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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 the majority of data useful for studying the properties of the deep and open ocean still comes from the time before the advent of modern electronic profiling systems. 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 specific water mass characteristics are in general only a small portion of the total paper requiring an oceanographer interested primarily in the water mass distribution to review the entire paper to extract the water mass information. Although water mass characteristics often play important roles in today's oceanographic research efforts there are few studies devoted solely to a better description of the distributions and characteristics of global water masses.

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 a '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, the maps of the various water mass distributions identify a 'formation region' 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 in 1939 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’ (a conservative 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 beginning to talk about and describe the global distribution of water masses some of the basic tools used in such a description are introduced. One of the most basic tools is the use of property vs. property plots to summarize the 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. An average of all of the data in a 10° square just north east of Hawaii in this TS curve is typical of features that can be found in all TS curves. In this example 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 composite TS curves computed from a number of closely spaced hydrographic stations no longer have a specific relationship between temperature, salinity, and depth.

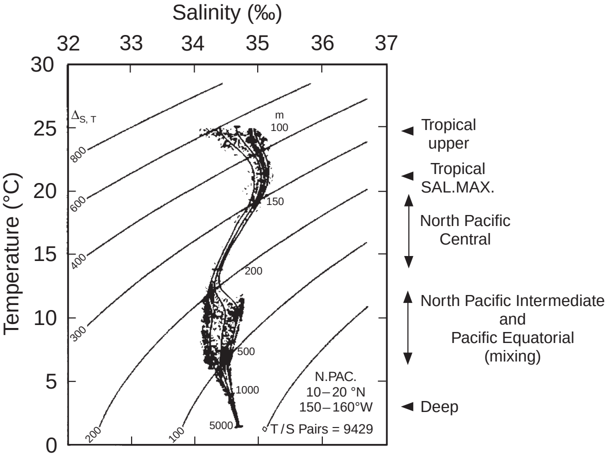

Figure 1 Example of TS ‘scatter plot’ for all data within a 10° square with mean TS curve (centre line) and curves for one standard deviation in salinity on either side. (1‰ ≑ 1 PSU.)

As with the more traditional ‘single station’ TS curve these area average TS curves can be used to define and locate water masses which is done by locating extrema in salinity associated with particular water masses. Ignoring the near-surface values, the salinity minimum in this TS curve 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 **Figure 1**. There are two separate clusters of points at this salinity minimum temperature with one terminating at about 13°C and the other transitioning up to the highest 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.

Although there is no general 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 described the ‘core properties’ of that water mass. In the above example the salinity characteristics of the two intermediate waters was a salinity minimum, which was the overall characteristic of the two intermediate waters. 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 has sunk from the surface down to about 1000 m and start to erode, broadening the salinity minimum and slowly increasing its magnitude. By comparing conditions of the salinity extreme at a location with the salinity characteristics typical of the formation region one can estimate the amount of the source water mass 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 form that is particularly instructive is the '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 be plotted, in a perspective format (**Figure 2**). In this plot the two horizontal axes are temperature and salinity while the elevation represents the volume 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 to 4.0°C. The arrows show which parts of the ocean various features are from. That the Atlantic is the saltiest of the oceans is very clear with a branch to high salinity values at higher temperatures. The largest volume 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 we turn to the TS curve description of the water masses we need to indicate the geographic distribution of the basic water masses. The reader is cautioned that only the major water masses, which most oceanographers accept and agree upon, will be discussed. In a particular region of interest close inspection will reveal a great variety of smaller water mass classifications, which 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. Here the area name is given together with the corresponding acronym, and the appropriate temperature and salinity range. Recall that the property extreme becomes less distinct because of diffusion the further one goes 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.

Here the water masses have been divided, as is traditionally the case, into deep and abyssal waters, intermediate waters and upper waters. Although the upper waters have the largest property ranges they occupy the smallest 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 diffuse the least and have the longest lifetime. Surface waters on the other hand are strongly influenced by fluctuations at the ocean surface which rapidly erode the water mass properties. In mean average TS curves as in **Figure 1** the spread of the standard deviation at the highest temperatures reflects this influence from the heat and freshwater flux exchange that occurs near and at the ocean's surface.

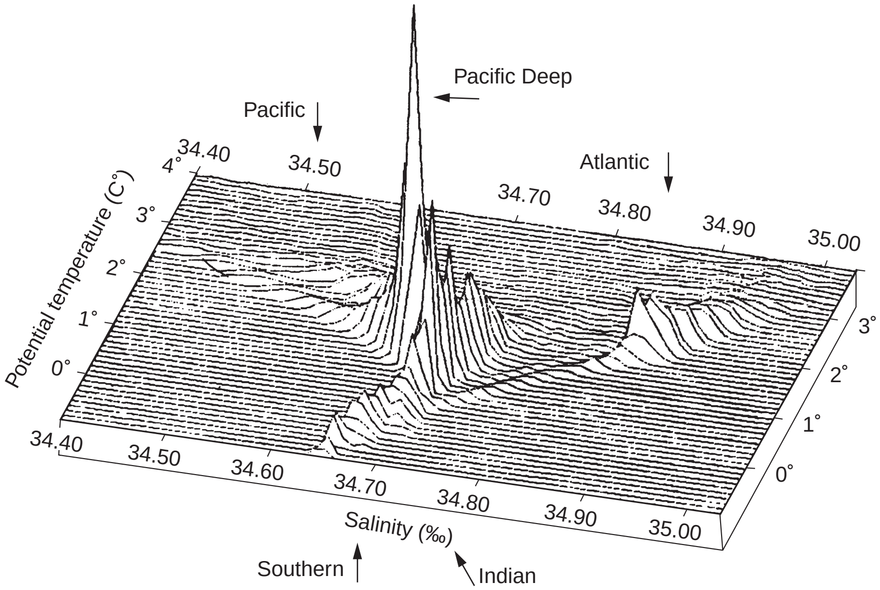

Figure 2 Simulated three-dimensional T–S–V diagram for the cold water masses of the world ocean.

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– −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‰)

To accompany **Table 1** global maps of water mass at all three of these levels are presented. The upper waters in **Figure 3** have the most complex distributions with significant meridional and zonal changes. We have also indicated a best guess at the formation regions for the corresponding water mass as indicated by the hatched regions. For its relatively small size the Indian Ocean has a very complex

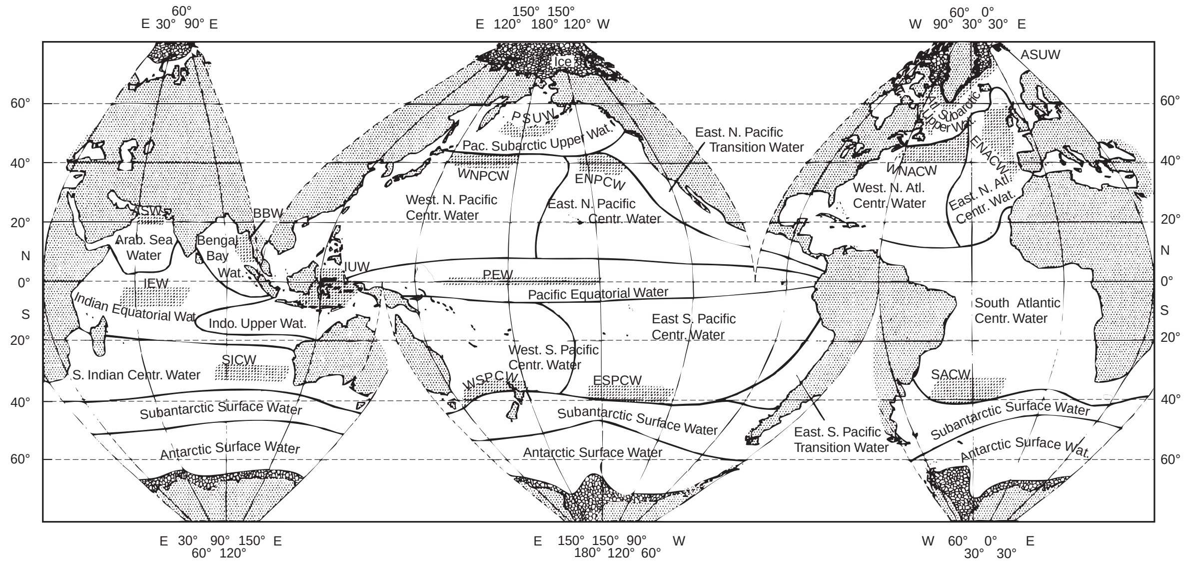

Figure 3 Global distribution of upper waters (0–500 m). Water masses are labeled in abbreviated form with their boundaries indicated by solid lines. Formation regions for these water masses are marked by cross-hatching and labeled with the corresponding acronym title.

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) and 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. Neither of the other two ocean basins has this equatorial water mass in the upper ocean. The Atlantic has northern hemisphere upper water masses that can be separated east–west and 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 there are 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 that of the upper ocean water masses (**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 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 1000 m where it sinks below the vertical range of the less saline Antarctic Intermediate Water (AIW) and joins 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 AIW is marked as the location of the oceanic polar front, which is known to vary considerably in strength and location moving the formation region north and south. It can clearly be seen in all of the ocean basins that this AIW fills a large part of the ocean. In the Pacific the AIW extends north to

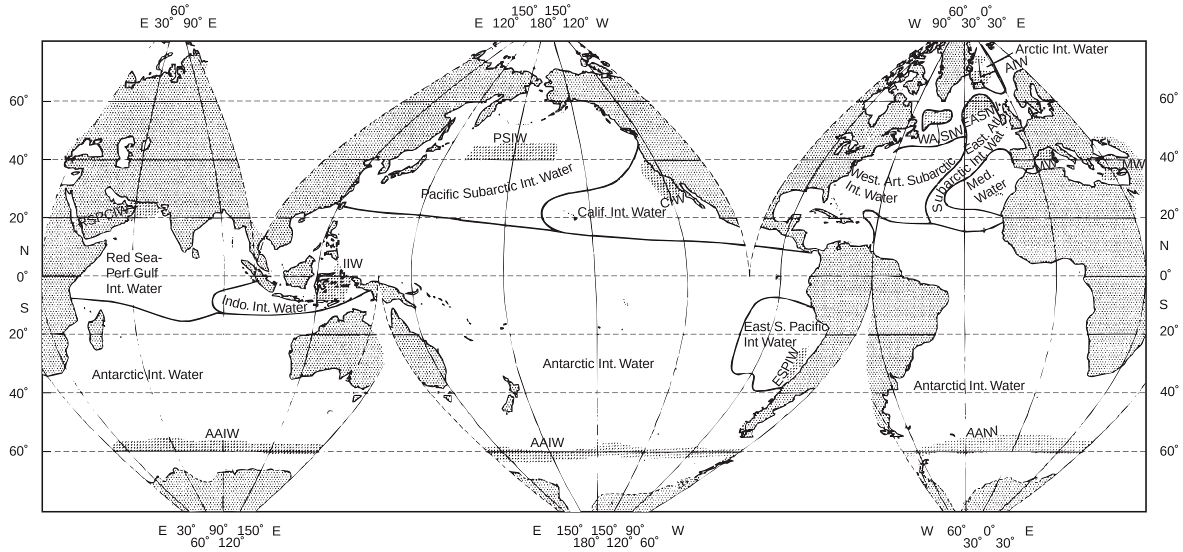

Figure 4 Global distribution of intermediate water (550–1500 m). Lines, labels and hatching follow the same format as described for **Figure 3.**

about 20°N where it meets the North Pacific Intermediate Water (NPIW) as shown in **Figure 1**. The AIW 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 is 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 meaning 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 three-dimensional TS curve of **Figure 2** showed that the most abundant water mass marked by the highest peak in this TS curve corresponded to Pacific Deep Water. **Table 1** shows there is 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 North Atlantic Deep Water (NADW), AABW and the two intermediate waters present in the Pacific. The AABW forms in the Weddell Sea as the product of very cold, dense, fresh water flowing off the continental shelf which then sinks and encounters the upwelling NADW which adds a little 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.

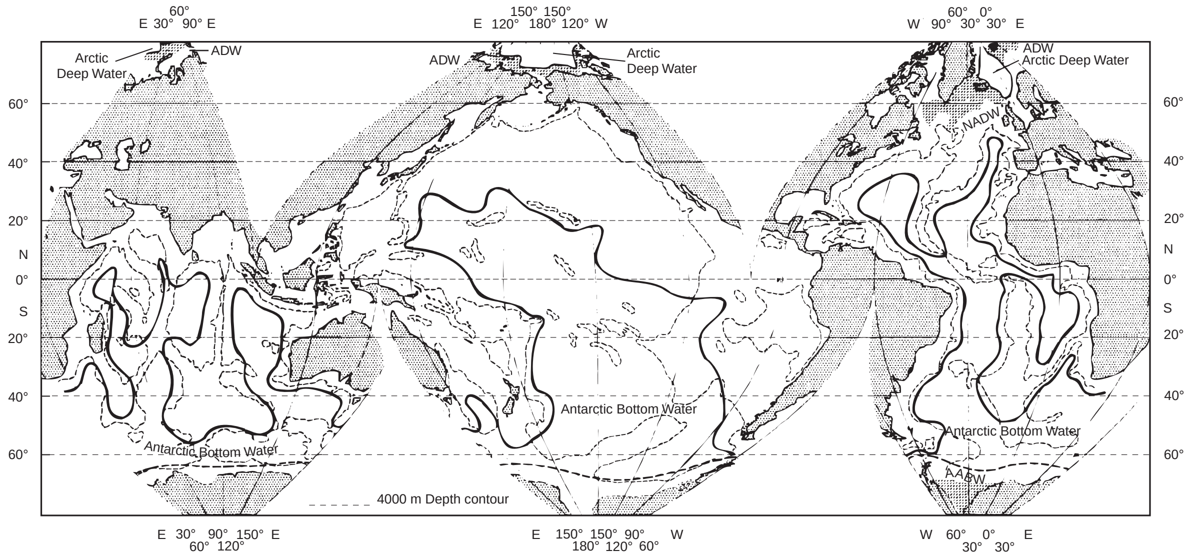

Figure 5 Global distribution of deep and abyssal waters (1500–bottom). Contour lines describe the spreading of abyssal water (primarily AABW). The formation of NADW is indicated by hatching and its spreading terminus, near the Antarctic, by a dashed line which also suggests the global communication of this deep water around the Antarctic. The formation and distribution of CDW is not shown since it overlies the abyssal water in both the Pacific and Indian Oceans.

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 a 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 clearly be 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 as $\sigma_t = $).

The rather long segments stretching to the highest temperature and salinity values represent the upper water in the Atlantic. Although 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

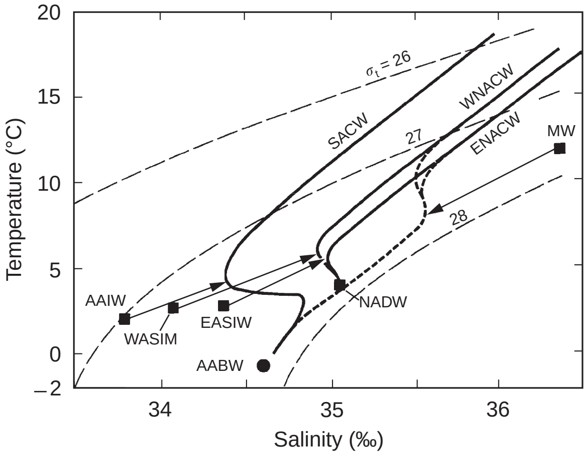

Figure 6 Characteristic temperature–salinity (TS) curves for the main water masses of the Atlantic Ocean. Water masses are labeled by the appropriate acronym (see **Table 1**) and core water properties are indicated by a dark square with an arrow to suggest their spread. The cross-isopycnal nature of some of these arrows is not intended to suggest a mixing process but merely to connect source waters with their corresponding characteristic extrema.

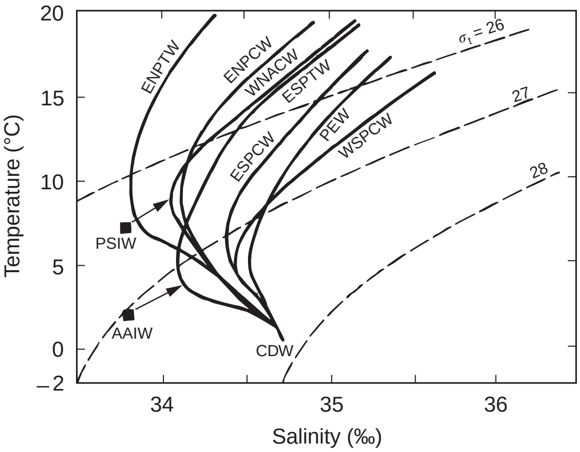

Figure 7 Characteristic temperature–salinity (TS) curves for the main water masses of the Pacific Ocean. All labels as in **Figure 6.**

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 identify a wide range of TS properties that are known to be deep and bottom water but 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 Pacific Subarctic Intermediate Waters (PSIW) can be clearly seen in this diagram. The AAIW is colder and saltier than 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 salinity as for 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. There is therefore 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 also true of the South Pacific. 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 quasi-linear 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 the 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 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 square marked RSPGIW (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 as seen 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°C to the maximum temperature at 20°C. There is an 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.

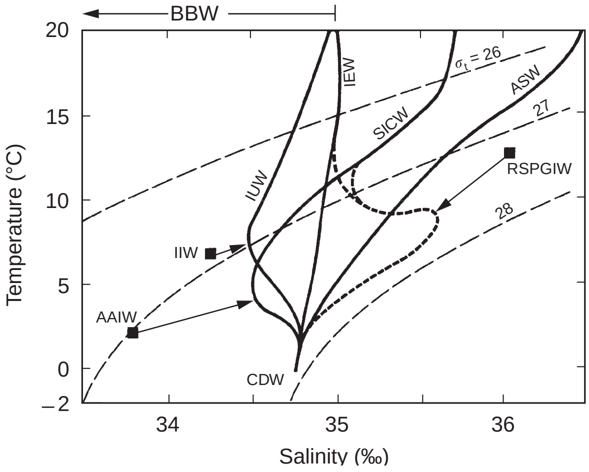

Figure 8 Characteristic temperature–salinity (TS) curves for the main water masses of the Indian Ocean. All labels as in **Figure 6.**

Discussion and Conclusion

The descriptions provided in this review 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 other important properties can be used to specify water masses not obvious in the TS curves. Although 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 in this review article.

See also

California and Alaska Currents. Kuroshio and Oyashio Currents. Ocean Circulation. Ocean Subduction. Pacific Ocean Equatorial Currents. Thermohaline Circulation. Wind Driven Circulation.

Further Reading

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WAVE ENERGY

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Introduction

In the last half of the twentieth century, humankind finally realized that fossil fuel resources are finite and that use of those fuels has environmental consequences. These realizations have prompted the search for other energy resources that are both renewable and environmentally 'friendly'. One such resource is the ocean wind wave. This is a form of solar energy in that the sun is partly responsible for the winds that generate water waves.

The exploitation of water waves has been a goal for thousands of years. Until recent times, however, only sporadic efforts were made, and these were generally directed at a specific function. In the 1960s, Yoshio Masuda, the 'renaissance man' of wave energy conversion, came up with a scheme to convert the energy of water waves into electricity by using a floating pneumatic device. Originally, the Masuda system was used to power remote navigation aides, such as buoys. One such buoy system was purchased by the US Coast Guard which, in turn, requested an analysis of the performance of the system. The results of that analysis were reported by McCormick (1974). This was the first of a long list of theoretical and experimental studies of the pneumatic and other wave energy conversion systems. (For summaries of some of the works, see the Further Reading section.) The most recent collective type of publication is that edited by Nicholls (1999), written under the joint sponsorship of the Engineering Committee on Oceanic Resources (ECOR) and the Japan Marine Science and Technology Center (JAMSTEC). In the late 1970s and early 1980s, JAMSTEC co-sponsored a full-scale trial of a floating, offshore pneumatic system called the Kaimei. The 80 m long, 10 m wide Kaimei