

5.4

Mode Waters

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5.4.1 Ventilation and mode water generation

'Mode Water' is the name given to a layer of nearly vertically homogeneous water found over a relatively large geographical area. Mode waters usually occur within or near the top of the permanent pycnocline, and hence are apparent through the contrast in stratification with the pycnocline waters. Therefore, in a volumetric census in, for instance, a temperature–salinity diagram, this homogeneity in comparison with surrounding higher stratification produces a maximum inventory. Masuzawa (1969) first introduced the term 'Subtropical Mode Water' (STMW) in reference to the thick layer of temperature 16–18°C in the northwestern North Pacific subtropical gyre, on the southern side of the Kuroshio Extension. This STMW is the counterpart of the previously identified Eighteen Degree Water associated with the Gulf Stream Extension in the North Atlantic (Worthington, 1959). The terminology 'Mode Water' was extended to the thick near-surface layer north of the Subantarctic Front by McCartney (1977), who identified and mapped the properties of the Subantarctic Mode Water (SAMW). McCartney and Talley (1982) then applied the term 'Subpolar Mode Water' (SPMW) to the thick near-surface mixed layers in the North Atlantic's subpolar gyre. The term 'Mode Water' now is nearly ubiquitous for describing any thick, broadly distributed, near-surface layer. To distinguish it from other mode waters, the Subtropical Mode Water described by Masuzawa (1969, 1972) is now usually referred to as North Pacific Subtropical

Mode Water (NPSTMW) and the North Atlantic's Eighteen Degree Water is sometimes called North Atlantic Subtropical Mode Water (NASTMW).

Mode waters have been identified in every ocean basin, always on the warm side of a current or front. Subtropical mode waters are associated with every separated western boundary current of subtropical gyres. Mode waters have been identified recently in the northeastern portions of several subtropical gyres – this identification is extended herein to all basins. In the southern hemisphere, the Subantarctic Front is the southern boundary of the subtropical gyres. Because isopycnals plunge so rapidly towards the north across the front, a very thick mode water is found to the north of the front.

Mode waters are generally distributed below the surface far beyond their formation areas. Ventilation of the ocean interior occurs when fluid is subducted, or pushed down, from the ocean surface. The initial view of how this occurs dates back to Iselin (1939), who proposed that water would be pushed downwards along sloping isopycnals from the base of the Ekman layer by the wind-induced vertical Ekman pumping velocity. Stommel (1979) recognized that only the fluid leaving the deep winter mixed layer irreversibly enters the permanent pycnocline (the 'mixed-layer demon' hypothesis), and this biases the temperature and salinity properties of the main thermocline toward those of the deep winter mixed layer. Consequently, it is actually the flow through the base of the winter mixed layer (rather than the Ekman layer) that ventilates the underlying ocean,

and, as pointed out by Woods (1985), the absence of a mixed layer in idealized models precludes lateral induction (by horizontal advection) across the sloping base of the mixed layer. Williams (1989) therefore included a spatially varying mixed layer in the model of Luyten *et al.* (1983), and found that the volume of ventilated fluid within the subtropical gyre was indeed much increased due to lateral induction. In fact, several studies have now shown that the subduction rate in the North Atlantic subtropical gyre due to lateral induction is about two to four times greater than that resulting from Ekman pumping alone (Jenkins, 1982; Sarmiento, 1983; Marshall *et al.*, 1993; New *et al.*, 1995). The readers may refer to Chapter 5.3 of this book by Jim Price for more detailed discussion of subduction.

Mode water studies are useful from various view points. First, mode water reflects temporal variations of oceanic and hence climatic conditions. Variations in mode water properties, distribution and circulation are manifestations of variations in wintertime air–sea interaction (surface cooling) in the formation area, oceanic heat transport to the formation area, eddy activity in the formation area and spin-up/spin-down of the gyre. Second, mode water simulation is a good target for numerical models, particularly those with mixed layers. In order to model mode waters and their variations accurately various processes must be correctly simulated, including: plausible separation of western boundary currents and their extensions, frontal systems, mixed-layer processes given proper surface forcing, eddy activity in the formation area, advection/ventilation/subduction processes and isopycnal/diapycnal mixing. Numerical simulations of NASTMW (Marsh and New, 1996; Hazeleger and Drifhout, 1998, 1999) and SAMW (Ribbe and Tomczak, 1997) have been carried out. Reproducing mode water distribution, circulation and variability in numerical models will assist mode water studies as well as improvement of the numerical models themselves. Third, mode water in the sense of its potential vorticity signal is a good tracer of subtropical ventilation, as useful as chemical tracers of ventilation (Sarmiento *et al.*, 1982; Talley, 1988; Joyce *et al.*, 1998; Schneider *et al.*, 1999). This could be particularly useful in the case of the eastern subtropical mode waters and the SAMW, which are subducted in the eastern parts of the gyres.

In this chapter, we describe the distribution and water properties of mode waters in the world's oceans. Mode waters are defined and their general characteristics presented in Section 5.4.2. The global distributions and basin descriptions of mode waters are presented in Section 5.4.3. Intermediate waters are discussed in several chapters (see Davis and Zenk, Chapter 3.2; Rintoul *et al.*, Chapter 4.6; Gordon, Chapter 4.7; and Schlosser *et al.*, Chapter 5.8). Here in Section 5.4.3. a brief discussion is presented of the low-salinity intermediate waters as they relate to mode waters. In Section 5.4.4, temporal variations of subtropical mode water properties in the North Pacific and North Atlantic are reviewed, and some information about variation of SPMW properties is presented.

5.4.2 Definition, detection and general characteristics of mode waters

Mode waters are characterized by homogeneity of water properties in the vertical as well as the horizontal. Thickening of isopycnal layers occurs in many places, so the following several characteristics are generally used to identify mode waters. (1) In a volumetric sense, a mode water has a substantial volume in some region, in comparison with surrounding water masses. (2) Water properties such as temperature, salinity and oxygen are highly homogeneous in the horizontal and vertical. (3) At a given station, that is, in a single vertical profile, mode water appears as a pycnostad (low vertical density gradient) between the seasonal and main (or lower) pycnoclines (high vertical density gradient). (4) Mode water is found well beyond its outcropping area as a result of advection. (5) Mode water formation or maintenance is usually associated with wintertime convective mixing due to buoyancy loss from the ocean surface, in a much more limited region than the total area occupied by the mode water. (6) Mode water formation areas occur in conjunction with permanent fronts, on the low-density side of the front, where the isopycnal slopes precondition the region for a thicker layer than occurs on the high-density side of the front.

A minimum in the vertical gradient of potential density (σ_θ), or equivalently in the Brunt–Väisälä frequency, is often used to identify mode water (Fig. 5.4.1). Isopycnic potential vorticity is a related quantity that is useful as well, since it is a

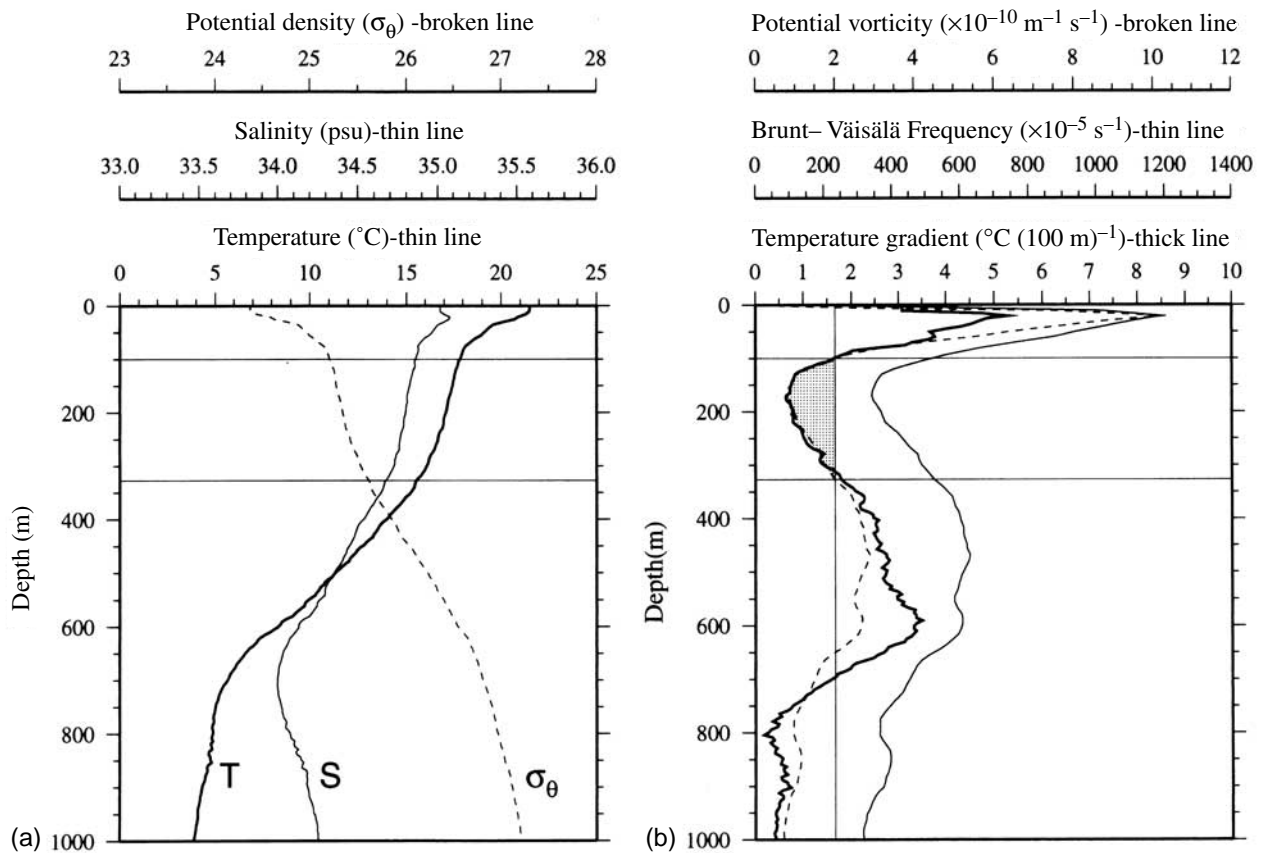


Fig. 5.4.1 Example of a single vertical profile with mode water. This CTD profile was taken at $29^{\circ}5'N$, $158^{\circ}33'E$ on May 16, 1993 during KH-93-2 *Hakuho-Mar* cruise. (a) Profiles of potential temperature, salinity and potential density and (b) those of Brunt-Väisälä frequency, potential vorticity (PV) and temperature gradient (sign reversed). The vertical line in the right panel denotes $2 \times 10^{-10} \text{ m}^{-1} \text{ s}^{-1}$ of PV which is approximately equivalent to $1.5^{\circ} \text{C} (100 \text{ m})^{-1}$ of temperature gradient (sign reversed) to be used as threshold to identify North Pacific subtropical mode water (NPSTMW). Shaded layer (bounded by two horizontal lines) with PV less than this value can be regarded as NPSTMW.

dynamically conserved property. Potential vorticity depends on the Coriolis parameter (planetary component), the vertical density gradient (stretching component) and local vorticity of the flow (relative vorticity). The last is demonstrably small compared with the stretching component in most regions, and is also difficult to compute from hydrographic data. When relative vorticity is ignored, the potential vorticity quantity (PV) is

$$PV = \frac{f}{\rho} \frac{\partial \rho}{\partial z} \quad (5.4.1)$$

where f is the Coriolis parameter and ρ is the potential density. This is sometimes referred to as isopycnic potential vorticity.

Temperature profiles are more abundant than profiles that include salinity, particularly for studies of variability of mode waters in the North

Pacific. Since both salinity and temperature are relatively homogeneous in mode water, vertical temperature gradients are sometimes used instead of potential vorticity or the vertical gradient of potential density to identify the core of the mode water.

The specific values of potential vorticity or temperature gradient that have been used to define the boundaries of a given mode water are empirical. Values that have been used to trace NPSTMW in space and time are potential vorticity less than $2.0 \times 10^{-10} \text{ m}^{-1} \text{ s}^{-1}$ (Suga *et al.*, 1989) or temperature gradient less than $1.5^{\circ} \text{C} (100 \text{ m})^{-1}$ (Hanawa *et al.*, 1988a).

Mode waters have been mapped on isopycnal or core layer surfaces. Core layers are the locus of a vertical extremum of a property (Wüst, 1935). For mode waters, the core layer is the vertical

minimum of potential vorticity, potential density or temperature (e.g. McCartney, 1982).

The low-salinity intermediate waters in the North Atlantic and Southern Ocean are closely associated with mode waters; this association is described in more detail in the next section. The low-salinity intermediate water of the North Pacific on the other hand has not been shown to be associated with mode waters. All three major intermediate waters have some regions of low potential vorticity resulting from convective formation at the sea surface, and in this sense there are similarities to mode waters. The Labrador Sea Water of the North Atlantic is formed from mode waters of the subpolar gyre (Talley and McCartney, 1982). The Antarctic Intermediate Water of the Pacific is a subducted mode water associated with the Antarctic Circumpolar Current. The Antarctic Intermediate Water of the Atlantic and Indian Oceans also arises from this circumpolar mode water, but through advection and modification of the Pacific mode water in Drake Passage (McCartney, 1977).

5.4.3 Geographical distribution of mixed-layer depth and mode waters in the world's oceans

Mode water formation areas are generally characterized by wintertime mixed layers that are relatively thick compared with other mixed layers in the same geographical region. Talley (1999a) mapped the global winter mixed-layer thicknesses, using Reid's (1982) approach employing the depth of high oxygen saturation. This map is reproduced here as Fig. 5.4.2 (see Plate XX).

Globally the thickest mixed layers are in the northern North Atlantic and around the northern region of the Southern Ocean in the Pacific and eastern Indian Oceans. These thick layers are associated with the North Atlantic's Subpolar Mode Water and the Southern Ocean's Subantarctic Mode Water, described below. Relatively thick mixed layers are also found in the subtropical mode water areas near the separated western boundary currents.

Mode waters originate as thick winter mixed layers, but are then subducted and advected away from the formation areas. They are usually defined as mode waters after they are capped by either a seasonal pycnocline or the permanent pycnocline

under which they are subducted. The global distribution of mode waters as it was understood in the late 1970s was mapped by McCartney (1982). Talley (1999a) used the global hydrographic data sets compiled by J. Reid and A. Mantyla (personal communication) as well as numerous World Ocean Circulation Experiment (WOCE) stations to produce a new schematic map of mode waters, including the same features as McCartney (1982) and adding newly defined eastern subtropical mode waters and central mode waters (see below). Figure 5.4.3a (see Plate XX) is a slightly updated version of Talley's (1999a) map, including here more information regarding the density of the mode waters.

Subtropical mode waters associated with western boundary current extensions of subtropical gyres, Type I, are found in all basins (associated with the Kuroshio, Gulf Stream, East Australian Current, Brazil Current and Agulhas Current). These arise from convection in the thickened layers on the south (north) side of the current axes in the northern (southern) hemisphere, where a natural bowl in isopycnal surfaces occurs between the separated current and its recirculation. STMWs, especially in the northern hemisphere, are associated with large surface heat loss from the ocean as a result of cold, dry air outbreaks in winter from the nearby continents. Low potential vorticity (weak stratification or thick mixed layer in winter) associated with these mode waters arises as a result of convection near the axis of the separated western boundary currents, and possibly also from the origin of some of the source water from the equatorward, negative relative vorticity side of the separated current. Equatorward Ekman transport into the STMW formation area may also modify STMW properties, particularly in making them fresher to the east, as is observed in the North Pacific (Suga and Hanawa, 1990). Eddy exchange across the separated boundary current could also accomplish a freshening (Talley, 1997).

A second type of subtropical mode water, of density not very different from STMWs associated with the western boundary current, Type II, is found in the eastern part of the subtropical gyres (light pink in Fig. 5.4.3a, see Plate XX). The Madeira Mode Water (Käse *et al.*, 1985; Siedler *et al.*, 1987) is the archetype of this mode water. Hautala and Roemmich (1998) have described this mode water for the North Pacific. A similar low-density mode

water is evident in the southeastern South Pacific (mapped in Talley, 1999a, but not fully described anywhere yet). The mechanism for the existence of eastern STMWs, however, has not been elucidated. They appear in the subtropical gyre regions bounded by the equatorward side of permanent zonal fronts (such as the Azores Front in the North Atlantic and the subtropical fronts in the North and South Pacific) and the western side of eastern boundary current fronts (such as the Canary, California and Peru Currents). These eastern mode waters are much weaker than the western STMWs in terms of thickness and area of extent. The North Atlantic and North Pacific eastern STMWs have been studied through the seasons and show major seasonal variability associated with advection and seasonal outcropping. These mode waters are in the primary subduction areas of the gyres and thus provide a useful tracer for ventilation studies within the subtropical gyre.

A third, denser, type of subtropical mode water, Type III, is associated with the subpolar fronts on the poleward boundaries of the subtropical gyres (dark in Fig. 5.4.3a, see Plate XX). The densities of these mode waters are considerably higher than for the first two types just described. The archetype is the Subantarctic Mode Water, found just north of the Subantarctic Front (McCartney, 1977). A similar mode water is found in the North Pacific (North Pacific Central Mode Water; Nakamura, 1996; Suga *et al.*, 1997), just south of the Subarctic Front. In the North Atlantic, the Subpolar Mode Water of density near 26.9 to $27.0 \sigma_\theta$ on the south side of the North Atlantic Current should be identified as this denser type of subtropical mode water, circulating southward into the subtropical gyre, as described by McCartney (1982).

Mode waters are also found around the outside of the cyclonic subpolar circulations. The North Atlantic Subpolar Mode Water (SPMW; McCartney and Talley, 1982) is the most obvious of these mode waters, since it is associated with very thick mixed layers (see Fig. 5.4.2 (Plate XX) and description below). A weak version of subpolar mode water is found around the periphery of the North Pacific subpolar gyre, although it has not been singled out and named. Thick layers occur in the Nordic Seas but have not been singled out as mode waters. Finally, although mode waters have not been reported around the periphery of the cyclonic gyres south of the Antarctic Circumpolar

Current, it is possible that they exist as a result of the downward slope of isopycnals towards the outer side of cyclonic circulations. This could be explored further.

A weak mode water, Type IV, has been described in the high evaporation region of the South Atlantic, in conjunction with the high-salinity water observed in the subsurface layer of the subtropical gyre (Tsuchiya *et al.*, 1994), as described below. A feature like this has also been found in the North Pacific, assumed to be due to subduction of high-salinity surface water (Shuto, 1996). High-evaporation, high-salinity surface waters and subducted saline subsurface layers occur in every subtropical ocean. Thus a subsurface potential vorticity minimum (mode water) might be associated with the subtropical underwater in every ocean. These shallow salinity extrema have been given various names in different oceans. We follow the name 'Subtropical Underwater' used by Worthington (1976) for the feature in the North Atlantic. These water masses are described in numerous publications (for the North Atlantic, e.g. Worthington, 1976; for the South Pacific, e.g. Tsuchiya and Talley, 1996; and for the Indian Ocean, e.g. Wyrski, 1973; Toole and Warren, 1993).

The mode waters of each basin are described now in more detail. The two northern hemisphere oceans are described first, as they have many features in common, both with limited subtropical and subpolar gyres. The subtropical mode waters of the southern hemisphere subtropical oceans are then treated together since they share similar features. The circumpolar Subantarctic Mode Water, which as mentioned above is actually a type of subtropical mode water, is then described in a section on the Southern Ocean. Table 5.4.1 is the summary of mode waters in the world's ocean, in which acronym, full name, type of mode waters, characteristic temperature ($^{\circ}\text{C}$), salinity, potential density (σ_θ) and references are given.

Here note that in the following description, terminology is based on original references as much as possible: Eighteen Degree Water and North Atlantic Subtropical Mode Water (NASTMW) are synonymous.

5.4.3.1 North Atlantic Ocean

The North Atlantic subtropical mode water (Eighteen Degree Water: Worthington, 1959) has properties centred at 18°C , 36.5 psu and $26.5 \sigma_\theta$ (this

Table 5.4.1 Mode waters of the world's oceans. Acronym, full name, type, characteristic temperature ($^{\circ}\text{C}$), salinity, potential density (σ_{θ}) and references are given. Types of mode waters are those associated with separated western boundary current (I), those found in the eastern region of the subtropical gyre (II) and those associated with the subpolar front (III). See the text for details. Type IV mode waters ('Subtropical Underwaters', e.g. shallow subtropical salinity maxima) are not included in the list but are present in each ocean

Acronym	Full name	Type	Temperature ($^{\circ}\text{C}$)	Salinity	Potential Density σ_{θ}	References
<i>Atlantic Ocean</i>						
NASTMW ^a	North Atlantic STMW	I	18	36.5	26.5	Worthington (1959)
MMW	Madeira Mode Water	II	16–18	36.5–36.8	26.5–26.8	Käse <i>et al.</i> (1985), Siedler <i>et al.</i> (1987)
SPMW ^b	Subpolar Mode Water	III	8–15	35.5–36.2	26.9–27.75	McCartney (1982), McCartney & Talley (1982)
SASTMW	South Atlantic STMW	I	12–18	35.2–36.2	26.2–26.6	Provost <i>et al.</i> (1999)
SAESTMW	South Atlantic Eastern STMW	II	15–16	35.4	26.2–26.3	Provost <i>et al.</i> (1999)
<i>Pacific Ocean</i>						
NPSTMW	North Pacific STMW	I	16.5	34.85	25.2	Masuzawa (1967, 1972)
NPESTMW	North Pacific Eastern STMW	II	16–22	34.5	24–25.4	Hautala & Roemmich (1998)
NPCMW	North Pacific Central Mode Water	III	9–12	34.1–34.4	26.2	Nakamura (1996), Suga <i>et al.</i> (1997)
SPSTMW	South Pacific STMW	I	15–19	35.5	26.0	Roemmich & Cornuelle (1998)
SPESTMW ^c	South Pacific Eastern STMW	II	13–20	34.4–35.5	25.5	Tsuchiya & Talley (1996)
<i>Indian Ocean</i>						
IOSTMW	Indian Ocean STMW	I	17–18	35.6	26.0	Gordon <i>et al.</i> (1987), Toole & Warren (1993)
<i>Southern Ocean</i>						
SAMW	Subantarctic Mode Water	III	4–15	34.2–35.8	26.5–27.1	McCartney (1977)
SEISAMW ^d	Southwest Indian SAMW	III	8	34.55	26.8	Thompson & Edwards (1981), McCarthy & Talley (1999)
^a Eighteen Degree (18°) Water. ^b There are various varieties of SPMW. See the text for details. ^c This terminology is tentative and no formal name is given yet. ^d SEISAMW is a variety of SAMW.						

form will be used in the present chapter to indicate characteristic temperatures, salinities and densities). It is found throughout the northwestern part of the subtropical gyre. Its formation area is just south of the Gulf Stream Extension, most likely associated with the wall and meanders of the current (Talley and Raymer, 1982), and in an area of very high surface heat loss to the atmosphere. In winter the mixed layer where Eighteen Degree Water is formed is as deep as 350 to 400 m (Worthington, 1959). The temperature of the core

is lower to the east, suggesting that advection and cooling along the Gulf Stream are part of the formation process. The Eighteen Degree Water is advected southward out of the Gulf Stream Extension region, filling the western subtropical gyre (Worthington, 1976).

The stability of Eighteen Degree Water properties was demonstrated by Schroeder *et al.* (1959) using data near Bermuda dating back to the *Challenger* voyage in 1873 and including the then 4-year time series at the Panulirus station

(1954–58). Ebbesmeyer and Lindstrom (1986) showed that newly formed NASTMW may persist for several years within the Gulf Stream recirculation. On the other hand, within the relative stability of Eighteen Degree Water existence and properties, variations are clear – thickness changes reflect variations in formation rate while temperature and salinity changes also reflect changes in surface forcing and possibly exchange with other regions, as reviewed below (Section 5.4.4).

The Madeira Mode Water (MMW; Siedler *et al.*, 1987; earlier observations by Käse *et al.*, 1985) is the archetype of the relatively low-density subtropical mode waters of the eastern subtropical gyres. Using hydrographic and historical XBT (eXpendable Bathy Thermograph) data, Siedler *et al.* documented the existence of this mode water, which is clearly distinct from the Eighteen Degree Water of the western subtropical gyre. It is associated with the warm side of the Azores Front and is offshore of the coastal upwelling area. The MMW has temperature and potential density ranges of 16–18°C and 26.5–26.8 σ_θ . Winter mixed layers in its formation region are about 200 m thick (Käse *et al.*). Although the MMW almost disappears as a thick mode by the end of summer (Siedler *et al.*), it is advected southwestward from its formation and joins the thermocline as part of the North Atlantic Central Water. This layer has been the focus of intensive investigations into the subduction process, in which the water was observed from winter outcrop to restratification, deepening and potential vorticity homogenization (Joyce *et al.*, 1998).

Mode waters of higher density in the northern subtropical gyre and the subpolar gyre of the North Atlantic were documented by McCartney and Talley (1982), and called Subpolar Mode Water (SPMW), with a density range of 26.9 σ_θ , east of Newfoundland to 27.75, in the Labrador Sea. The very smooth, broad-scale description of the SPMW in that first paper suggested that SPMW originates as thick layers at 14–15°C in the North Atlantic Current loop. The concept was that these layers are advected eastward south of the North Atlantic Current to the eastern Atlantic, becoming cooler and denser along the path. These 11–12°C SPMWs were then thought to split to the south and north, with the southward flow entering the subtropical gyre thermocline (McCartney, 1982). These southward flowing SPMWs are often called Eastern North Atlantic Water (e.g. Harvey,

1982; Pollard *et al.*, 1996) The northward flow becoming the inflowing warm surface water of the subpolar gyre. These northward-flowing SPMWs continue to cool and increase in density, with 8°C water found east of Iceland. This SPMW then splits, with a portion entering the Norwegian Sea as the main part of the warm Atlantic inflow to the Arctic, and hence the precursor to North Atlantic Deep Water formation. The remainder was thought to circulate westward past Iceland into the Irminger Sea and then on into the Labrador Sea, eventually cooling enough to become Labrador Sea Water (Talley and McCartney, 1982).

There is a reason however to consider major modifications to this picture of the SPMW formation, transformation and circulation. The portion of the SPMW that is south of the North Atlantic Current and the 11–12°C water of the northeastern subtropical gyre are really mode waters of the northern subtropical gyre, located south of the wind-stress curl gyre boundary. In this sense, these waters are similar to the North Pacific Central Mode Water described by Nakamura (1996) and Suga *et al.* (1997). The relative amount of the SPMW that turns northward to continue transformation to higher density has not yet been quantified well. Other modifications to the large-scale picture of SPMW transformation are emerging as well (Talley, 1999b): the Subarctic Front, which is the extension of the North Atlantic current, turns northeastward between the Reykjanes Ridge and Rockall Plateau. It separates SPMWs of the eastern and western subpolar gyre. A connection between the eastern and western SPMWs is not clear since strong, permanent westward surface flow just south of Iceland is not apparent in the climatological circulation. The warmer SPMWs of the eastern subpolar gyre feed the Norwegian Sea. The origin of the colder SPMWs of the western subpolar gyre, which feed the Labrador Sea convection, are not as clear, but may come from a different part of the North Atlantic Current/Subarctic Front. This region is under intensive study as one of the last WOCE process studies, leading into a CLIVAR (Climate Variability and Predictability) study of decadal and centennial change.

The fresh intermediate water of the North Atlantic, the Labrador Sea Water (LSW), arises from convection in the western Labrador Sea (Clarke and Gascard, 1983; Pickart *et al.*, 1997; Lazier *et al.*, Chapter 5.5) and is advected

throughout the subpolar Atlantic and into the subtropical Atlantic (Fig. 5.4.3b, see Plate XX; from Talley, 1999a). The source waters of LSW are the Subpolar Mode Waters – LSW can be considered the densest of the SPMWs. It is characterized in the subpolar North Atlantic as a pycnostad, a salinity minimum and an oxygen maximum (Talley and McCartney, 1982). It is a salinity minimum in the subpolar region because of the large inflow of saline subtropical surface waters (that become the SPMW). LSWs signature in the subtropical North Atlantic is not as clear because it is opposed by the saline Mediterranean Outflow Water, which occupies a similar density range and which mixes with LSW. In the tropical and South Atlantic, LSW and Mediterranean Outflow Water are considered to be part of the southward-flowing North Atlantic Deep Water. Here LSW contributes the high-oxygen core known as Middle North Atlantic Deep Water (Wüst, 1935).

5.4.3.2 North Pacific Ocean

North Pacific Subtropical Mode Water (NPSTMW) is found throughout the northwestern part of the subtropical gyre (Hanawa, 1987; Bingham, 1992). Hanawa and Suga (1995) provided a thorough review of NPSTMW studies.

The core of NPSTMW is 16.5°C, 34.85 psu and 25.2 σ_θ . The approximate outcrop area is the zonal band from the Izu Ridge to the international date-line in longitude and from 28°N to the Kuroshio Extension (Hanawa and Hoshino, 1988; Yasuda and Hanawa, 1997, 1999; Hanawa and Yoritaka, 2000). In late winter, a well-developed mixed layer thicker than 300 m is formed in this area. In the formation area, temperature and salinity decrease from west to east (Suga and Hanawa, 1990; Bingham, 1992). This decrease of salinity to the east reflects the input of northern surface water with lower salinity through Ekman transport.

The source water of NPSTMW is apparently the Kuroshio Extension (Bingham, 1992). The surface temperature of the Kuroshio Extension decreases eastward, corresponding to a local heat loss of more than 800 W m⁻² in winter. Maps of acceleration potential, which yield the geostrophic flow on isopycnals (Montgomery, 1938), suggest that the Kuroshio water detrains southward into the thick layers in the formation area of NPSTMW. Thus the eastward decrease in NPSTMW temperature is more a function of the Kuroshio Extension

temperature than an indication of eastward advection of the NPSTMW itself. The NPSTMW formation area lies dynamically between the Kuroshio Extension and a westward recirculation south of the Kuroshio Extension. Winter convection in the narrow region just south of the Kuroshio, perhaps accentuated in anticyclonic meander regions, thickens the NPSTMW layer further. Using maps of potential vorticity on isopycnals, Suga and Hanawa (1995b) showed the seasonal movement of NPSTMW formed in the western part of the formation region. Based on synoptic surveys in 1987 and 1888, Suga and Hanawa (1995a) described the substantial advection of NPSTMW by anticyclonic eddies propagating westward in the region south of Japan. During Kuroshio large meander periods, the intrusion of NPSTMW into the region just south of Japan is blocked and the NPSTMW path is shifted further south (Suga and Hanawa, 1995b).

A denser type of subtropical mode water was described by Nakamura (1996) and Suga *et al.* (1997), who named it North Pacific Central Mode Water (NPCMW). This mode water is distributed in the central North Pacific (approximately 170°E to 150°W) between the Kuroshio Extension Front (approx. 33°N) and the Kuroshio Bifurcation Front (approx. 40°N). NPCMW has a temperature of 9–12°C and potential density around 26.2 σ_θ . This water is synonymous with the ‘stability gap’ described by Roden (1970), by which was meant the lowered stability region south of the Subarctic Front. Southward Ekman transport of cool, fresh water may play a role in decreasing the stability of this region. Reid (1982) showed that winter mixed layers in this region are thicker than anywhere else in the North Pacific, including the NPSTMW region. Very thick mixed layers (>500 m) are found locally in Kuroshio warm core rings just east of Honshu, which may precondition the central region to have particularly thick winter mixed layers, and hence be a precursor to the NPCMW.

The third, low-density, mode water of the subtropical gyre is found in the eastern North Pacific. Using the WOCE high-density XBT data between Honolulu and San Francisco as well as historical XBT data in this well-observed region, Hautala and Roemmich (1998) described this mode water (NPESTMW), whose low potential vorticity influence was documented by Talley (1988). This water is analogous to the Madeira Mode Water of the

North Atlantic (Siedler *et al.*, 1987). NPESTMW has temperatures from 12 to 22°C and potential density 24–25.4 σ_θ . As with the Madeira Mode Water, NPESTMW is subducted and advected southward, mixing along its path. Hautala and Roemmich showed the formation of NPESTMW in each winter. The temperature of the potential vorticity minimum was similar in the periods 1970–79 and 1991–97 (with inadequate data for the intervening period). This eastern region of the North Pacific has received some attention as a possible source for decadal changes that might propagate to the tropics and influence El Niño. Schneider *et al.* (1999) used depths of isopycnal surfaces and its variations as a primary tracer of subduction/advection changes in the eastern subtropical Pacific, finding that the tropical influence of the subtropical waters was minimal.

Unlike the North Atlantic and Southern Ocean, the North Pacific does not have a distinct subpolar mode water, in the sense of thick layers that are maintained by winter convection. However, relatively thick layers, marked by lower potential vorticity, are found around the rim of the subpolar gyre, particularly in the Gulf of Alaska (Talley, 1988). These layers lie above the strong and relatively shallow pycnocline, which is maintained in part by freshwater input at the sea surface. It might, however, be misleading to call the thick layers mode waters, except insofar as they are dynamically similar to the much more dramatic Subpolar Mode Water of the North Atlantic.

The low-salinity intermediate water of the North Pacific, North Pacific Intermediate Water (NPIW), is not closely associated with mode waters, unlike the LSW of the North Atlantic. The ventilation source of NPIW is the Okhotsk Sea and Oyashio region (Reid, 1965; Talley, 1993). In the Okhotsk Sea, brine rejection during sea-ice formation on the broad shelves ventilates the intermediate densities (Kitani, 1973; Talley, 1991). Convection in the southern Okhotsk Sea creates a low potential vorticity signature in the upper portion of the ventilated layer (Yasuda, 1997), and could be considered an indicator of mode water. The newly ventilated waters enter the North Pacific and are advected into both the subpolar and subtropical gyres. NPIW is not apparent as a core layer in the subpolar gyre because the overlying surface waters are even fresher than NPIW (unlike the situation in the North Atlantic), and

because the potential vorticity signature of NPIW is weak. NPIW is characterized by a salinity minimum in the evaporative subtropical gyre because there are no other sources of water at this density, unlike the North Atlantic, which has saline subsurface input from the Mediterranean.

5.4.3.3 Subtropical South Atlantic Ocean

The South Atlantic subtropical gyre has several prominent fronts, each with its own subtropical mode water (Tsuchiya *et al.*, 1994; Provost *et al.*, 1999). Tsuchiya *et al.* documented three mode waters along 25°W, plus a weak pycnostad at the Antarctic Intermediate Water density. Provost *et al.* showed the geographical distribution of these mode waters and provided details regarding their formation regions. These include two types of Subantarctic Mode Water (SAMW; McCartney, 1977, 1982) and a type of subtropical mode water that is associated with the surface salinity maximum of the central subtropical gyre. The SAMWs are clearly part of the subtropical gyre rather than of a high-latitude cyclonic gyre, and should perhaps be best identified as subtropical mode waters, which is how Provost *et al.* identify them. The southernmost SAMW lies between the Subtropical Front and the separated Brazil Current Front, with approximate properties of 12°C, 35.1 psu and 26.7 σ_θ . North of the Brazil Current Front is found a less dense SAMW, at about 13.5°C, 35.3 psu and 26.6 σ_θ . McCartney (1982) mapped these two modes as a single mode water at about 26.5 σ_θ , showing the limited geographical area and weakness of the mode compared with those of other oceans.

Provost *et al.* also describe a lighter STMW, at 26.2 σ_θ , in the Brazil Current recirculation region and restricted to a smaller western region than the mode waters they identified at 26.5 and 26.6 σ_θ (corresponding to the mode waters identified by Tsuchiya *et al.*, 1994). They mapped the winter outcrop windows and extent of influence of all three of these mode waters, showing that all originate primarily in the western South Atlantic, in the overshoot and recirculation area of the Brazil Current, i.e. the southwestern corner of the Brazil Current. The dominant mode water has properties of 14–16°C, 35.5–35.9 psu and 26.5 σ_θ . They also showed a qualitative correlation between the observed variations of SASTMW and interannual atmospheric forcing using National Centers for Environmental Prediction (NCEP) re-analysis data.

Provost *et al.* also note mode waters associated with Agulhas Rings containing Indian Ocean waters.

A fourth subtropical gyre mode water shown by Tsuchiya *et al.* (1994) in the region between 24°30'S and 11°30'S. It is associated with the subtropical high-salinity water, with properties of 21°C, 36.5 psu and 25.6 σ_θ . This salinity maximum water, which is also known as Subtropical Underwater, apparently achieves its thickness from the buoyancy loss associated with evaporation, and is considered a mode water here since it retains its thickness after subduction.

5.4.3.4 Subtropical South Pacific Ocean

The subtropical gyre of the South Pacific has a weak subtropical mode water between New Zealand and Fiji, as shown by Roemmich and Cornuelle (1992) using WOCE high-density XBT lines. This South Pacific STMW lies north of the Tasman Front and East Auckland Current, which originate as the separated East Australian Current. Perhaps in accord with the weakness of the East Australian Current itself, the SPSTMW is relatively poorly developed (thin) compared with NASTMW and NPSTMW. The STMW properties are 15–19°C with a typical salinity of 35.5 psu and core density around 26.0 σ_θ . Roemmich and Cornuelle showed that the SPSTMW volume (inventory in the cross-section) decreased dramatically between 1986 and 1991. They speculated that this decrease might be due either to long-period change in air–sea heat exchange or to fluctuations in heat transport by ocean currents.

A shallow, low-density subtropical mode water, similar to the Madeira Mode Water (MMW) of the North Atlantic and the northeastern subtropical mode water of the North Pacific (NPESTMW), is found in the southeastern Pacific. Its core density is 25.5 σ_θ , with a temperature range of 13–20°C and salinity of 34.3–35.5 psu. This feature is evident in WOCE sections (e.g. Tsuchiya and Talley, 1996), and has not yet been described in a separate publication.

5.4.3.5 Subtropical Indian Ocean

Subtropical mode water is found in the southwest Indian subgyre (Gordon *et al.*, 1987; Olson *et al.*, 1992; Stramma and Lutjeharms, 1997). Indian Ocean STMW properties are 17–18°C and 35.6 psu. Toole and Warren (1993) found this

STMW (at 17°C and 26.0 σ_θ) west of about 45°E on their hydrographic section at 32°S. They remarked on the relative weakness of this pycnocline compared with its northern hemisphere counterparts, suggesting that surface heat loss in the Agulhas region is likely much lower than in the northern hemisphere regions. Colder, fresher mode water is found within the Agulhas rings that detach from the retroflexion and propagate westward into the South Atlantic (Olson *et al.*, 1992). The data used in these studies are from synoptic surveys. The distribution area, water properties and temporal variability of this STMW have not been mapped.

The eastern South Indian Ocean is dominated by the local type of Subantarctic Mode Water, called the Southeast Indian Subantarctic Mode Water (SEISAMW), which is discussed in the next section.

5.4.3.6 Southern Ocean

The Southern Ocean is dominated by the major fronts of the Antarctic Circumpolar Current. The northernmost front is the Subantarctic Front (SAF), which lies close to the zero wind-stress curl line and hence is the southern boundary of the subtropical gyres (see also Rintoul *et al.*, Chapter 4.6, Fig. 4.6.2). The SAF is furthest north in the western South Atlantic, where it is identical with the Falkland Current front. The SAF moves southward as it rounds Antarctica, and is furthest south in the southeastern Pacific where it enters Drake Passage. North of the SAF, the winter mixed layers reach to more than 700 m thickness (Fig. 5.4.2, see Plate XX). McCartney (1977, 1982) first described the totality of these thick mixed layers, giving them the name Subantarctic Mode Water (SAMW). The SAMW water properties vary in relation to the southward spiralling of the SAF around Antarctica. The warmest SAMW (15°C, 35.8 psu, 26.5 σ_θ), which is the same as the main Subtropical Mode Water discussed by Provost *et al.* (1999), occurs where the SAF is furthest north, in the western Atlantic. The coldest SAMW (4–5°C, 34.2 psu, 27.1 σ_θ) occurs just west of Drake Passage.

It is not clear how continuous the SAMW is around the whole of the Subantarctic Front. McCartney's (1977) hypothesis was that the warmest, least dense SAMW in the western Atlantic smoothly transforms to the coldest, densest SAMW and hence Antarctic Intermediate Water (AAIW) west of Chile. On the other hand,

McCartney (1982) showed substantial northward circulation of the SAMW in each ocean basin. The thick SAMW in the southeast Indian Ocean is singled out and called the SEISAMW because of its major impact on ventilation of the Indian Ocean's subtropical gyre thermocline through subduction and northward advection. The SEISAMW advection leads to a thick layer of high oxygen that persists even into the tropics (McCarthy and Talley, 1999). A less dense SAMW is subducted and advected northwards in the western Indian Ocean (McCartney, 1982). Likewise, the northward circulation of the densest SAMW in the east, near Chile, provides a major ventilation signal of high oxygen for the South Pacific, associated with the low salinity. This subducted SAMW is the Antarctic Intermediate Water (AAIW) of the Pacific. SAMW subducted and advected northward in the western South Pacific is less dense than the AAIW and provides an oxygen-rich layer in the western South Pacific.

It is likely that, as with the North Atlantic SPMW, both hypotheses – of continuous eastward flow and of substantial equatorward advection – are correct. Thus the SAMW ventilates the Indian as SEISAMW and the Pacific as both SAMW and AAIW through subduction, while at the same time a portion of the SAMW continues eastward and is gradually transformed into colder, denser SAMW, with the final portion flowing through Drake Passage to become the main core of the AAIW in the Atlantic and Indian Oceans (Talley, 1997). The SAMW is modified somewhat during this passage, and then at the confluence of the Falkland and Brazil Currents enters the South Atlantic and Indian gyres as a salinity minimum (Atlantic/Indian Antarctic Intermediate Water; Talley, 1996a).

There is a wide variation in the thickness of SAMW (reflected in mixed-layer thickness in Fig. 5.4.2, see Plate XX), with the thickest layers being found in the eastern Indian Ocean (SEISAMW) and across the South Pacific, with somewhat shallower layers in the South Atlantic and western Indian Ocean (Piola and Georgi, 1982). The transition to thick layers in the central Indian Ocean is sudden and occurs just east of Kerguelen Plateau; a cause has not been established. Thompson and Edwards (1981) observed winter formation of SEISAMW with approximate properties of 8°C and 34.55 psu, confirming McCartney's (1977) finding for SAMW properties in this region. They

pointed out, as did McCartney, that unlike in the South Atlantic, SAMW in this area cannot contribute locally to the formation of AAIW.

A major open question regarding SAMW is the role of northward Ekman transport across the SAF in maintaining the volume and thickness of the SAMW. The SAF lies near the maximum westerly wind stress (and hence zero wind-stress curl), and so northward Ekman transport is largest there. Various estimates place the net northward Ekman transport at about 10 Sv ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$) around the circumpolar belt. This is a good fraction of the net 5 Sv and 14 Sv of SEISAMW and AAIW, respectively, that move northward into the subtropical gyres (Talley, 1999a for SEISAMW, and Schmitz, 1995 for AAIW). The remaining subducted transport would then originate in the subtropical gyres. Using a high-resolution numerical model, Ribbe and Tomczak (1997) and Ribbe (1997) examined the effect of northward Ekman transport of the Antarctic surface water on water properties of SAMW. They noted that this cold and fresh water might also drive mid-latitude convection itself to form SAMW. Using air-sea fluxes, Speer *et al.* (1997) estimated a formation rate of 25 Sv of SAMW in the Indian Ocean in the density range $26.5\text{--}27.2 \sigma_\theta$, with a peak formation rate at $26.9 \sigma_\theta$; geostrophic estimates from their inverse model suggest that half remains in the Indian and half is exported to the Pacific. This large SAMW formation rate is reflected in the proxy mixed-layer map of Fig. 5.4.2 (see Plate XX) where an abrupt change in mixed-layer depths is apparent in the central Indian Ocean.

Antarctic Intermediate Water (AAIW) is the low-salinity intermediate-depth layer of the southern hemisphere (distribution in Fig. 5.4.3b, see Plate XX). As noted above, it is very closely associated with SAMW. AAIW in the Pacific Ocean originates in the southeast near Chile, where it is identical with the local SAMW (McCartney, 1977). Convection in this region reaches to about 600 m based on oxygen profiles (Tsuchiya and Talley, 1998). SAMW/AAIW is subducted northward into the South Pacific subtropical gyre. The resulting low-salinity layer is apparent throughout the Pacific up to the southern boundary of the North Pacific's subtropical gyre. Part of the convected water near Chile flows through Drake Passage on the northern side of the Subantarctic Front. Some modification of properties occurs in

this region. When the thick layer reaches the confluence of the Brazil and Malvinas Currents, it plunges down and spreads out into the South Atlantic/Indian subtropical gyre as a salinity minimum (McCartney, 1977; Talley, 1996a). An oxygen maximum is associated with the AAIW through much of the South Atlantic. A pycnostad is also associated with this new AAIW in the southwestern South Atlantic, but is much weaker and more geographically restricted than in the South Pacific, presumably because of vigorous mixing at the western boundary as it enters the Atlantic. There are no sources of AAIW elsewhere in the Atlantic and Indian Oceans, as is apparent from the changes in salinity, oxygen and potential vorticity away from the Brazil/Malvinas confluence. Major modification of AAIW occurs through mixing, and the various AAIWs referred to in the literature reflect these regional mixings rather than new ventilation.

5.4.4 Temporal variability of mode water properties and distribution

A marked characteristic of mode waters is their apparent stability in properties and location (Schroeder *et al.*, 1959; Warren, 1972). Thus mode water distributions, such as shown in Fig. 5.4.3a (see Plate XX), and approximate core properties can be mapped using data sets from all decades. The stability of properties and, indeed, the inter-basin similarity in temperature (although not density because of interbasin salinity differences) are remarkable and clearly associated with the largest scale, longest time-scale wind and buoyancy forcing. Of course, however, there is some variation in properties of the mode waters, which has been studied in areas where time series are adequate. These variations in these near-surface water masses, in temperature, salinity, density and thickness, are linked to surface forcing changes, although in some cases the connection is not yet obvious. In this section, we briefly review the temporal variability of mode waters where it has been documented.

5.4.4.1 Seasonal variation

After the formation of mode water in late winter, it is capped by the seasonal thermocline, due to incident solar radiation. As the seasons progress, mode water is advected away from the formation area

and sometimes becomes permanently capped. In order to trace the seasonal evolution of North Pacific STMW, Suga and Hanawa (1995b) mapped potential vorticity and deduced that the main body of NPSTMW formed in the western part of the formation area is advected westward by the Kuroshio recirculation. During this movement, the NPSTMW is subject to substantial diapycnal mixing.

The seasonality of NASTMW has not been investigated to the same degree as NPSTMW. At Bermuda, which is well downstream of the formation area, seasonality of the mixed layer depths is clear, with a sudden shoaling of near-surface isopycnals during late winter followed by a gradual deepening of the isopycnals through the rest of the year (Talley and Raymer, 1982). However, a seasonal cycle in mode water properties at this site, which is some distance from the mode water outcrop, is not easily apparent.

In the South Pacific STMW, Roemmich and Cornuelle (1992) showed a large seasonal change in mode water inventory and properties using seasonal XBT sampling.

The eastern Subtropical Mode Waters of the North Atlantic and North Pacific have both been studied at the seasonal cycle. Siedler *et al.* (1987) and Hautala and Roemmich (1998) both show the seasonal outcropping of the Madeira Mode Water (MMW) and eastern North Pacific STMW (NPESTMW). Siedler *et al.* show the advection of the MMW downstream after capping in late winter and the near disappearance of the mode in late fall after heating from above and possibly diapycnal mixing. Likewise Hautala and Roemmich show the strength of the eastern North Pacific mode just after it is capped at the end of winter, and its decline in strength as the surface layer restratifies further through the summer and fall.

The seasonality of other mode waters has not been documented to our knowledge.

5.4.4.2 Interannual variations

Interannual variability is roughly defined as variability on time scales of 2 to about 7 years, encompassing the El Niño time scale, but not extending to the decadal time scale.

In the North Pacific STMW, large year-to-year variabilities in temperature and its distribution have been described, especially in relation to the strength of interannual Wintertime East Asian Monsoon. Monsoon strength is well represented

by the Monsoon Index (MOI), which can be defined as the sea-level pressures between Nemuro, Japan, and Irkutsk, Russia (Hanawa *et al.*, 1988b; Watanabe, 1990). Suga and Hanawa (1995c) demonstrated a good correlation between the MOI and the potential vorticity and apparent oxygen utilization of NPSTMW along the repeated 137°E section. This means that severe wintertime cooling in the formation region causes the high formation rate of colder and oxygen-rich NPSTMW. Hanawa and Yoritaka (2000) described the year-to-year variation of NPSTMW core layer temperatures using XBT data taken along 32°30'N once a year from 1990 to 1993. Over the data period of 4 years, core layer temperatures in the western part of the formation area between 140°E and 160°E substantially changed, with a range of 0.7°C, apparently associated with the MOI. These changes were confirmed by Taneda *et al.* (2000) using data taken around the Ogasawara Islands, which is the downstream site of the Kuroshio recirculation. Yasuda and Hanawa (1999) clarified the above change in temperature and area distribution by making composites of water properties with respect to the MOI.

A local interannual signal of NPSTMW in the region south of Honshu is due to the existence or disappearance of the large meander of the Kuroshio (Suga and Hanawa, 1995a). When the Kuroshio large meander is present, NPSTMW is blocked from advecting westward by the Kuroshio recirculation into the region south of Japan. This is also confirmed by the repeat hydrographic observations at 137°E (Suga and Hanawa, 1995c).

For the South Pacific STMW, as mentioned in the previous subsection, Roemmich and Cornuelle (1992) described variations over 5 years using the first WOCE high-density XBT survey. However, the time series was too short to determine if the time scale of the variations was actually interannual or longer.

An interannual signal for the North Atlantic STMW (Eighteen Degree Water) has not been sought using long time series, since the record appears to be dominated by decadal variation (see below). Klein and Hogg (1996) described the variation of water properties and formation rate from 1987 to 1990 using moored data as well as XBT data in the eastern part of the recirculation region of the Gulf Stream. They found that the severe winter of 1988 led to the formation of a colder

type of mode water, followed by increasing temperature after the mild winter of 1989. They also pointed out that since the relationship between winter forcing and water properties was qualitative, advection could strongly influence the water properties.

5.4.4.3 Decadal variations and abrupt shifts

The North Atlantic Eighteen Degree Water has demonstrable decadal variations, possibly associated with variations in the North Atlantic Oscillation. Using Sea Surface Temperature (SST) records in the Eighteen Degree Water formation area and at Bermuda and Ocean Weather Station E, Fieux and Stommel (1975) described a warming of late winter SST from 1910–20 to a maximum in 1950–60, and thereafter cooling. Talley and Raymer (1982), Jenkins (1982) and Talley (1996b) documented the variability of Eighteen Degree Water core and isopycnal properties using the hydrographic time series at Bermuda, which was started in 1954 (Fig. 5.4.4, see Plate XX; from Talley, 1996b). Joyce and Robbins (1996) and Talley (1996b) continued the Bermuda time series analysis, showing that salinity changes on isopycnals in the upper ocean at Bermuda, including through the Eighteen Degree Water core, correlate well with the North Atlantic Oscillation (NAO) index. The Eighteen Degree Water was strong in three periods – 1956–57, the late 1960s and the early 1980s – coinciding with low NAO. The mode water was weakest from 1975 to 1978, just following a year with high NAO and low surface salinity. Looking at potential vorticity as a marker of the core of Eighteen Degree Water, it appears that the core density, rather than being somewhat cyclic like isopycnal salinity, changes discretely. Such changes occurred around 1965, 1975, 1980 and 1985–87. During the intervening periods, the density was rather stable, with the exception of the very weak STMW period of 1975–78. The density of the core for these periods has ranged from 26.4 to 26.55 σ_θ .

Dickson *et al.* (1996) showed that SST in the Sargasso Sea (Eighteen Degree Water formation area) is out of phase on a decadal scale with SST in the Labrador Sea and in phase with SST in the Greenland Sea (see also Dickson *et al.*, Chapter 7.3, in particular Fig. 7.3.5). Thus formation of Eighteen Degree Water is out of phase with convective formation of intermediate water in the

Labrador Sea. Dickson *et al.* attributed this large-scale pattern to the NAO, in which Labrador Sea Water formation is vigorous when the westerlies take a northern path, and in which Eighteen Degree Water formation is vigorous when the westerlies shift towards the south and west.

In the North Pacific subtropical gyre, Bingham *et al.* (1992) compared surface temperature structures of the western North Pacific in two pentads, 1938–42 and 1978–82, using hydrographic data for the former and mostly XBT data for the latter. They found that NPSTMW during the former period was thicker, more uniform in temperature and more confined geographically. They speculated that the greater thickness during the former pentad resulted from stronger wintertime cooling, and that the difference in geographic extent between the two pentads might be caused by reduced advection of the Kuroshio, which was in a large meander state for a larger fraction of the former pentad.

In the mid-1970s, all environmental variables for the North Pacific showed a shift into a state dominated by a deep Aleutian Low (Nitta and Yamada, 1989; Trenberth, 1990; Tanimoto *et al.*, 1993). Yasuda and Hanawa (1997) compared temperature fields for the decades before and after the shift: 1966–75 and 1976–85. In the latter decade, North Pacific Central Mode Water (NPCMW) was widely distributed and its temperature was much colder than before. In the western subtropical gyre, in the North Pacific STMW (NPSTMW) formation area, the water in the southwest was warmer in the latter decade, while colder water occupied the eastern part. These decadal changes in temperature for NPSTMW and NPCMW were attributed partly to the enhancement of heat loss at the sea surface and from enhanced Ekman heat divergence and partly to the larger heat advection by the Kuroshio, which was spun-up during the latter decade.

5.4.4.4 Comments on temporal variability of mode waters

As mentioned in the beginning of this Section 5.4.4, the existence of substantial temporal variability on various time scales is expected since mode water formation reflects late winter conditions, which

have interannual and decadal variability. Variability in circulation strength, which is related to wind-field strength, also affects mode water properties, for instance in the effect of a strengthened Kuroshio on NPSTMW temperature, or the effect of the Kuroshio large meander on NPSTMW distribution. The variability of NASTMW and NPSTMW have been documented to some degree, although the mechanisms for their variations have not been fully explored. Unfortunately at present data are lacking to undertake such studies for the rest of the mode waters. It is expected that the accumulation of monitoring data like XBT/XCTD measurements, among others, will make the description of variability possible in the near future and that these results will provide new insight to ocean climatic variations and changes.

5.4.5 Summary

Mode waters are part of the continuous stratification of the upper oceans, where they are prominent because of their volumetric significance. Thus they are likely to have a disproportionate influence on surface water and surface temperature evolution, which are central to ocean–atmosphere climate interactions. As a community, we have not yet fully documented the properties and distribution of mode waters, which must be the first step. This work is in progress by a number of investigators, including the authors and collaborators. Second, fluxes, formation rates and mechanisms are far from elucidated, including for instance basic questions about the reason for the existence of the eastern subtropical mode waters, the role of eddies in formation, and even the role of topography and local mixing for some mode waters such as Subpolar Mode Water that are close to boundaries.

The authors hope that in the WOCE-AIMS (Analysis, Interpretation, Modelling and Synthesis) period, using various kinds of observations taken during WOCE, including hydrography, XBTs, surface temperatures and fluxes, every mode water in the world's oceans will be fully described, with major progress in understanding mechanisms for formation and feedback of mode waters on the atmosphere.