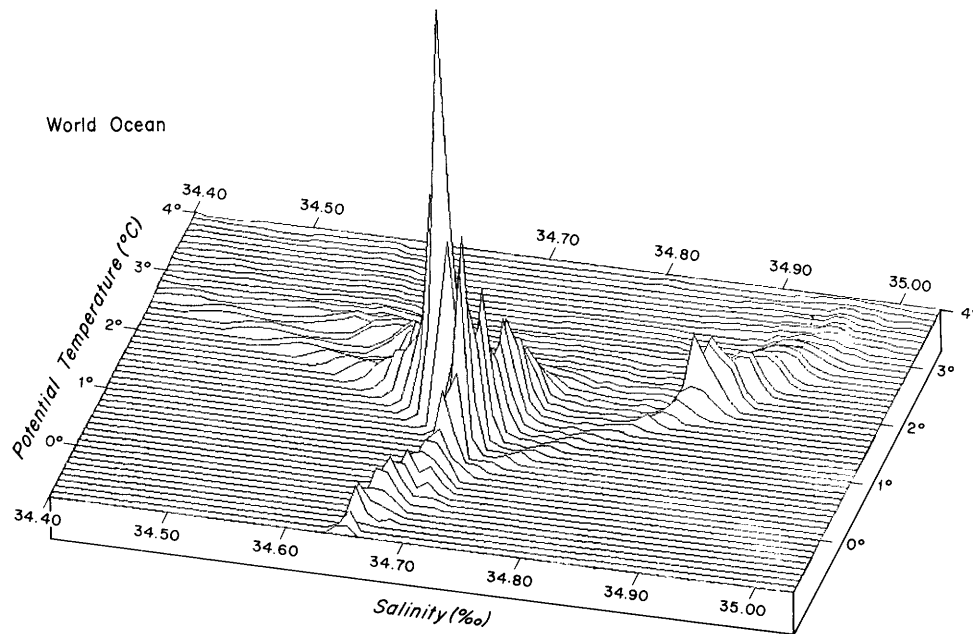


Figure 2.2 Simulated three-dimensional  $T$ - $S$  diagram of the water masses of the world ocean. Apparent elevation is pro-

portional to volume. Elevation of highest peak corresponds to  $26.0 \times 10^6 \text{ km}^3$  per bivariate class  $0.1^\circ\text{C} \times 0.01\text{‰}$ .

$10^6 \text{ km}^3$ ) than *all* the water in the world ocean warmer than  $19^\circ\text{C}$  ( $21.9 \times 10^6 \text{ km}^3$ ) and more than *all* the continental ice caps ( $23 \times 10^6 \text{ km}^3$ ). It is represented by the highest peak in figure 2.2. The coldest water ( $<0^\circ\text{C}$ ) is confined to the Southern Ocean (which has been defined as south of  $55^\circ\text{S}$ ) except for a small volume in the South Atlantic that has penetrated north of  $55^\circ\text{S}$ . The Atlantic is the most eccentric of the oceans, standing aloof on the saline side of this diagram, connected to the Southern Ocean only by a narrow umbilicus that contains little water. The Indian and Pacific Oceans are much more similar to each other than to the Atlantic; in order to show this, the computer has drawn figures 2.3, 2.4, and 2.5 for the Pacific, Indian, and Atlantic Oceans, respectively. By referring to these figures, the reader should be able to identify, by ocean, the gross features that appear in the world-ocean diagram (figure 2.2).

Such well-known water masses as Antarctic Intermediate Water and Mediterranean Outflow Water are barely perceptible in these figures. These mid-depth water masses have little volume relative to the deep water, and moreover, their  $T$ - $S$  characteristics are diverse, so that their volumes are spread over a wide area of figure 2.2 with little elevation.

For purposes of this census, the oceans have been subdivided: North Pacific, South Pacific, and Southern Ocean (Pacific); Indian and Southern Ocean (Indian); North Atlantic, South Atlantic and Southern Ocean (Atlantic). The Southern Ocean has also been totaled separately.

The volumes of all these subdivisions and the totals for each ocean and for the world ocean are listed in

table 2.1, with the mean potential temperature and mean salinity of each. For reasons that will become clear when these results are compared with those of Montgomery, Cochrane, and Pollak, the accuracy of these means depends on the percentage of the ocean that has been surveyed. It has been assumed that all the water in the *unsurveyed* areas of each ocean listed in table 2.1 is divided into the same  $T$ - $S$  classes as that in the surveyed areas and in the same proportion. This assumption has the effect of assigning artificially large volumes of water to classes that are found where coverage is good. In particular, the reader should be skeptical about my means for the Pacific, which has been less than one-third surveyed.

Mention should also be made of the two regions that I have designated as 100% surveyed. In the case of the Southern Ocean (Pacific) this designation is correct; the *Eltanin* stations have missed almost nothing. In the North Atlantic (figure 2.1), there are 11  $5^\circ$ -squares that have no reliable data, but in their census Wright and Worthington (1970) assigned these  $5^\circ$ -squares to neighboring stations in order to bring their total to 100% (a procedure not generally followed in this census). I have adopted the totals of Wright and Worthington (1970) uncritically.

In order to compare the new results with those of Montgomery (1958), Cochrane (1958), and Pollak (1958), it was necessary to remove the inland seas from the totals given by these authors and reaverage without them. The results of this comparison are shown in table 2.2, and the new means for the world ocean are remarkably close to the old ones, differing by only  $0.03^\circ\text{C}$  in temperature and  $0.01\text{‰}$  in salinity. Closer

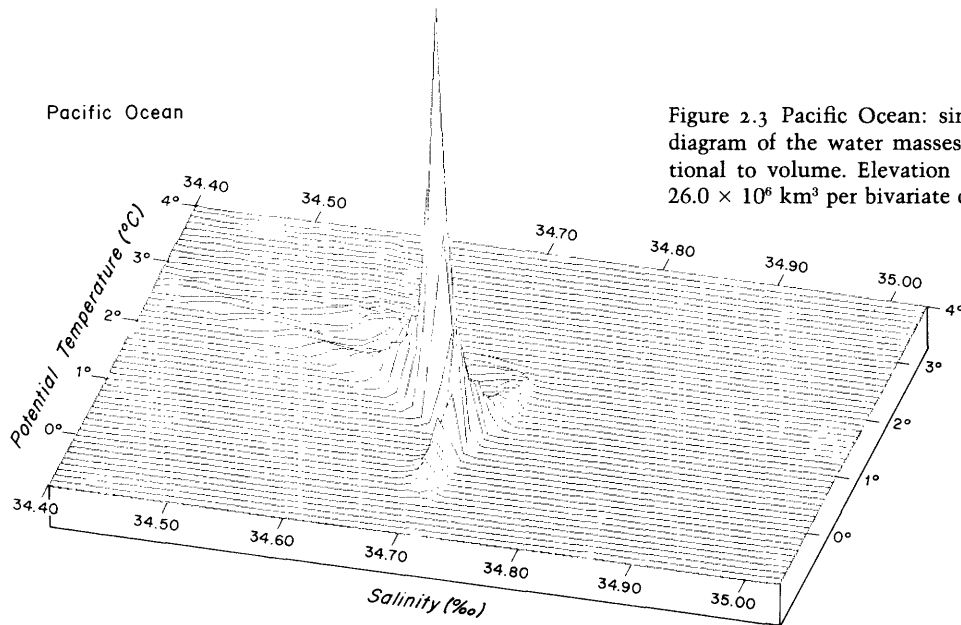


Figure 2.3 Pacific Ocean: simulated three-dimensional  $T$ - $S$  diagram of the water masses. Apparent elevation is proportional to volume. Elevation of highest peak corresponds to  $26.0 \times 10^6 \text{ km}^3$  per bivariate class  $0.1^\circ\text{C} \times 0.01\text{‰}$ .

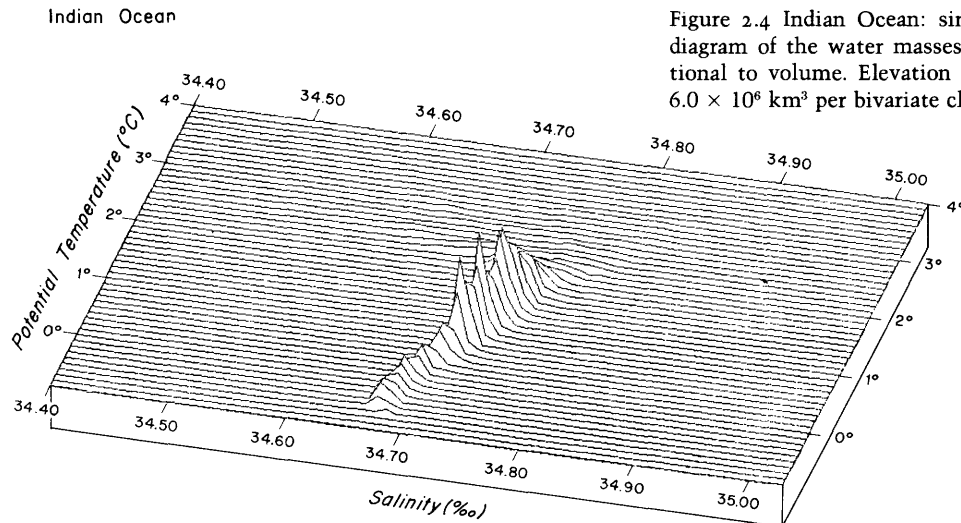


Figure 2.4 Indian Ocean: simulated three-dimensional  $T$ - $S$  diagram of the water masses. Apparent elevation is proportional to volume. Elevation of highest peak corresponds to  $6.0 \times 10^6 \text{ km}^3$  per bivariate class  $0.1^\circ\text{C} \times 0.01\text{‰}$ .

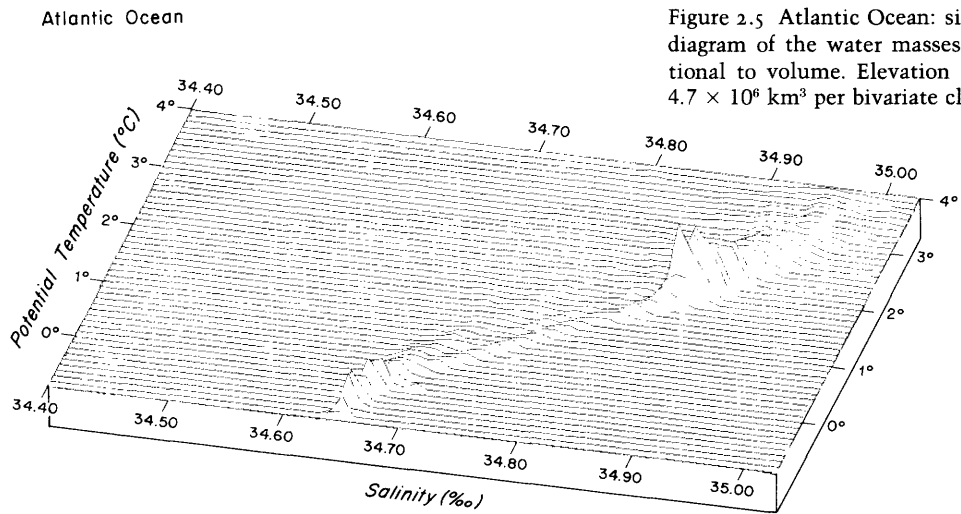


Figure 2.5 Atlantic Ocean: simulated three-dimensional  $T$ - $S$  diagram of the water masses. Apparent elevation is proportional to volume. Elevation of highest peak corresponds to  $4.7 \times 10^6 \text{ km}^3$  per bivariate class  $0.1^\circ\text{C} \times 0.01\text{‰}$ .

Table 2.1 Volumes [ $\text{km}^3 \times 10^6$ ] of the Oceans, Excluding Adjacent Seas

	Ocean volume	Volume surveyed	Percentage surveyed	Mean $\theta$	Mean S (‰)
North Pacific	332,222	95,469	28.7	3.13	34.57
South Pacific	323,951	98,458	30.4	3.50	34.63
Southern Ocean (Pacific)	55,413	55,413	100.0	1.07	34.64
Pacific Ocean total	711,586	249,340	35.0	3.14	34.60
Indian	245,974	108,585	44.1	4.36	34.79
Southern Ocean (Indian)	36,730	17,163	46.7	0.72	34.66
Indian Ocean total	282,704	125,748	44.5	3.88	34.78
North Atlantic	137,222	137,222	100.0	5.08	35.09
South Atlantic	158,238	70,397	44.5	3.81	34.84
Southern Ocean (Atlantic)	30,738	24,980	81.3	0.04	34.64
Atlantic Ocean total	326,198	232,599	71.3	3.99	34.92
(Southern Ocean total)	122,881	97,556	79.4	0.71	34.65
World Ocean total	1,320,488	607,687	46.0	3.51	34.72

Table 2.2 Comparative Volumes and Means

	This census			Montgomery (1958), Cochrane (1958), and Pollak (1958), modified to exclude adjacent seas		
	Volume ( $\text{km}^3 \times 10^6$ )	Mean ( $^{\circ}\text{C}$ )	Mean S (‰)	Volume ( $\text{km}^3 \times 10^6$ )	Mean $\theta$ ( $^{\circ}\text{C}$ )	Mean S (‰)
North Pacific	332.2	3.13	34.57	346.1	3.39	34.59
South Pacific	379.4	3.14	34.63	376.5	3.36	34.64
Pacific	711.6	3.14	34.60	722.6	3.37	34.62
Indian	282.7	3.88	34.78	291.6	3.70	34.75
Atlantic	326.2	3.99	34.92	321.8	3.76	34.87
World Ocean	1320.5	3.51	34.72	1336.0	3.54	34.71



examination of the table will show that there is no cause for celebration of this similarity—in individual oceans, the new results differ by much larger amounts, particularly in temperature. The new-census mean temperature for the Pacific is lower than the old mean, and the new mean is higher for both the Atlantic and Indian Oceans.

Cochrane (table 2.2) has provided separate averages for the North and South Pacific, as I have, and it is instructive to examine the reasons for the discrepancy in the North Pacific (3.13°C, contrasted with 3.39°C) in some detail. The first step was to see whether Cochrane's (relatively) coarse intervals were responsible for the disagreement; it was reasoned that, in an ocean where the vertical temperature gradient generally decreases with depth, larger volumes of water would be found toward the colder side of each coarse temperature interval, resulting in artificially low averages. Accordingly, the *new-census* mean was recalculated, using Cochrane's coarse intervals. This resulted in an artificial increase in the *new* mean from 3.13°C to 3.15°C, a change in the expected direction but not nearly sufficient to account for the discrepancy. This step does suggest, however, that Montgomery, Cochrane, and Pollak may all have overestimated the mean temperatures of the oceans by a small amount due to the coarseness of their scale.

The real reason for the discrepancy can be seen in table 2.3, in which the volumes and mean temperatures found by Cochrane in four temperature ranges are compared with those of this census.

It can be seen that Cochrane's total volume is slightly larger than mine. This reflects the difference in Cochrane's depth estimates [which agree closely with those of Kossina (1921)] and those of Menard and Smith (1966). The table shows that there is little difference in the mean temperature for each of these layers, although the new census does show a higher mean in the 10–20°C layer. The main difference is that this census has counted (relatively) more cold water (<4°C) and much less warm water (>20°C). This is presumably

Table 2.3 Cochrane's North Pacific Volumes ( $\text{km}^3 \times 10^6$ ) Compared with Those of This Census in Four Layers, and the Ratio of These Volumes, with Mean Potential Temperature for Each Layer

	Total volume	<4°C	4–10°C	10–20°C	20–30°C
(A) Cochrane	346.1	274.2	48.9	15.6	7.4
(B) This census	332.2	271.1	41.8	15.0	4.3
(A)/(B)	1.04	1.01	1.17	1.04	1.72
	Mean T	Mean $\theta$ <4°	Mean $\theta$ 4–10°C	Mean $\theta$ 10–20°C	Mean $\theta$ 20–30°C
Cochrane	3.39	1.77	6.05	13.64	24.55
This census	3.15	1.76	6.08	13.93	24.48

due to the artificially small area of the North Pacific assigned to stations at *low* latitudes in this census (figure 2.1) relative to that of Cochrane (1958, his figure 1).

The conclusion to be drawn is that Cochrane's (1958) mean temperature for the North Pacific is closer to the truth than the mean obtained by this census, although it is probably very slightly too warm due to the coarse temperature interval used. By inference, the new means in other poorly surveyed oceans are also in doubt. This is regrettable since the whole object of this census was to describe, accurately, the temperature and salinity of the world ocean as they exist in the second half of this century in case this description should be useful to future oceanographers (if any) whose interests might lie in the climatic mean ocean and its changes. Nevertheless, I think I can show that this census has been worthwhile, especially in the deep ocean, by virtue of its finer scale.

Montgomery (1958) combined Cochrane's (Pacific Ocean) and Pollak's (Indian Ocean) totals in each bivariate class with his own Atlantic totals to provide a volumetric *T-S* diagram for the world ocean. In the deep ocean, he lists three bivariate classes (0.5°C  $\times$  0.1‰) that contain more than  $100 \times 10^6 \text{ km}^3$ . These classes are listed in table 2.4 with the comparative values obtained by this census (given in italics below Montgomery's values).

The big difference here is that the new census has  $43.3 \times 10^6 \text{ km}^3$  more water in the class 1.0–1.5°C, 34.6–34.7‰, and  $34.7 \times 10^6 \text{ km}^3$  less in the class 1.0–1.5°C, 34.7–34.8‰. This, I believe, is almost entirely due to a disagreement between this census and Cochrane's about how much water there is in the North Pacific with a salinity greater than 34.7‰. Of Montgomery's  $121.2 \times 10^6 \text{ km}^3$  in the class 1.0–1.5°C, 34.7–34.8‰ (table 2.4), the North Pacific contributes  $44.6 \times 10^6 \text{ km}^3$ , according to Cochrane, while my figures show only  $4.6 \times 10^6 \text{ km}^3$ . In this case, I believe, my numbers are more correct than Cochrane's because his data are all from chemical titration. Nobody has claimed an accuracy better than  $\pm 0.02\%$  for salinity analyses made at sea, and experience has taught me that few of the old titrators could justifiably claim an accuracy of better than  $\pm 0.03\%$ . It is easy to see how even a quantity as large as  $45 \times 10^6 \text{ km}^3$  in the North Pacific could be assigned to the more saline class since (as Cochrane himself has remarked) this water lies close to the borderline at 34.7‰.

My estimate of the distribution of water in the class 1.0–1.5°C, 34.6–34.7‰ is listed in table 2.5.

This table, I believe, justifies the fine scale used in this census because it shows that most of the water is concentrated in a few fine-scale classes on the salt-cold side of Montgomery's relatively coarse-scale class (0.5°C  $\times$  0.1‰). There are *small* amounts of water on

Table 2.4 Montgomery's (1958) Volumes ( $\text{km}^3 \times 10^6$ ) in Three Principal Bivariate Classes of The World Ocean (Volumes from This Census in Italics)

2.0°C	112.1 <i>115.6</i>	
1.5°C	115.3 <i>158.6</i>	121.2 <i>86.5</i>
1.0°C	34.6‰	34.7‰    34.8‰

the fresh-cold side of this table, and two fine-scale classes contain no water whatsoever. The high concentrations of water that are numbered 1, 2, 4, 5, 6, and 9 fall on the  $T$ - $S$  curve for the deep Pacific Ocean. These numbers represent their rank by volume in the world ocean. The class 1.1–1.2°C, 34.68–34.69‰,  $26.0 \times 10^6 \text{ km}^3$ , is the most abundant class; it is represented, as we have seen, by the peak in figures 2.2 and 2.3. One hundred percent of this water (to the nearest percentage point) is found in the North Pacific, as is also 100% of the next most abundant class (1.2–1.3°C, 34.67–34.68‰).

The third-ranked class, which does not appear in table 2.4, is 0.7–0.8°C, 34.71–34.72‰. This is a circumpolar class, common to the South Pacific, 48%; the Southern Ocean (Pacific), 9%; the Indian Ocean, 35%; the Southern Ocean (Indian), 5%; the South Atlantic, 2%; and the Southern Ocean (Atlantic), 1%. This cosmopolitan water type is found in all the oceans except the North Pacific and the North Atlantic. The most abundant classes, those that, together, contain 50% of the world ocean (according to this census), all fall in the numbered squares (and rectangles) in figure 2.6. The numbers, 1–186, are their rank by abundance. The least of these, number 186, contains just under  $1 \times 10^6 \text{ km}^3$ . All of them fall below 3°C. All these classes are also listed by rank in the appendix (23 pages at the end of this chapter), with their volumes and the percentages of these volumes that are found in each of the subdivi-

sions of this census. Thus the reader can, for example, identify class number 80 in figure 2.6, turn to the appendix and find that it contains  $2,449 \times 10^3 \text{ km}^3$ ; he will see that it is a circumpolar class since it is found throughout the Southern Ocean (16% in the Pacific sector, 44% in the Indian Ocean sector, and 15% in the Atlantic sector), and that it is also found north of 55°S in the Indian Ocean (17%) and the South Atlantic (15%).

The classes that contain 50% of the volume of the world ocean (figure 2.6) are divided into two groups: a larger, Y-shaped group composed of the large-volume classes of the Southern Ocean, the Pacific and Indian Oceans (with some South Atlantic water present); and a smaller, lozenge-shaped group, somewhat warmer and about 0.2‰ more saline, that is exclusively Atlantic. A discussion of these two groups follows, but the reader is asked to bear in mind that the world-wide distribution of high-quality deep hydrographic data (figure 2.1) is far from satisfactory.

The deep North Pacific contains no water colder than 0.8°C, and so it is absent from the base of the Y-shape. It is the freshest of all the deep oceans, and we shall see that this relative freshness extends well up into the thermocline. It is also the most exclusive of the oceans—15 of its large-volume classes, which contain a total of  $88.9 \times 10^6 \text{ km}^3$ , are shared with no other ocean. In many more, relatively fresh, classes, the contribution from other oceans is trivial. These classes occupy the fresher side of the left-hand arm of the Y-shape (figure 2.6). In the middle of this left-hand arm it shares a number of classes (e.g., 4, 5, 9, 15, and 40) with the South Pacific, but shares virtually no deep water with any other ocean.

The coldest class that contains South Pacific water is class 84; 0.2–0.3°C, 34.70–34.71‰. This class is cosmopolitan, being found in the Southern Ocean (Pacific and Indian), the Indian Ocean, and in the South Atlantic. It is lacking in the Southern Ocean (Atlantic). Considerable amounts of South Pacific water can be found in a number of circumpolar classes (3, 24, 32, 70, 89, and 94) that lie between 0.3 and 0.8°C and between

Table 2.5 Volumes ( $\text{km}^3 \times 10^6$ ) in the Class 1.0–1.5°C, 34.6–34.7‰ According to This Census<sup>a</sup>

Potential temperature (°C)	Salinity (‰)											
1.5	34.60	34.61	34.62	34.63	34.64	34.65	34.66	34.67	34.68	34.69	34.70	
1.4			0.1	0.7	3.1	4.1	5.3	7.0	4.8	5.3		
1.3					0.5	3.0	6.1	9.8 <sup>9</sup>	5.5	3.8		
1.2						0.5	3.7	14.0 <sup>2</sup>	13.5 <sup>4</sup>	4.0		
1.1						0.1	0.5	6.0	26.0 <sup>1</sup>	12.9 <sup>5</sup>		
1.0								0.2	5.8	12.0 <sup>6</sup>		

a. Classes containing less than  $0.05 \times 10^6 \text{ km}^3$  have been omitted. Superscript numbers (1, 2, 4, 5, 6, and 9) indicate rank, by volume, in the world ocean.

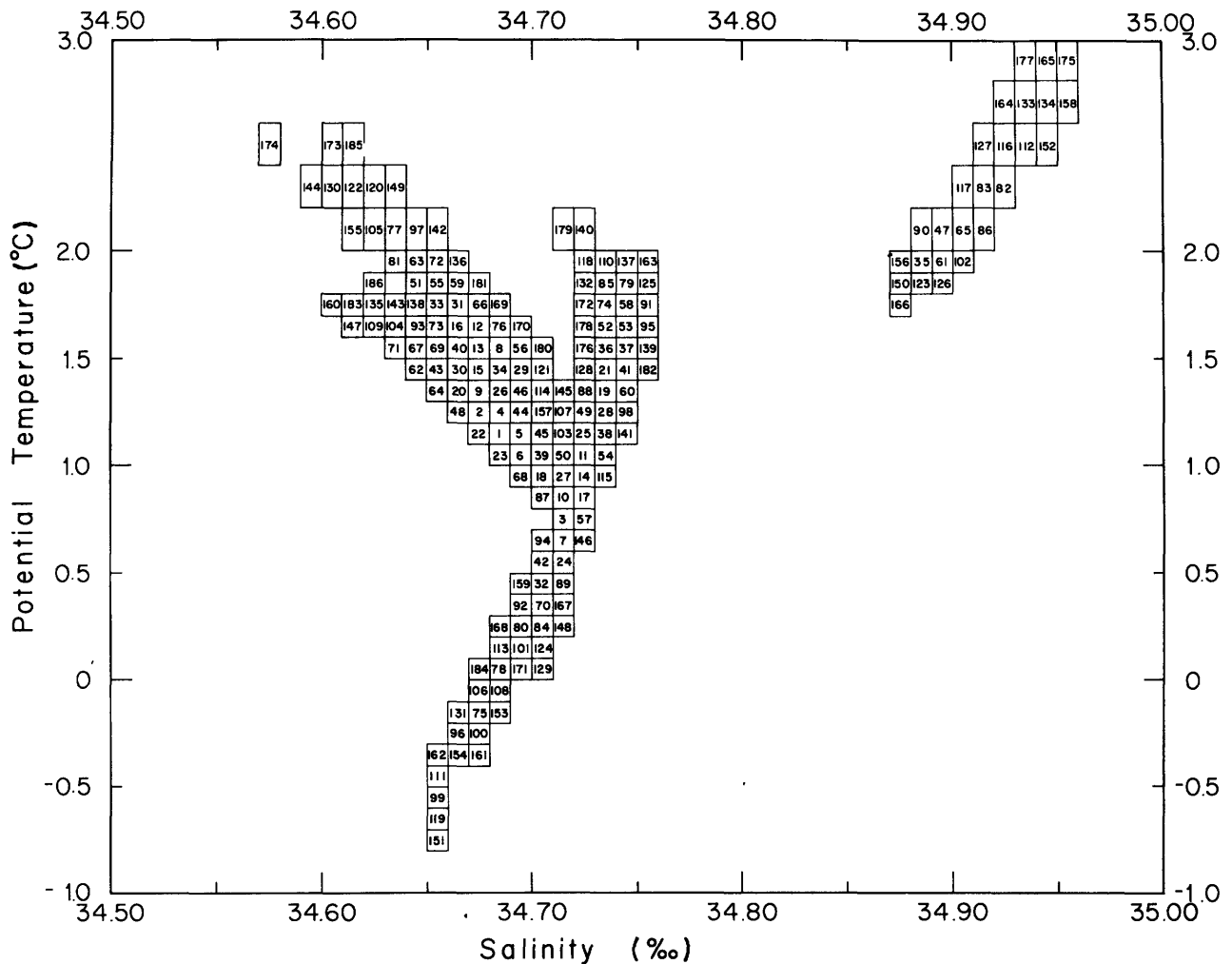


Figure 2.6 Catalog of the 186 most abundant fine-scale bivariate classes in the world ocean. These classes contain 50% of

the world-ocean volume. The number in each bivariate class represents its ranking according to volume.

34.70 and 34.72‰. These circumpolar classes comprise the warmer portions of the base of the Y-shape (figure 2.6). The bulk of South Pacific water is found on the saline side of the left-hand arm of the Y-shape; the fresher side of this arm, as we have seen, is almost wholly North Pacific water. Large amounts of more saline water in the South Pacific are found on the fresher side of the right-hand arm of the Y-shape (e.g., classes 140, 118, 132, 172, 178, 76, and 128). These classes are all shared with the Indian Ocean. They represent, typically, the saline water found by Stommel *et al.* (1973) in the western South Pacific in the *Scorpio* sections at 28°S and 43°S. This water has entered the western South Pacific from the Indian Ocean. Traces of this more saline water are present in classes 137, 79, 58, 53, 37, 41, 60, 98, and 141. These classes lie between 1.0 and 2.0°C and between 34.74 and 34.75‰. (It is also of course found in the intermediate salinity range, 34.73–34.74‰; e.g., classes 110, 85, and 79.)

By far the greater part of the right-hand arm of the Y-shape is Indian Ocean water, although traces of

South Atlantic water are found there, particularly on the saline side of the arm (e.g., classes 139, 182, 60, 98, 141, 54, and 115). Indian Ocean water (as can also be seen from figure 2.4) is represented by a nearly straight line from 2.0°C, 34.74‰ to –0.3–0.2°C, 34.66–34.68‰ (classes 154 and 161). The colder Indian Ocean classes in the base of the Y-shape are shared with the Southern Ocean classes from all the sectors.

The Atlantic Ocean *T-S* curve extends from about 3.0°C, 34.95‰ to class 166, 1.7–1.8°C, 34.87–34.88‰. All these classes (figure 2.6) are common to the North and South Atlantic; on the fresh side of the curve (e.g., classes 156, 90, 117, 127, 164, and 177), South Atlantic water predominates, and on the saline side, the North Atlantic water predominates. There are no large-volume classes that connect the Atlantic Ocean to the circumpolar oceans, but we shall see later that there is a thin group of relatively small-volume classes that does make this connection.

The coldest classes in the Southern Ocean (99, 119, and 151) belong exclusively to the Atlantic sector of

that ocean, being found in the Weddell Sea. Class 110 contains a trace of South Atlantic water (north of 55°S). Class 162 (−0.4 to −0.3°C, 34.65 to 34.66‰) is exclusively in the Atlantic sector, but the two classes found on the saline side of this class (154 and 161) contain water from the Indian Ocean sector of the Southern Ocean and the Indian Ocean itself. Surprisingly, in the temperature range −0.3 to +0.3°C, the classes that are predominantly from the Atlantic sector of the Southern Ocean (classes 96, 131, 184, and 168) are found on the fresh side of the *T-S* curve; between 0.0 and 0.1°C (classes 184, 78, 171, and 129), what one considers the “normal” situation is exactly reversed. The Pacific sector dominates the saline side of the curve and the Atlantic sector the fresh side; 93% of class 129 is in the Pacific sector of the Southern Ocean, and 70% of class 184 is in the Atlantic sector.

There is a group of classes between 0.0 and 1.7°C that are truly circumpolar, being found in *all* sectors of the Southern Ocean. The warmer end of this group (classes 176 and 178) claim a niche on the *fresh* side of the right-hand arm of the Y-shape and contain water found in all oceans except the North Atlantic and the North Pacific. These circumpolar classes represent water carried by the Antarctic Circumpolar Current.

The water masses that embrace 50% of the world ocean (when ranked in order of volume) are diverse, owing to the widely different locations in which they have been formed and, presumably, to slow changes that have taken place in these water masses since their formation as the result of mixing with their neighbors. For example, all the relatively fresh North Pacific water (figure 2.6) must have been formed near the periphery of Antarctica, but the South Pacific water masses found in the warm half of the base of the Y-shape, which intervene between the North Pacific and the Southern Ocean (Pacific), are far more saline at the present time. There is thus no connection, at present, between the circumpolar water masses and the vast volumes of deep North Pacific water. The relatively low salinity of this North Pacific deep water is probably the result of slow mixing with the even fresher waters that lie above them. We have no conception of the time scale of such a mixing process, but I would hazard a guess that it is of the order of centuries or, conceivably, millennia.

By contrast with the world ocean (figure 2.6), the North Atlantic is far less diverse; it takes 186 fine-scale classes (ranked in order of volume) to contain 50% of the world ocean (figure 2.6), but Wright and Worthington (1970) show that 50% of the North Atlantic is contained in only 43 classes, 75% in 157 classes, and 90% in 295—in spite of the fact that they identify five separate sources of deep water for the North Atlantic.

The Sea of Japan is probably the least diverse of any considerable *inland* sea (this sea has not been included

in this census, but its water masses have been tallied). The Sea of Japan contains  $1,590 \times 10^3 \text{ km}^3$ ; 50% of it is found in only three fine-scale classes, 75% in 7 classes, and 90% in 28 classes. The sea surface within the Sea of Japan is its sole source of deep and bottom water, and this is undoubtedly the cause of its homogeneity.

The process of ranking the fine-scale classes of the world ocean for this census has been carried out until 75% of its volume was classified. To carry this process out to 90% [as Wright and Worthington (1970) have done for the North Atlantic] would not only be excessively time consuming but also unjustified by the distribution of reliable deep hydrographic data (figure 2.1). The classes that make up the third quarter of the volume of the world ocean are shown in figure 2.7 (included in the pocket at the back of the book). The first half of the ocean, the classes that are ranked by number in figure 2.6, are represented by the blacked-out areas in figure 2.7. One should always remember that the volume of water represented by these blacked-out classes is *double* that of the remainder of the water represented by the numbered classes in figure 2.7; these latter classes (187–693) are also listed in the appendix. Their volume diminishes with rank from class 187 ( $975 \times 10^3 \text{ km}^3$ ) to class 693 ( $192 \times 10^3 \text{ km}^3$ ). The *pro rata* volume of class 693 is  $96 \times 10^3 \text{ km}^3$ . As the volume of these classes diminishes, their diversity increases; 50% of the world ocean is in only 186 classes, while the next 25% requires 507 classes.

The *T-S* diagram for these 507 classes (figure 2.7) again resembles a primitively drawn, lopsided Y-shape. Roughly speaking, the Pacific Ocean dominates the fresher side of the Y-shape, and the Atlantic the more saline side. Indian Ocean water is found in both arms of the Y-shape, but its greater volume is found in the center, where the base and the arms of the Y-shape are joined.

In the temperature range 0.9–3.6°C, North Pacific water dominates the fresher edge of the Y-shape. From class 332 (0.9–1.0°C, 34.68–34.69‰) to class 627 (3.4–3.6°C, 34.24–34.26‰), all classes on this edge contain at least 50% North Pacific water. In the warmer part of the fresh edge, above 3.0°C, considerable volumes of (eastern) South Pacific and South Atlantic water are found. Virtually all the classes between 3.0 and 4.0°C and between 34.30 and 34.64‰ are shared among the North Pacific, the South Pacific, the Indian Ocean, and the South Atlantic; the exceptions are classes 673 and 565 (3.0–3.2°C, 34.30–34.34‰), which contain no Indian Ocean water. These classes represent an unnamed water mass of considerable volume that lies below the Antarctic Intermediate Water and above the Antarctic Bottom Water in the South Pacific and Indian Oceans, and between the Antarctic Intermediate Water and the

North Atlantic Deep Water in the South Atlantic. They are also found south of the southern limit of North Atlantic Deep Water. In the North Pacific they fall between the North Pacific Intermediate Water and the bottom water. This unnamed water mass presumably originates south of the Antarctic Polar Front. A typical class from the middle of this group is class 573—3.4–3.6°C, 34.44–34.46‰. It contains  $594 \times 10^3 \text{ km}^3$  of water: 31% in the North Pacific; 31% in the South Pacific; 17% in the Indian Ocean; and 21% in the South Atlantic.

There are only 10 classes above 4°C that are included in the third quarter of the world-ocean volume. These 10 classes are relatively coarse scale, each of them having the equivalent area on the *T-S* diagram of 25 of the finest-scale classes (those below 2°C). The combined volume is considerable— $28,723 \times 10^3 \text{ km}^3$ ; this is slightly more than the volume of the highest-ranking class ( $25,973 \times 10^3 \text{ km}^3$ ), but the *pro rata* volume of these classes, that is, the volume contained in each  $0.1^\circ\text{C} \times 0.01\text{‰}$  bivariate fine-scale class is quite small. Class 586, the richest of these classes, contains  $3,574 \times 10^3 \text{ km}^3$ , but its *pro rata* volume is only  $143 \times 10^3 \text{ km}^3$ . Four of the saltier of these classes (586, 609, 631, and 677) are cosmopolitan, being found in all five of the major oceans, north of 55°S. These represent the Antarctic Intermediate Water, which is formed north of the South Polar Front and pushes across the equator into the North Pacific and the North Atlantic; these four classes are the only ones shared by these northern hemisphere oceans. Wright and Worthington (1970) show that none of this water penetrates north of 15°N in the North Atlantic. The South Pacific dominates the remaining five classes (688, 659, 669, 680, and 619).

The Indian Ocean occupies the center of the Y-shape (figure 2.7). The classes in the square representing the temperature range 2.0–3.0°C and the salinity range 34.70–34.80‰ are predominantly Indian Ocean classes, but in the warmer part of this square considerable volumes of South Atlantic water are present. For example, class 493 (2.6–2.8°C, 34.75–34.76‰;  $392 \times 10^3 \text{ km}^3$ ) contains 60% Indian Ocean water and 40% South Atlantic water. We have seen above that Indian Ocean water is found in nearly all the classes between 3 and 4°C and 34.30 and 34.64‰, in the left-hand arm of the Y-shape. Indian Ocean water is also found on the fresher side of the right-hand arm of the Y-shape (e.g., classes 665, 472, 676, 530, 553, 660, 516, and 657). These classes contain the most saline water found in the Indian Ocean between 3.2 and 4.0°C. This high salinity results from the contribution of saline overflow water from the Red Sea.

A closer examination of one of these classes (665) is instructive. This class contains  $436 \times 10^3 \text{ km}^3$ ; 37% of this volume is found in the Indian Ocean. Its *high*

salinity relative to the rest of that ocean is the result of the contribution from the Red Sea outflow. The North Atlantic claims 39% of this class, and examination of the atlas of Wright and Worthington (1970) reveals that 100% of this North Atlantic water ( $172 \times 10^3 \text{ km}^3$ ) is found in the Labrador Basin, where its *low* salinity is the result of the formation of Labrador Sea water, the freshest of the deep-water masses in that ocean. This illustrates how water masses of widely different origin that never connect geographically with each other can occupy the same class in the *T-S* diagram. The remaining 24% of this class is South Atlantic water that is also isolated from Red Sea water by water from the southern Indian Ocean that contains no perceptible fraction of Red Sea Outflow water.

The right-hand arm of the Y-shape (figure 2.7) is composed entirely of Atlantic water except for the few Indian Ocean classes that have just been discussed. As one would expect, the North Atlantic dominates the more saline side of this arm and the South Atlantic the fresher side. The coldest class in figure 2.7 that contains South Atlantic water is class 555 (0.0–0.1°C, 34.66–34.67‰). We have seen, however, that in the first 50% of the ocean (figure 2.6) traces of South Atlantic water colder than  $-0.4^\circ\text{C}$  can be found.

The Atlantic *T-S* diagram extends from the coldest water in the Southern Ocean sector (classes 272 and 247) in a more-or-less straight line through the South Atlantic classes up to the large classes shown by the more saline blacked-out area (figure 2.7) that represents the North Atlantic Deep Water. All water on this curve is usually named the Antarctic Bottom Water. The warmest classes on this part of the *T-S* curve, those between 1.3 and 1.7°C, are common to the North and South Atlantic; the more saline of these warmer classes are found in the North Atlantic, and the fresher classes in the South Atlantic. Traces of Antarctic Bottom water as cold as 0.6°C (class 286: 0.6–0.7°C, 34.75–34.76‰) can be found in the North Atlantic, but these traces do not enter the deep North American Basin, according to Worthington and Wright (1970), but remain close to the equator. No classes in the Southern Ocean (Atlantic) can be traced to the North Atlantic. The “Antarctic Bottom Water” classes that are found in the North Atlantic are composed chiefly of the North Atlantic Deep Water with a very small amount of *true* Antarctic Bottom water mixed in. In other words, no “Antarctic Bottom Water” in the North Atlantic can be traced, unchanged, to its point of origin in the Weddell Sea. On the other hand, many North Atlantic Deep Water classes can be traced, unchanged, from their origin as overflow water from the Norwegian Sea all the way down into the South Atlantic. This argues either for a more rapid production rate for the North Atlantic Deep Water or (if production of both water masses is equal) for a higher mixing rate

along the  $T$ - $S$  curve that represents the Antarctic Bottom Water.

In the Southern Ocean, the extended classification of figure 2.7 includes a number of classes not represented in figure 2.6. These less abundant classes confirm the curious fact that the "normal" distribution of salinity is reversed; the Atlantic sector of the Southern Ocean contains the freshest water (e.g., class 316:  $-0.3$ – $-0.2^{\circ}\text{C}$ ,  $34.65$ – $34.66\text{‰}$ ) and the Pacific sector the most saline (e.g., class 513:  $-0.3$ – $-0.2^{\circ}\text{C}$ ,  $34.71$ – $34.72\text{‰}$ ).

In general, expanding the description from 50% to 75% of the ocean results in the addition of few cold, deep classes, compared to the greater number of warmer classes. I believe that if we all made perfect observations of temperature and salinity, the number of deep classes would be even fewer than those listed in the appendix. The ocean is probably more finely stratified than we can observe at the present time.

One is tempted to play endless games with figures 2.6 and 2.7 and the appendix, and the reader is, of course, invited to do so, but, again, he should bear in mind that the coverage (figure 2.1) is really quite poor and the real rankings may be somewhat different from those listed in the appendix.

In order that the less abundant classes should not be wholly slighted, figures 2.8 and 2.9 have been constructed. These are contoured volumetric  $T$ - $S$  diagrams for the cold water ( $<4^{\circ}\text{C}$ ), and the thermocline and warm water ( $>4^{\circ}\text{C}$ ), respectively. The crosshatched area ( $<4^{\circ}\text{C}$ ) attached to the warm-water diagram (figure 2.9) encloses the cold water that is contoured in detail in figure 2.8. Each contour represents the volume in  $\text{km}^3 \times 10^3$  that is found in each  $0.1^{\circ}\text{C} \times 0.01\text{‰}$  class, and the contours mapped are  $2^n \times 10^5 \text{ km}^3$ , where  $n = -2, -1, 0, 1, 2, \dots, 8$ ; this last contour contains only the winning class from the North Pacific. Contours of  $5$  and  $10 \times 10^3 \text{ km}^3$  have been added in figure 2.9 because otherwise the thermocline and warm-water masses of the oceans would scarcely appear at all.

For example, the  $5 \times 10^3\text{-km}^3$  contour in the upper right-hand corner of figure 2.9 contains two classes that comprise the  $18^{\circ}$  Water in the North Atlantic (Worthington, 1959). These classes are  $17$ – $18^{\circ}\text{C}$ ,  $36.4$ – $36.5\text{‰}$ ,  $827 \times 10^3 \text{ km}^3$ , and  $18$ – $19^{\circ}\text{C}$ ,  $36.5$ – $36.6\text{‰}$ ,  $556 \times 10^3 \text{ km}^3$ ; there are 100 fine-scale classes in each of these relatively coarse-scale warm-water classes, so the *pro rata* volumes of these two classes are  $8.3 \times 10^3$  and  $5.6 \times 10^3 \text{ km}^3$ , respectively.

The analogy between these figures and a physical relief map is difficult to avoid because the dominant water masses in this presentation (and in figures 2.2–2.5) resemble mountain ranges. The highest of these ranges (below  $34.8\text{‰}$ ) is roughly Y-shaped. The left-hand branch of the Y-shape is composed predominantly of Pacific water (in which the highest peak is found),

and the right-hand branch of the Y-shape contains mostly South Pacific and Indian Ocean water. The far lower range centered on  $2.0^{\circ}\text{C}$ ,  $34.89\text{‰}$  is the Atlantic. The highest peak in this range contains only  $4659 \times 10^3 \text{ km}^3$ . The warmer extensions of these ranges fall off rapidly into what might be analogous to a coastal peneplain—however, no prominent monadnocks appear. An isolated elevation of  $100 \times 10^3 \text{ km}^3$  per class occurs near  $6^{\circ}\text{C}$ ,  $34.35\text{‰}$ . This represents part of the Subantarctic Mode Water described by McCartney (1977). The warm extension of this elevation ( $>50 \times 10^3 \text{ km}^3$  per class) toward the northeast also consists of Subantarctic Mode Water, mostly in the South Pacific and in the Indian Ocean.

The warmest water ( $>10^{\circ}\text{C}$ ) is divided into three low prongs. The freshest of these prongs consists principally of North Pacific water, but there is a considerable contribution from the eastern South Pacific. The central prong is cosmopolitan—it contains water formed in the subtropical convergences of the southern hemisphere. The saline side of the central prong consists principally of South Atlantic and Indian Ocean water, but a considerable volume was found in the Guiana and Guinea Basins of the North Atlantic by Wright and Worthington (1970). In the center of the central prong, South Atlantic, South Pacific, and Indian Ocean waters are found in roughly equal proportions. On the fresh side of the central prong, South Pacific water predominates, but there is a considerable volume of water from the subtropical North Pacific. The saline prong is composed of Western North Atlantic Water, but in temperature intervals below  $13^{\circ}\text{C}$  the Red Sea water in the Indian Ocean claims a significant proportion of the water ( $>25\%$ ).

The contour of  $5 \times 10^3 \text{ km}^3$  per class encloses two warm islands isolated from the main prongs; one of these, an extension of the saline prong, comprises the  $18^{\circ}$  Water in the North Atlantic, as we have seen. The other, an extension of the central prong, is composed mainly of South Pacific water. This one is probably artificial because much of the surface mixed layer on the western half of the *Scorpio* section at  $28^{\circ}\text{S}$  was between  $19$  and  $20^{\circ}\text{C}$  and between  $35.6$  and  $35.8\text{‰}$ , according to Stommel et al. (1973, plates 1 and 2). Undue weight was given to this section on account of the shortage of other high-precision hydrographic data in the South Pacific.

The thermocline and warm water-mass parts of this census, as they are illustrated here (figure 2.9), are merely a sketch, and no really reliable quantitative estimates of the volumes of these water masses in the world ocean exist. The reader is referred to Wyrтки's (1971, pp. 526–527) admirable volumetric diagrams for the Indian Ocean and to those of Wright and Worthington (1970) for the North Atlantic. For the other oceans, the warm-water diagrams (coarse scale) of Montgomery

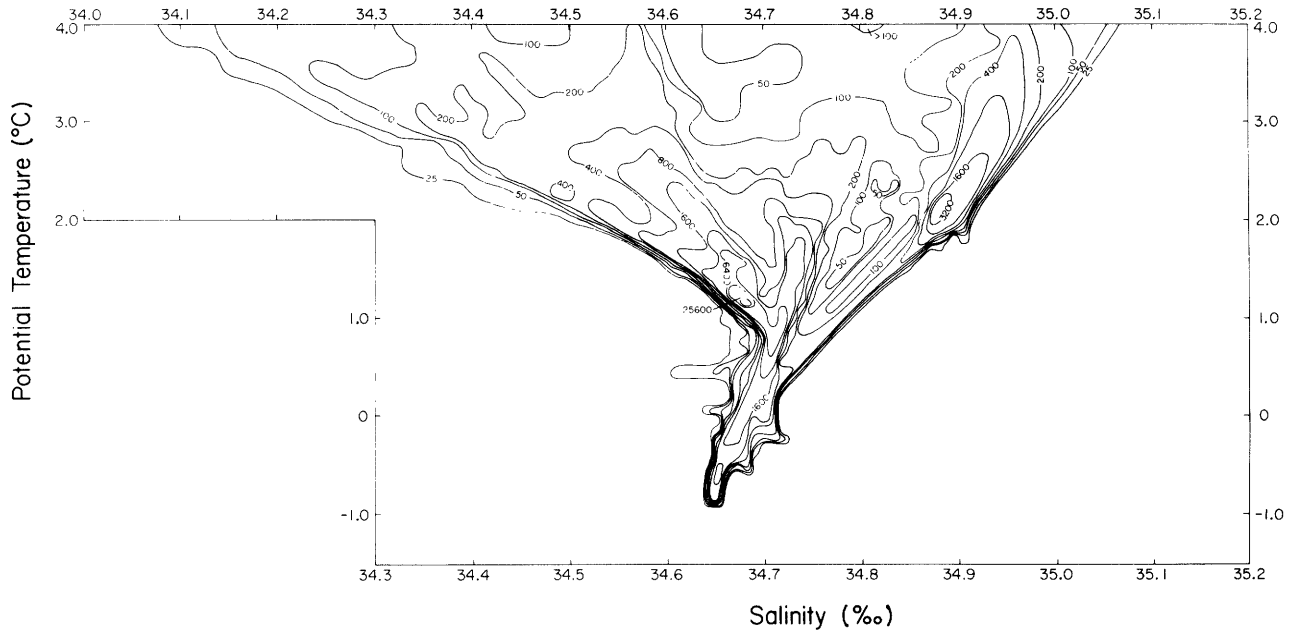


Figure 2.8 Contoured volumetric  $T$ - $S$  diagram for the cold ( $<4^{\circ}\text{C}$ ) water in the world ocean. The values are volumes ( $\text{km}^3 \times 10^3$ ) that are found in each class of  $0.1^{\circ}\text{C} \times 0.01\text{‰}$ .

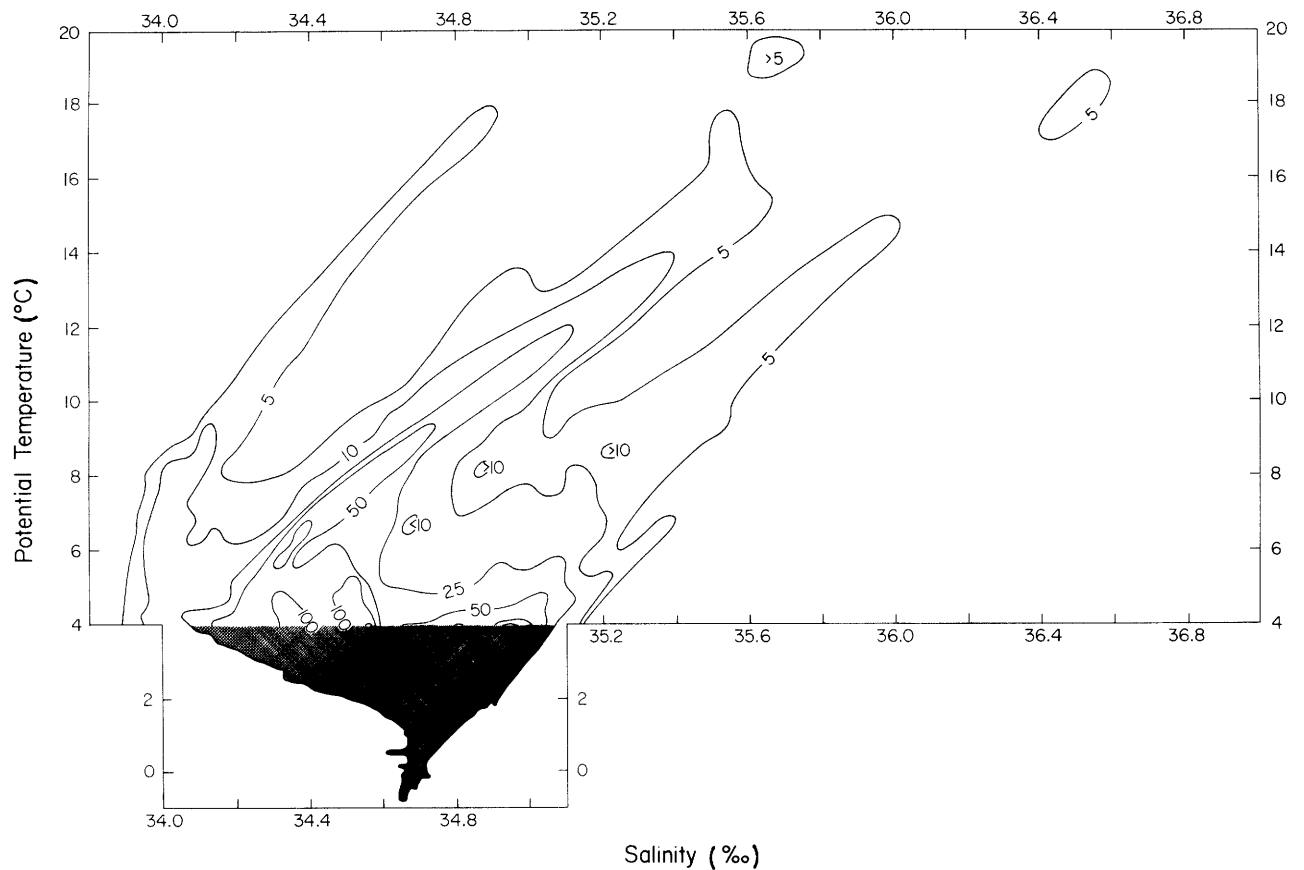


Figure 2.9 Contoured volumetric  $T$ - $S$  diagram for the thermocline ( $>4^{\circ}\text{C}$ ) and warm ( $>16^{\circ}\text{C}$ ) waters of the world ocean. The values are the volumes ( $\text{km}^3 \times 10^3$ ) that are found in each class of  $0.1^{\circ}\text{C} \times 0.01\text{‰}$ . Shaded area encloses the cold-water classes that appear in figure 2.8.

(1958), Cochrane (1958), and Pollak (1958) still stand, but I believe that their classes are too large. One can see that by merging the present classes into divisions as large as 0.5‰ of salinity, as Cochrane and Pollak have done, or 1.0‰, as Montgomery has done, the high-volume warm prongs (figure 2.9) would be artificially blurred and merged with one another.

One or two colleagues have asked whether I could not use a logarithmic volume scale in such presentations as figures 2.2-2.5 so that the warm water masses (if included) could be made to stand out more clearly, but one of the principal virtues of the volumetric *T-S* diagram is that it displays the relative abundances of the water masses as they actually exist. The *concentration* of water in the most abundant North Pacific class exceeds that in the warm-water prongs (shown in figure 2.9) by a ratio of about 25,973 to 10 or less. This is analogous to comparing the elevation of Mount Everest to that of Water Street, Woods Hole, near the original building of the Woods Hole Oceanographic Institution. In fact, if we were able to sample and measure salinity more perfectly, the apparent elevations shown in the deep water in figure 2.8 would probably be even higher.

The feelings I have about the census are compounded equally of fascination and frustration. The frustration is the result of the decrease in the rate of acquisition of new high-quality data. This decrease is due in part to the trends in modern physical oceanography in which the dramatic improvements in direct current measurements have understandably taken priority over routine measurements of water properties on a large scale. It is also clear that there is a long delay (as much as 5 years) between the time hydrographic data are obtained at sea and the time these data become available on tape from the National Oceanographic Data Center (in part because some investigators take a long time to turn their data in to the Data Center). I have been reluctant to obtain new data informally, from friendly colleagues, however, because I do not think that the Data Center should be bypassed at present; its function would be impaired if data were only exchanged between a cabal of skilled observers.

The fascination results from the precise but peculiar way in which the water masses of the oceans are arranged—particularly the deep water masses that make up the greater part of the oceans. Why, for instance, are the big, exclusive North Pacific classes fresher than existing circumpolar and South Pacific waters? Are they fossil water masses that were formed in some past millennium when the oceans were somewhat fresher, or are they still undergoing a change toward the fresher as the result of slow vertical mixing (across density surfaces) with the still fresher water that lies above them at the present time? I do not think that we can supply answers to such questions at present, and an-

swers will not be available even in the future without painstaking observations. There are indications this style of observations may be coming back into vogue. The authorless Scripps data report of the INDOPAC expedition (Scripps Institution of Oceanography Reference: 78-21) is an excellent example. It should be worthwhile to reactivate this census (which was closed as of June 1977) when more high-quality data of this kind are available from NODC, and I shall probably propose to do so at some time in the future.

## 2.4 The Formation of Water Masses

There is only one hypothesis about water-mass formation that is universally agreed upon, that is, that the cold, dense water that fills the great ocean basins has been formed at high latitudes. The manner in which the thermocline-halocline is formed is under dispute, and there are almost as many notions of the *rate* at which all the various water masses are formed as there are investigators.

Given the extraordinary regularity of the *T-S* curves that are found in much of the oceans, it is natural to assume that these curves are the result of vertical mixing between two end water masses. Very simply stated, this assumption implies that the bottom water (as all agree) has been formed at high latitudes, that the surface water at middle and low latitudes has received its *T-S* characteristics from the atmosphere by the uneven processes of evaporation and heating, and that the remainder of the water column is a mixture of surface and bottom water. Wüst (1935) clearly recognized that this was an oversimplification, and his use of the “core-layer” method reflects his conviction that different water masses can be traced to a small number of more-or-less point sources at the sea surface over a wide range of latitude.

The notion that *all* the thermocline water masses can be traced to the sea surface is generally attributed to Iselin (1939a). He constructed a *T-S* diagram from winter observations at the surface of the western North Atlantic, and found that it corresponded closely to the *T-S* diagram obtained from a typical hydrographic station in that ocean. It is worth noting that Wüst (1935, p. 3) anticipated Iselin (in the South Atlantic) by 4 years. He wrote, “The vertical structure of the Subantarctic Intermediate Water, with its horizontal spreading at depths, is analogous to a vertical figure of the horizontal arrangement of temperature and salinity at the surface of the formation region.” Wüst did not dwell on this subject further, and it is clear that he regarded core layers as more important as indices of ocean circulation.

In his 1939a paper, Iselin stressed “lateral mixing” as responsible for the *T-S* curve in the western North Atlantic. Sverdrup, in chapter XV of *The Oceans* (Sver-