Water Types and Water Masses

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Introduction

Much of what is known today about the currents of the deep ocean has been inferred from studies of the water properties such as temperature, salinity, dissolved oxygen, and nutrients. These are quantities that can be observed with standard hydrographic measurement techniques which collect temperatures and samples of water with a number of sampling bottles strung along a wire to provide the depth resolution needed. Salinity or 'salt content' is then measured by an analysis of the water sample, which combined with the corresponding temperature value at that 'bottle' sample yields temperature and salinity as a function of depth of the sample. Modern observational methods have in part replaced this sample bottle method with electronic profiling systems, at least for temperature and salinity, but many of the important descriptive quantities such as oxygen and nutrients still require bottle samples accomplished today with a 'rosette' sampler integrated with the electronic profiling systems. These new electronic profiling systems have been in use for over 30 years, but still the majority of data useful for studying the properties of the deep and open ocean come from the time before the advent of modern electronic profiling system. This knowledge is important in the interpretation of the data since the measurements from sampling bottles have very different error characteristics than those from modern electronic profiling systems.

This article reviews the mean properties of the open ocean, concentrating on the distributions of the major water masses and their relationships to the currents of the ocean. Most of this information is taken from published material, including the few papers that directly address water mass structure, along with the many atlases that seek to describe the distribution of water masses in the ocean. Coincident with the shift from bottle sampling to electronic profiling is the shift from publishing information about water masses and ocean currents in large atlases to the more routine research paper. In these papers the water mass characteristics are generally only a small portion, requiring the interested descriptive oceanographer to go to considerable trouble to extract the information he or she may be interested in. While water mass distributions play a role in many of today's oceanographic problems, there is very little research directed at improving our knowledge of water mass distributions and their changes over time.

What is a Water Mass?

The concept of a 'water mass' is borrowed from meteorology, which classifies different atmospheric characteristics as 'air masses'. In the early part of the twentieth century physical oceanographers also sought to borrow another meteorological concept separating the ocean waters into 'warm' and 'cold' water spheres. This designation has not survived in modern physical oceanography but the more general concept of water masses persists. Some oceanographers regard these as real, objective physical entities, building blocks from which the oceanic stratification (vertical structure) is constructed. At the opposite extreme, other oceanographers consider water masses to be mainly descriptive words, summary shorthand for pointing to prominent features in property distributions.

The concept adopted for this discussion is squarely in the middle, identifying some 'core' water mass properties that are the building blocks. In most parts of the ocean the stratification is defined by mixing in both vertical and horizontal orientations of the various water masses that advect into the location. Thus, in the maps of the various water mass distributions a 'formation region' is identified where it is believed that the core water mass has acquired its basic characteristics at the surface of the ocean. This introduces a fundamental concept first discussed by Iselin (1939), who suggested that the properties of the various subsurface water masses were originally formed at the surface in the source region of that particular water mass. Since temperature and salinity are considered to be 'conservative properties' (property is only changed at the sea surface), these characteristics would slowly erode as the water properties were advected at depth to various parts of the ocean.

Descriptive Tools: The TS Curve

Before focusing on the global distribution of water masses, it is appropriate to introduce some of the basic tools used to describe these masses. One of the most basic tools is the use of property versus property plots to summarize an analysis by making extrema easy to locate. The most popular of these is the

temperature–salinity or TS diagram, which relates density to the observed values of temperature and salinity. Originally the TS curve was constructed for a single hydrographic cast and thus related the TS values collected for a single bottle sample with the salinity computed from that sample. In this way there was a direct relationship between the TS pair and the depth of the sample. As the historical hydrographic record expanded it became possible to compute TS curves from a combination of various temperature–salinity profiles. This approach amounted to plotting the TS curve as a scatter diagram (**Figure 1**) where the salinity values were then averaged over a selected temperature interval to generate a discrete TS curve. The TS curve

shown in **Figure 1**, which is an average of all of the data in a 10° square just north east of Hawaii, shows features typical of those that can be found in all TS curves. As it turned out the temperature–salinity pair remained the same while the depth of this pair oscillated vertically by tens of meters, resulting in the absence of a precise relationship between TS pairs and depth. As sensed either by 'bottle casts' or by electronic profilers, these vertical variations express themselves as increased variability in the temperature or salinity profiles while the TS curve continues to retain its shape, now independent of depth. Hence a composite TS curve computed from a number of closely spaced hydrographic stations no longer has a
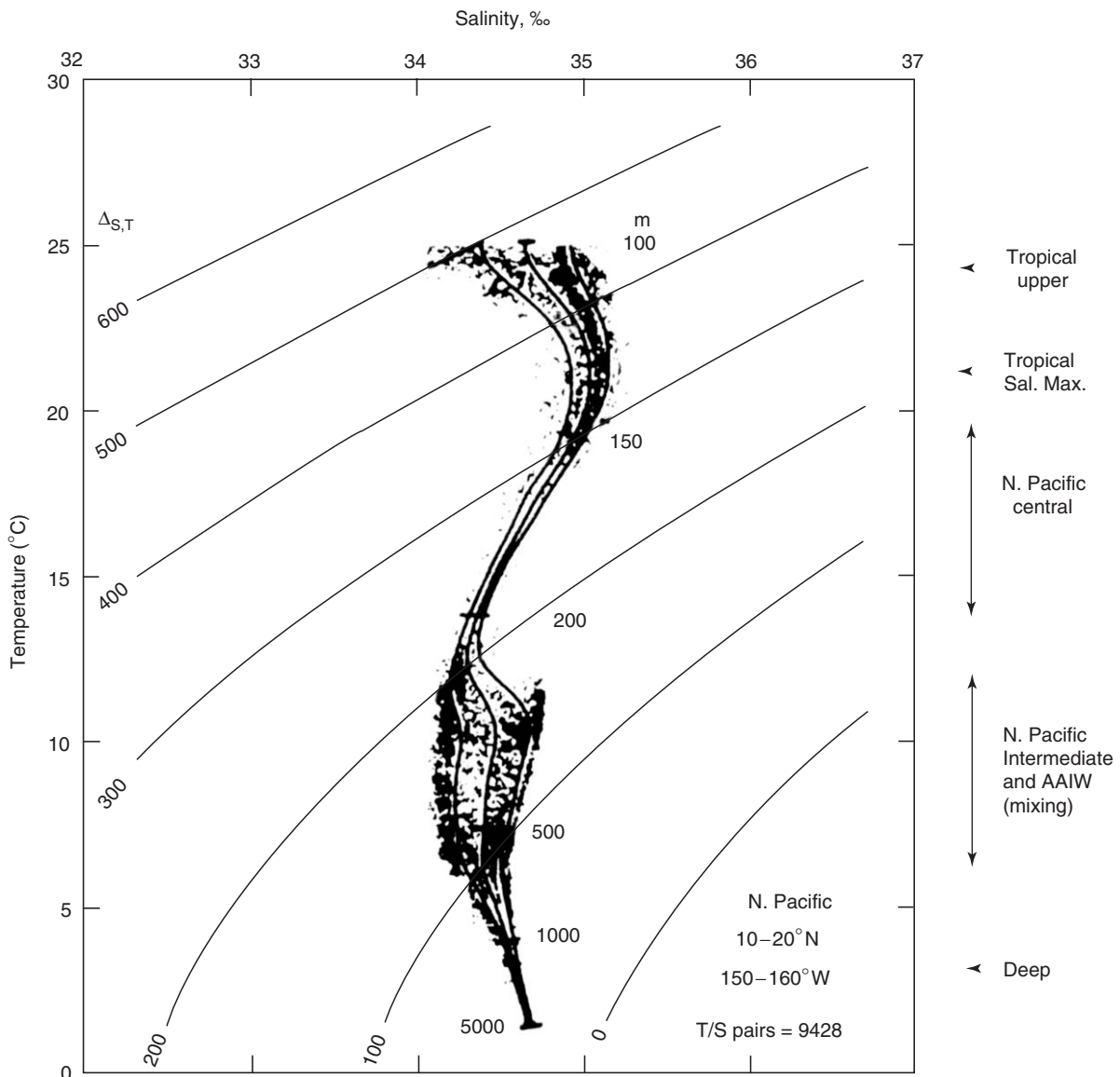

Figure 1   Example of TS 'scatter plot' for all data within a 10°square with mean TS curve (center line) and curves for one standard deviation in salinity on either side.

specific relationship between temperature, salinity and depth.

As with the more traditional 'single station' TS curve, these area average TS curves can be used to define and locate water masses. This is done by locating extrema in salinity associated with particular water masses. The salinity minimum in the TS curve of **Figure 1** is at about 10°C, where there is a clear divergence of TS values as they move up the temperature scale from the coldest temperatures near the bottom of the diagram. There are two separate clusters of points at this salinity minimum temperature with one terminating at about 13°C and the other transitioning on up to the warmest temperatures. It is this termination of points that results in a sharp turn in the mean TS curve and causes a very wide standard deviation. These two clusters of points represent two different intermediate level water masses. The relatively high salinity values that appear to terminate at 13°C represent the Antarctic Intermediate Water (AIW) formed near the Antarctic continent, reaching its northern terminus after flowing up from the south. The coincident less salty points indicate the presence of North Pacific Intermediate Water moving south from its formation region in the northern Gulf of Alaska.

While there is no accepted practice in water mass terminology, it is generally accepted that a 'water type' refers to a single point on a characteristic diagram such as a TS curve. As introduced above, 'water mass' refers to some portion or segment of the characteristic curve, which describes the 'core properties' of that water mass. In the above example the salinity characteristics of the two intermediate waters were salinity minima, which were the overall characteristic of the two intermediate waters. We note that the extrema associated with a particular water mass may not remain at the same salinity value. Instead, as one moves away from the formation zone for the AIW, which is at the oceanographic 'polar front', the sharp minimum that marks the AIW water which has sunk from the surface down to about 1000 m starts to erode, broadening the salinity minimum and slowly increasing its magnitude. By comparing conditions of the salinity extreme at a location with salinity characteristics typical of the formation region one can estimate the amount of the source water mass that is still present at the distant location. Called the 'core-layer' method, this procedure was a crucial development in the early study of the ocean water masses and long-term mean currents.

Many variants of the TS curve have been introduced over the years. One particularly instructive form was a 'volumetric TS curve'. Here the oceanographer subjectively decides just how much volume is associated with a particular water mass. This becomes a three-dimensional relationship, which can then be plotted in a perspective format (**Figure 2**). In this plot the two horizontal axes are the usual temperature and salinity, while the elevation represents the volumes with those particular TS characteristics. For this presentation, only the deeper water mass characteristics have been plotted, which can be seen by the restriction of the temperature scale to −1.0°C to 4.0°C. Arrows have been added to show just which parts of the ocean various features have come from. That the Atlantic is the saltiest of the oceans is very clear with a branch to high salinity values at higher temperatures. The most voluminous water mass is the Pacific Deep Water that fills most of the Pacific below the intermediate waters at about 1000 m.

Global Water Mass Distribution

Before turning to the TS curve description of the water masses, it is necessary to indicate the geographic distribution of the basic water masses. The reader is cautioned that this article only treats the major water masses, which most oceanographers accept and agree upon. If a particular region is of interest close inspection will reveal a great variety of smaller water mass classifications; these can be almost infinite, as higher resolution is obtained in both horizontal and vertical coverage.

Table 1 presents the TS characteristics of the world's water masses. In the table are listed the area name, the corresponding acronym, and the appropriate temperature and salinity range. Recall that the property extreme erodes moving away from the source region, so it is necessary to define a range of properties. This is also consistent with the view that a water mass refers to a segment of the TS curve rather than a single point.

As is traditionally the case, the water masses have been divided into deep and abyssal waters, intermediate waters, and upper waters. While the upper waters have the largest property ranges, physically they occupy the least amount of ocean volume. The reverse is true of the deep and bottom waters, which have a fairly restricted range but occupy a substantial portion of the ocean. Since most ocean water mass properties are established at the ocean's surface, those water masses which spend most of their time isolated far from the surface will erode the least and have the longest lifetime. Surface waters, on the other hand, are strongly influenced by fluctuations at the ocean surface, which rapidly erodes the water mass properties. In mean TS curves, as in **Figure 1**, the spread of the standard deviation at the highest temperatures reflect this influence from the heat and fresh water flux exchange that occurs near and at the ocean's surface.
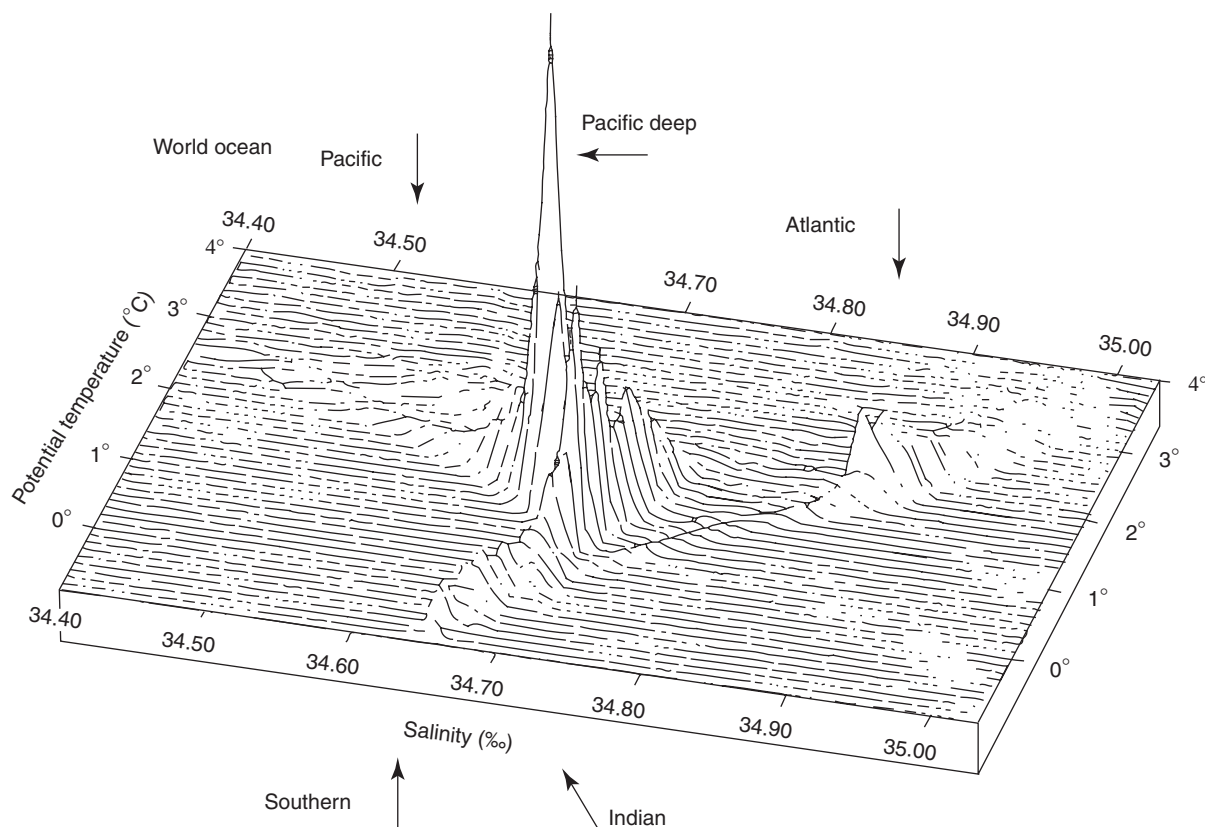
Figure 2   Simulated three-dimensional T–S–V diagram for the cold water masses of the World Ocean.

Accompanying the table are global maps of water masses at all three of these levels. The upper waters in **Figure 3** have the most complex distribution with significant meridional and zonal changes. A 'best guess' at the formation regions for the corresponding water mass is indicated by the hatched regions. For its relatively small size, the Indian Ocean has a very complex upper water mass structure. This is caused by some unique geographic conditions. First is the monsoon, which completely changes the wind patterns twice a year. This causes reversals in ocean currents, which also influence the water masses by altering the contributions of the very saline Arabian Gulf and the fresh Bay of Bengal into the main body of the Indian Ocean. All of the major rivers in India flow to the east and discharge into the Bay of Bengal, making it a very fresh body of ocean water. To the west of the Indian subcontinent is the Arabian Sea with its connection to the Persian Gulf and the Red Sea, both locations of extremely salty water, making the west side of India very salty and the east side very fresh. The other upper ocean water masses in the Indian Ocean are those associated with the Antarctic Circumpolar Current (ACC), which are found at all of the longitudes in the Southern Ocean.

As the largest ocean basin, the Pacific has the strongest east–west variations in upper water masses, with east and west central waters in both the north and south hemispheres. Unique to the Pacific is the fairly wide band of the Pacific Equatorial Water, which is strongly linked to the equatorial upwelling, which may not exist in El Niño years. None of the other two ocean basins have this equatorial water mass in the upper ocean. The Atlantic has northern hemisphere upper water masses that can be separated east–west while the South Atlantic upper water mass cannot be separated east–west into two parts. Note the interaction between the North Atlantic and the Arctic Ocean through the Norwegian Sea and Fram Strait. Also in these locations are found the source regions for a number of Atlantic water masses. Compared with the other two oceans, the Atlantic has the most water mass source regions, which produce a large part of the deep and bottom waters of the world ocean.

The chart of intermediate water masses in **Figure 4** is much simpler than was the upper ocean water masses in **Figure 3**. This reflects the fact that there are far fewer intermediate waters and those that are present fill large volumes of the intermediate depth ocean. The North Atlantic has the most complex horizontal structure of

Table 1 Temperature–salinity characteristics of the world's water masses

Layer	Atlantic Ocean	Indian Ocean	Pacific Ocean
Upper waters (0–500 m)	Atlantic Subarctic Upper Water (ASUW) (0.0–4.0°C, 34.0–35.0‰) Western North Atlantic Central Water (WNACW) (7.0–20.0°C, 35.0–36.7‰) Eastern North Atlantic Central Water (ENACW) (8.0–18.0°C, 35.2–36.7‰) South Atlantic Central Water (SACW) (5.0–18.0°C, 34.3–35.8‰)	Bengal Bay Water (BBW) (25.0–29°C, 28.0–35.0‰) Arabian Sea Water (ASW) (24.0–30.0°C, 35.5–36.8‰) Indian Equatorial Water (IEW) (8.0–23.0°C, 34.6–35.0‰) Indonesian Upper Water (IUW) (8.0–23.0°C, 34.4–35.0‰) South Indian Central Water (SICW) (8.0–25.0°C, 34.6–35.8‰)	Pacific Subarctic Upper Water (PSUW) (3.0–15.0°C, 32.6–33.6‰) Western North Pacific Central Water (WNPCW) (10.0–22.0°C, 34.2–35.2‰) Eastern North Pacific Central Water (ENPCW) (12.0–20.0°C, 34.2–35.0‰) Eastern North Pacific Transition Water (ENPTW) (11.0–20.0°C, 33.8–34.3‰) Pacific Equatorial Water (PEW) (7.0–23.0°C, 34.5–36.0‰) Western South Pacific Central Water (WSPCW) (6.0–22.0°C, 34.5–35.8‰) Eastern South Pacific Central Water (ESPCW) (8.0–24.0°C, 34.4–36.4‰) Eastern South Pacific Transition Water (ESPTW) (14.0–20.0°C, 34.6–35.2‰)
Intermediate waters (500–1500 m)	Western Atlantic Subarctic Intermediate Water (WASIW) (3.0–9.0°C, 34.0–35.1‰) Eastern Atlantic Subarctic Intermediate Water (EASIW) (3.0–9.0°C, 34.4–35.3‰) Antarctic Intermediate Water (AAIW) (2–6°C, 33.8–34.8‰) Mediterranean Water (MW) (2.6–11.0°C, 35.0–36.2‰) Arctic Intermediate Water (AIW) (−1.5–3.0°C, 34.7–34.9‰)	Antarctic Intermediate Water (AAIW) (2–10°C, 33.8–34.8‰) Indonesian Intermediate Water (IIW) (3.5–5.5°C, 34.6–34.7‰) Red Sea–Persian Gulf Intermediate Water (RSPGIW) (5–14°C, 34.8–35.4‰)	Pacific Subarctic Intermediate Water (PSIW) (5.0–12.0°C, 33.8–34.3‰) California Intermediate Water (CIW) (10.0–12.0°C, 33.9–34.4‰) Eastern South Pacific Intermediate Water (ESPIW) (10.0–12.0°C, 34.0–34.4‰) Antarctic Intermediate Water (AAIW) (2–10°C, 33.8–34.5‰)
Deep and abyssal waters (1500 m-bottom)	North Atlantic Deep Water (NADW) (1.5–4.0°C, 34.8–35.0‰) Antarctic Bottom Water (AABW) (−0.9–1.7°C, 34.64–34.72‰) Arctic Bottom Water (ABW) (−1.8 to −10.5°C, 34.88–34.94‰)	Circumpolar Deep Water (CDW) (1.0–2.0°C, 34.62–34.73‰)	Circumpolar Deep Water (CDW) (0.1–2.0°C, 34.62–34.73‰)
		Circumpolar Surface Waters	Subantarctic Surface Water (SASW) (3.2–15.0°C, 34.0–35.5‰) Antarctic Surface Water (AASW) (−1.0–1.0°C, 34.0–34.6‰)

the three oceans. Here intermediate waters form at the source regions in the northern North Atlantic. One exception is the Mediterranean Intermediate Water, which is a consequence of climatic conditions in the Mediterranean Sea. This salty water flows out through the Straits of Gibraltar at about 320 m depth, where it then descends to at least 1000 m, and maybe a bit more. It now sinks below the vertical range of the less saline Antarctic Intermediate Water (AAIW), instead joining with the higher salinity of the deeper North Atlantic Deep Water (NADW), which maintains the salinity maximum indicative of the NADW.

In the Southern Ocean the formation region for the AAIW is marked as the location of the oceanic Polar
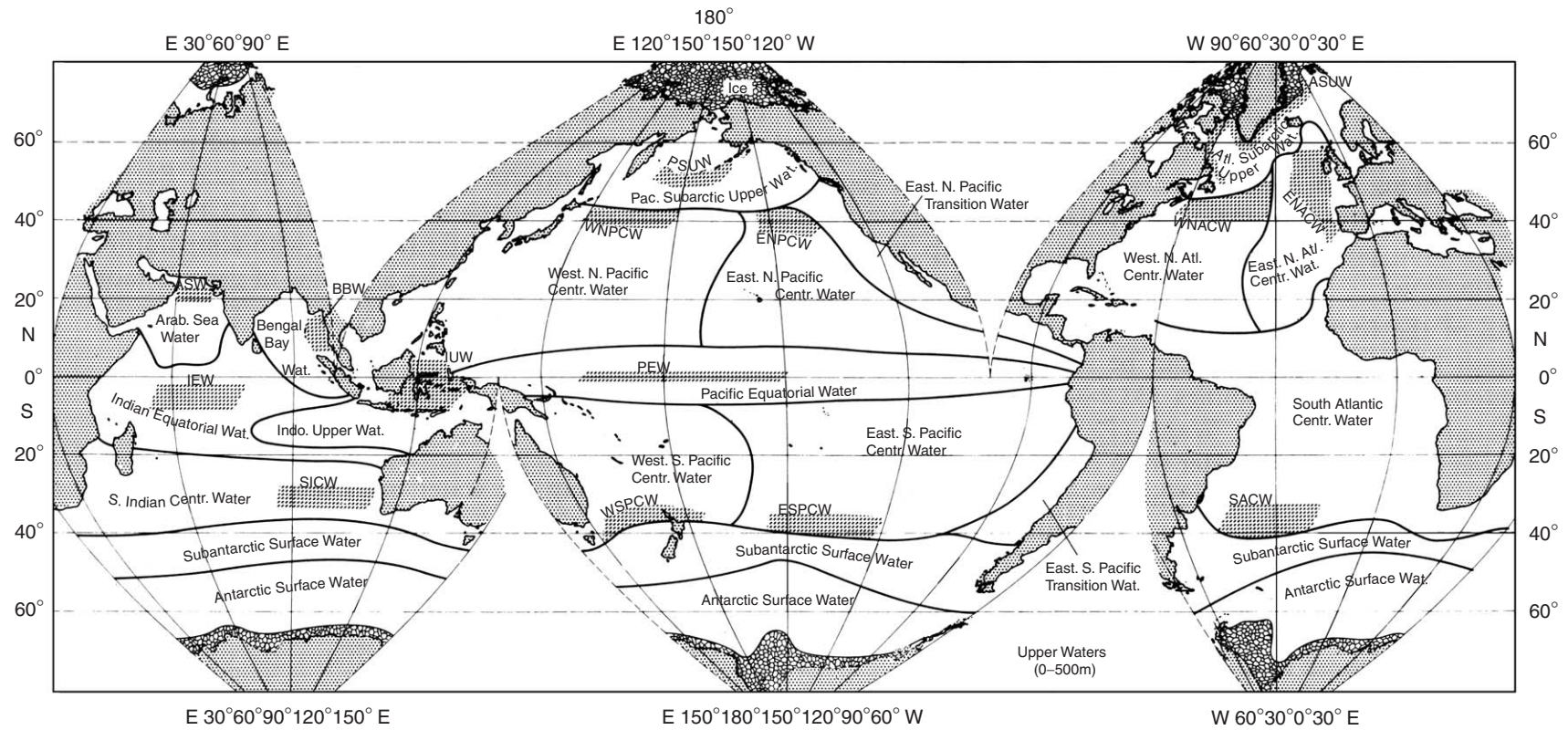
Figure 3 Global distribution of upper waters (0–500 m). Water masses are in abbreviated form with their boundaries indicated by solid lines. Formation regions for these water masses are marked by cross-hatching and labelled with the corresponding acronym title.
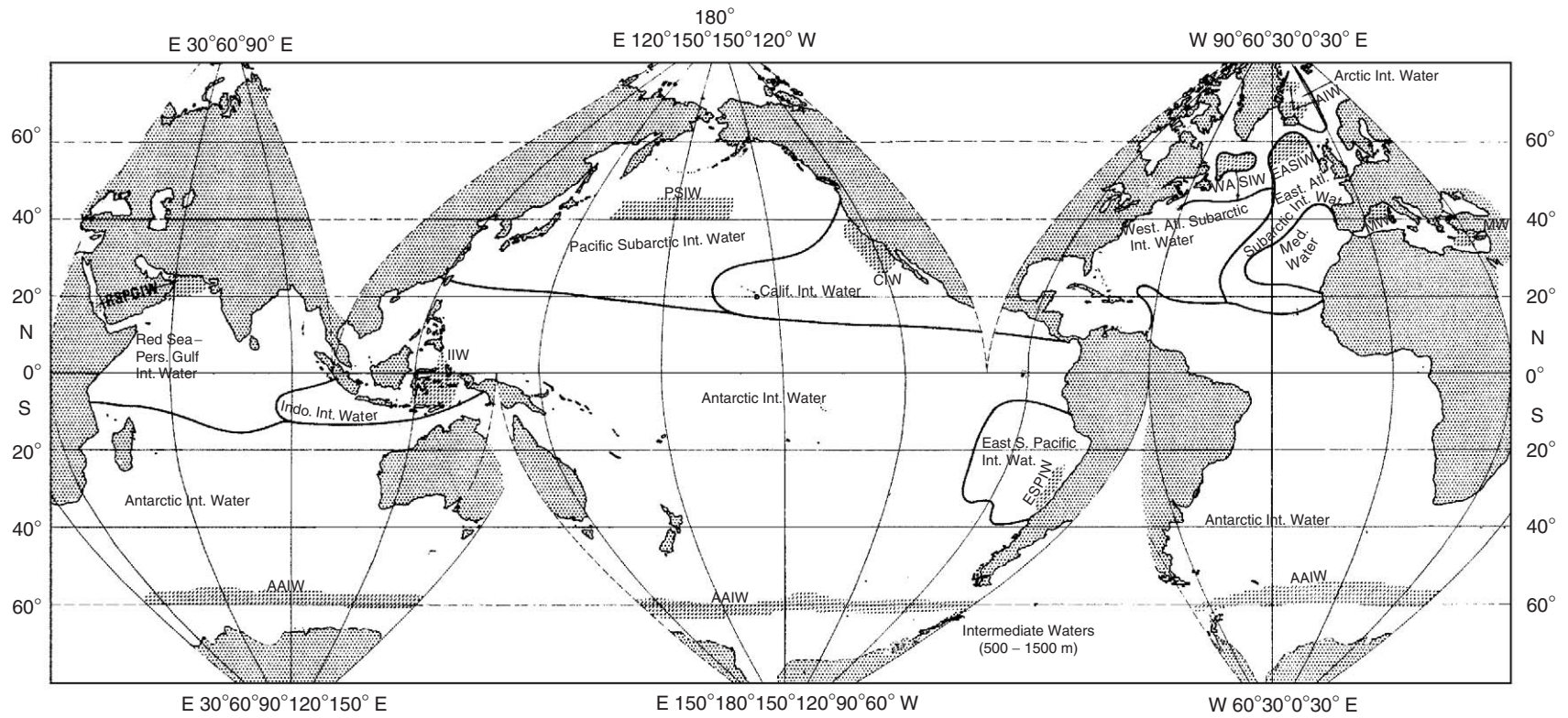
Figure 4   Global distribution of intermediate water (550–1500 m). Lines, labels and hatching follow the same format as described for **Figure 3**.

Front, which is known to vary considerably in strength and location, moving the formation region north and south. That this AAIW fills a large part of the ocean can be clearly seen in all of the ocean basins. In the Pacific the AAIW extends north to about 20° N, where it meets the NPIW as already noted from **Figure 1**. The AAIW reaches about the same latitude in the North Atlantic but it only reaches to about 5° S in the Indian Ocean. In the Pacific the northern intermediate waters are mostly from the North Pacific where the NPIW is formed. There is, however, another smaller volume intermediate water that is formed in the transition region west of California, mostly as a consequence of coastal upwelling. A similar intermediate water formation zone can be found in the south Pacific mainly off the coast of South America, which generates a minor intermediate water mass.

The deep and bottom waters mapped in **Figure 5** are restricted in their movements to the deeper reaches of the ocean. For this reason the 4000 m depth contour has been plotted in **Figure 5** and a good correspondence can be seen between the distribution of bottom water and the deepest bottom topography. Some interesting aspects of this bottom water can be seen in the eastern South Atlantic. As the dense bottom water makes its way north from the Southern Ocean, in the east it runs into the Walvis Ridge, which blocks it from further northward extension. Instead the bottom water flows north along the west of the mid-Atlantic ridge and, finding a deep passage in the Romanche Gap, flows eastward and then south to fill the basin north of the Walvis Ridge. A similar complex pattern of distribution can be seen in the Indian Ocean, where the east and west portions of the basin fill from the south separately because of the central ridge in the bottom topography. In spite of the requisite depth of the North Pacific, the Antarctic Bottom Water (AABW) does not extend as far northward in the North Pacific. This means that some variant of the AABW, created by mixing with other deep and intermediate waters, occupies the most northern reaches of the deep North Pacific. Because the North Pacific is essentially 'cut-off' from the Arctic, there is no formation region of deep and bottom water in the North Pacific.

The 3D TS curve of **Figure 2** indicated that the most abundant water, mass marked by the highest peak in this TS curve, corresponded to Pacific Deep Water. In **Table 1** there is listed something called 'Circumpolar Deep Water' in the deeper reaches of both the Pacific and Indian Oceans. This water mass is not formed at the surface but is instead a mixture of NADW, AABW, and the two intermediate waters present in the Pacific. The Antarctic Bottom Water (AABW) forms in the Weddell Sea as the product of very cold, dense, fresh water flowing off the continental shelf. It then sinks and encounters the upwelling NADW, which adds a bit of salinity to the cold, fresh water, making it even denser. This very dense product of Weddell Sea shelf water and NADW becomes the AABW, which then sinks to the very bottom and flows out of the Weddell Sea to fill most of the bottom layers of the world ocean. It is probable that a similar process works in the Ross Sea and some other areas of the continental shelf to form additional AABW, but the Weddell Sea is thought to be the primary formation region of AABW.

Summary TS Relationships

As pointed out earlier, one of the best ways to detect specific water masses is with the TS relationship, whether computed for single hydrographic casts or from an historical accumulation of such hydro casts. Here traditional practice is followed and the summary TS curves are divided into the major ocean basins starting with the Atlantic (**Figure 6**). Once again, the higher salinities typical of the Atlantic can be clearly seen. The highest salinities are introduced by the Mediterranean outflow marked as MW in **Figure 6**. This joins with water from the North Atlantic to become part of the NADW, which is marked by a salinity maximum in these TS curves. The AAIW is indicated by the sharp salinity minimum at lower temperatures. The source water for the AAIW is marked by a dark square in the figure. The AABW is a single point, which now does not represent a 'water type' but rather a water mass. The difference is that this water mass has very constant TS properties represented by a single point in the TS curves. Note that this is the densest water on this TS diagram (the density lines are shown as the dashed curves in the TS diagram marked with the value of σ).

The rather long segments stretching to the upper temperature and salinity values represent the upper waters in the Atlantic. While this occupies a large portion of the TS space, it only covers a relatively small part of the upper ocean when compared to the large volumes occupied by the deep and bottom water masses. From this TS diagram it can be seen that the upper waters are slightly different in the South Atlantic, the East North Atlantic and the West North Atlantic. Of these differences the South Atlantic differs more strongly from the other two than they do from each other.

By comparison with **Figure 6**, the Pacific TS curves of the Pacific (**Figure 7**) are very fresh, with all but the highest upper water mass having salinities below 35‰. The bottom property anchoring this curve is the Circumpolar Deep Water (CDW), which is used to
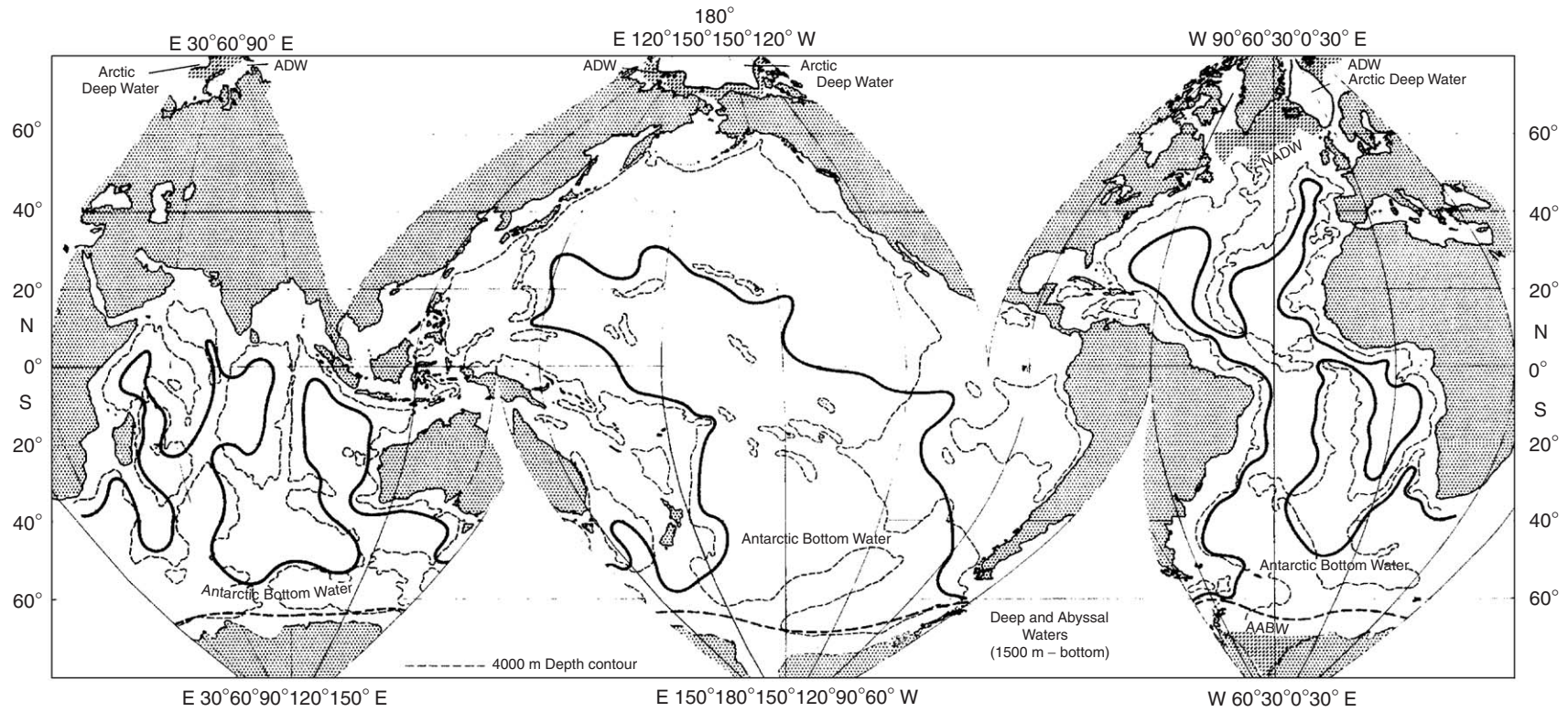
Figure 5 Global distribution of deep and abyssal waters (1500–bottom). Contour lines describe the spreading of abyssal water (primarily AABW). The formation of NADW is indicated again by hatching and its spreading terminus, near the Antarctic, by a dashed line which also suggests the global communication of this deep water around the Antarctic.
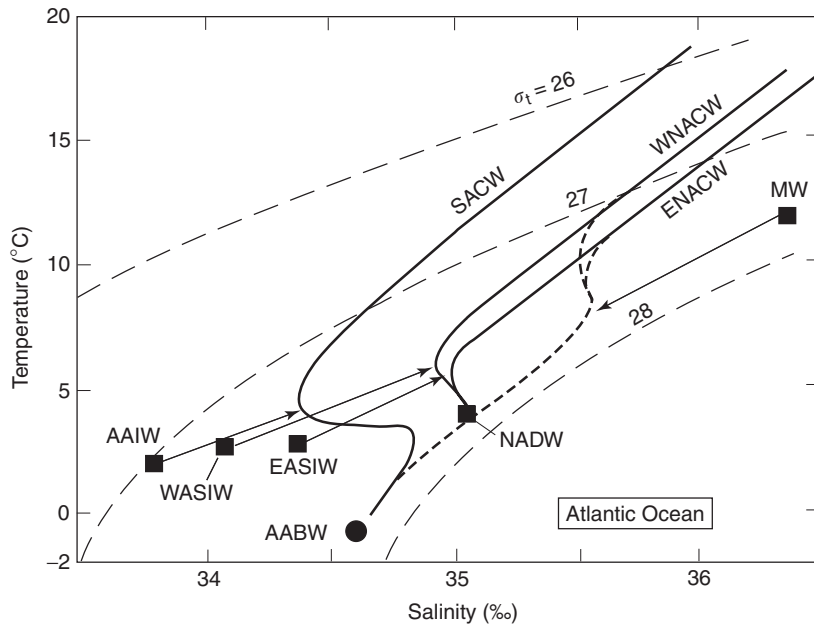
Figure 6 Characteristic temperature–salinity (TS) curves for the main water masses of the Atlantic Ocean. Water masses are labelled by the appropriate acronym and core water properties are indicated by a dark square with an arrow to suggest their spread. The cross isopycnal nature of some of these arrows is not intended to suggest a mixing process but merely to connect source waters with their corresponding characteristic extrema.

identify a wide range of TS properties that are known to be deep and bottom water but which have not been identified in terms of a specific formation region and TS properties. As with the AABW, a single point at the bottom of the curves represents the CDW. The

relationship between the AAIW and the PSIW can be clearly seen in this diagram. The AAIW is colder and saltier than is the PSIW, which is generally a bit higher in the water column, indicated by the lower density of this feature. There are no external sources of deep
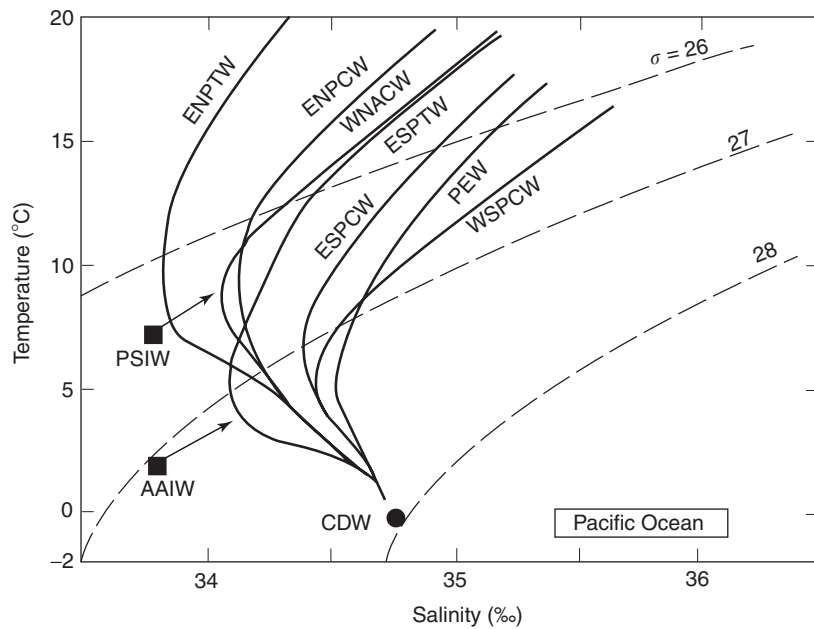

Figure 7 Characteristic TS curves for the main water masses of the Pacific Ocean.

salinity like with the Mediterranean Water in the Atlantic. Instead there is a confusing plethora of upper water masses that clearly separate the east–west and north–south portions of the basin. So we have Eastern North Pacific Central Water (ENPCW) and Western North Pacific Central Water (WNPCW), as well as Eastern South Pacific Central Water (ESPCW) and Western South Pacific Central Water (WSPCW).

The central waters all refer to open ocean upper water masses. The more coastal water masses such as the Eastern North Pacific Transition Water (ENPTW) are typical of the change in upper water mass properties that occurs near the coastal regions. The same is true of the South Pacific as well. In general the fresher upper-layer water masses of the Pacific are located in the east where river runoff introduces a lot of fresh water into the upper ocean. To the west the upper water masses are saltier as shown by the quasilinear portions of the TS curves corresponding to the western upper water masses. The Pacific Equatorial Water (PEW) is unique in the Pacific probably due to well-developed equatorial circulation system. As seen in **Figure 7**, the PEW TS properties lie between the east and west central waters.

The Indian Ocean TS curves in **Figure 8** are quite different from either the Atlantic or the Pacific. Overall the Indian Ocean is quite a bit saltier than the Pacific but not quite as salty as the Atlantic. Also like the Atlantic, the Indian Ocean receives salinity input from a marginal sea as the Red Sea deposits its salt-laden water into the Arabian Sea. Its presence is noted in **Figure 8** as the black box marked RSPGIW for the Red Sea–Persian Gulf Intermediate Water. Added at the sill depth of the Red Sea, this intermediate water contributes to a salinity maximum that is seasonally dependent.

The bottom water is the same CDW that we saw in the Pacific. Unlike the Pacific, the Indian Ocean equatorial water masses are nearly isohaline above the point representing the CDW. In fact the line that represents the Indian Ocean Equatorial Water (IEW) runs almost straight up from the CDW at about $0.0°C$ to the maximum temperature at $20°C$. There is expression of the AAIW in the curve that corresponds to the South Indian Ocean Central Water (SICW). A competing Indonesian Intermediate Water (IIW) has higher temperature and higher salinity characteristics which result in it having an only slightly lower density, creating the weak salinity minimum in the curve transitioning to the Indian Ocean Upper Water (IUW). The warmest and saltiest part of these TS curves represents the Arabian Sea Water (ASW) on the western side of the Indian subcontinent.

Discussion and Conclusion

The descriptions provided in this article cover only the most general of water masses, their core properties and their geographic distribution. In most regions of the ocean it is possible to resolve the water mass structure into even finer elements describing more precisely the differences in temperature and salinity. In addition,
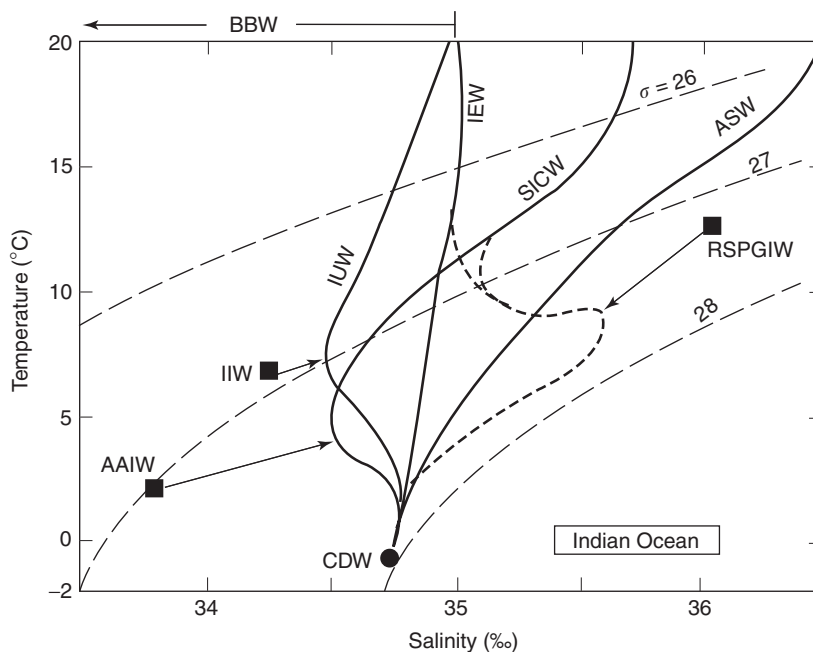

Figure 8 Characteristic TS curves for the main water masses of the Indian Ocean. All lables as in **Figure 6**.

other important properties can be used to specify water masses not obvious in TS space. While dissolved oxygen is often used to define water mass boundaries, care must be taken as this nonconservative property is influenced by biological activity and the chemical dissolution of dead organic material falling through the water column. Nutrients also suffer from modification within the water column, making their interpretation as water mass boundaries more difficult. Characteristic diagrams that plot oxygen against salinity or nutrients can be used to seek extrema that mark the boundaries of various water masses.

The higher vertical resolution property profiles possible with electronic profiling instruments also make it possible to resolve water mass structure that was not even visible with the lower vertical resolution of earlier bottle sampling. Again, this complexity is only merited in local water mass descriptions and cannot be used on the global-scale description. At this global scale the descriptive data available from the accumulation of historical hydrographic data are adequate to map the large-scale water mass distribution, as has been done in this article.

See also

Boundary Layers: Ocean Mixed Layer. **Convection:** Convection in the Ocean. **Coupled Ocean–Atmosphere Models**. **Ocean Circulation:** General Processes; Surface–Wind Driven Circulation; Thermohaline Circulation.

Further Reading

Emery WJ and Meincke J (1986) Global water masses: summary and review. *Oceanologica Acta* 9: 383–391.

Mamayev OI (1975) *Temperature–Salinity Analysis of World Ocean Waters*. Elsevier Oceanography Series, #11, Elsevier Scientific Pub. Co., Amsterdam, 374 pp.

Iselin CO'D (1939) The influence of vertical and lateral turbulence on the characteristics of the waters at mid-depths. *Transactions of the American Geophysical Union* 20: 414–417.

Pickard GL and Emery WJ (1992) *Descriptive Physical Oceanography*, 5th edn. Oxford, England: Pergamon Press.

Reid JL (1973) *Northwest Pacific Ocean Water in Winter*. The Johns Hopkins Oceanographic Studies #5, Johns Hopkins Press, 96 pp.

Sverdrup HU, Johnson MW and Fleming RH (1941) *The Oceans*. Prentice-Hall Inc., 1087 pp.

Worthington LV (1976) *On the North Atlantic Circulation*. The Johns Hopkins Oceanographic Studies #6, Johns Hopkins Press, 110 pp.

Worthington LV (1981) The water masses of the world ocean: some results of a fine-scale census. In: Warren BA and Wunsch C (eds) *Evolution of Physical Oceanography*, Ch. 2, pp. 42–69. Cambridge, MA: MIT Press.

OPERATIONAL METEOROLOGY

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Introduction

Operational meteorology involves the generation and widespread dissemination of weather information. Although the types of weather-related information generated and the methods of distribution have evolved throughout the history of operational forecasting, the basic focus of this subdiscipline of the atmospheric sciences has remained unchanged: to use scientific knowledge about how the atmosphere behaves to develop and distribute useful forecasts of weather conditions. In its modern application, this process typically involves the acquisition, examination, and interpretation of vast quantities of both observational meteorological data and numerical forecast model output, and thus tends to be extremely computer intensive. The content of the disseminated weather products varies according to the issuing organization and the type of weather information required by its customers; typically, they include periodic reports and forecasts of weather conditions over particular geographic regions and notification of any anticipated or observed hazardous weather conditions. These products are disseminated in many ways, including dedicated electronic communications systems maintained by national and local governments, the World Wide Web, newspapers, radio, and television.

Prior to the 1990s, countries with significant weather service programs generally relied on their respective national governments to provide weather information. While this practice is still common in