Web Supplement 10

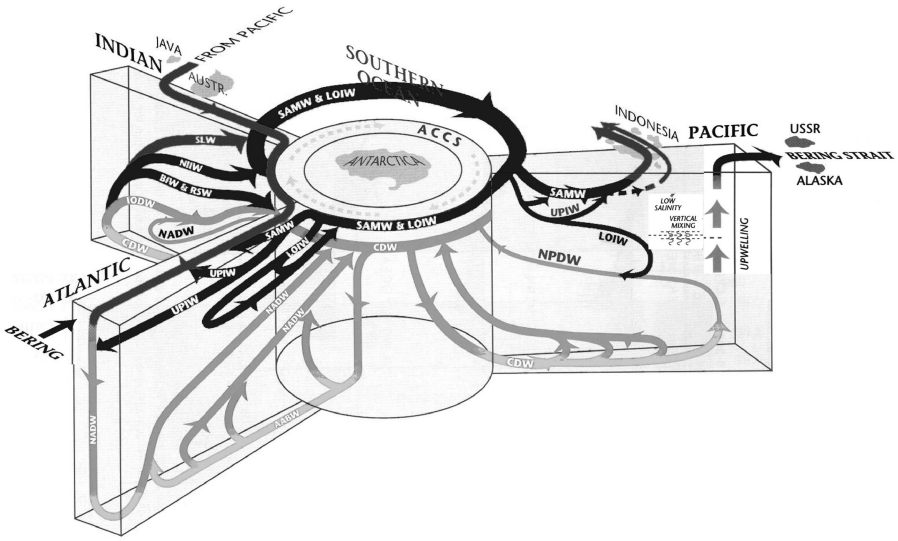
10.W1 CAUSES AND FLOW PATHS OF DEEP-WATER CIRCULATION

In Chapter 4, MOC was presented as global conveyor belt (Figure 4.6). The current understanding as to how MOC leads to the formation of subsurface water masses, followed by their lateral transport and eventual return to the sea surface, is presented in Figure W10.1.

Thermohaline circulation seems to be responsible for the formation of the deep and bottom waters, namely North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW). This circulation is initiated by evaporation and cooling of surface waters that leads to increased density. The waters sink to a level of matching potential density and then move horizontally along the plane of matching potential density (isopycnals) through the ocean basins. Deep and bottom water masses are currently forming only in the North Atlantic and Southern Ocean. In the North Atlantic, NADW is created in the Labrador Sea and in the Norwegian Sea between Greenland and Iceland. In the Southern Ocean, AABW forms along the continental shelf of Antarctica in the Weddell and Ross Seas. The former is located south of the Atlantic Ocean and the latter, south of the Pacific Ocean. NADW and AABW are the densest water masses in the open ocean and, thus, comprise most of the deep zone. The Weddell Sea source of AABW is about twice that of the Ross Sea.

As NADW and AABW move through the deep zone, turbulent mixing with the overlying water masses alters their temperature and salinity signatures. These signatures were presented in Table 4.1. Despite mixing, enough of the water masses' original *T-S* composition is retained to determine the pathway of flow through the deep ocean using the core technique of water mass tracing.

The global circuit of subsurface flow can be traced from the North Atlantic to the North Pacific as follows. After its formation, NADW flows into the South Atlantic, where it meets and mixes with AABW. The combined water masses then flow east, forming a circumpolar current that supplies deep water to the Indian and Pacific oceans. Since deep-water masses are not presently being formed in either of these oceans, their deep



SLW	Surface Layer Water	**NADW**	North Atlantic Deep Water
SAMW	Subantarctic Mode Water	**UPIW**	Upper Intermediate Water, $26.8 \leq \sigma_\theta \leq 27.2$
RSW	Red Sea Water	**LOIW**	Lower Intermediate Water, $27.2 \leq \sigma_\theta \leq 27.5$
AABW	Antarctic Bottom Water	**IODW**	Indian Ocean Deep Water
NPDW	North Pacific Deep Water	**BIW**	Banda Intermediate Water
ACCS	Antarctic Circumpolar Current System	**NIIW**	Northwest Indian Intermediate Water
CDW	Circumpolar Deep Water		

FIGURE W10.1

A three-dimensional model of meridional overturning circulation showing the formation, lateral transport, and upwelling of the world's major subsurface water masses. The surface circulation component is in purple. The intermediate waters and SAMW are in red, the deep waters in green and the bottom waters in blue. In this figure AAIW is differentiated into an upper flow (UPIW) and a lower flow (LOIW). *Source*: After Siedler, G., J. Church, and J. Gould (2001) *Ocean Circulation and Climate: Observing and Modeling the Global Ocean*, Academic Press; and Schmitz, W. J. (1996). On the world ocean circulation: Volume 1, Some global features / North Atlantic Circulation. WHOI Report-96-03. p. 140. (See companion website for color version.)

zones are composed entirely of water that has traveled from the Atlantic Ocean as NADW, AABW, or as an admixture of the two. As a result, the oldest deep water is located in the North Pacific Ocean.

Deep and bottom water formation occurs in a few select locations. In contrast, their return flow to the sea surface occurs throughout the ocean basins. In Chapter 4, this return process was described as resulting from the combined effects of slow upward advection and turbulent mixing. In some regions, the rates of upward advection and turbulent mixing are greatly enhanced. The two most important processes in this regard are the tides, particularly in areas where the seafloor is rough, and the westerlies in the Southern Ocean. The former enhances turbulence as explained in Section 4.3.2 and the latter induces a strong upward advection in the subpolar zone.

The westerlies in the southern hemisphere induce a strong Ekman transport and, hence, upwelling in the Southern Ocean. This sustains a circumpolar zone of divergence between 60 to 70°S where waters are drawn upward from depths of at least 1500 m. These westerlies also drive the Antarctic Circumpolar Current (ACC). The subsurface waters feeding the subpolar upwelling come from all three oceans. In the Atlantic, the inflow is supplied by two circulation loops shown in Figure W10.2. The first is a shallow loop in which AAIW, formed by sinking in a convergence zone located between 42 and 58°S, flows northward through the thermocline and shallower waters until it is entrained in the southerly flowing NADW. The strong upwelling in the Southern Ocean "pulls" NADW south. Along the way, the lower edge of the NADW creates a second deeper loop by mixing with northerly flowing AABW. This admixture is termed Circumpolar Deep Water (CDW). CDW is also "pulled" south by the strong upwelling in the Southern Ocean.

Some of the CDW upwells, and depending on its location, is cooled to form either AAIW or AABW. (AABW forms along the edges of Antarctica, much farther south than the site of formation of AAIW.) The rest of the CDW flows northward into the Indian and Pacific Oceans. As it mixes with overlying waters, its potential density decreases. The resulting lighter water masses, North Pacific Deep Water (NPDW) and Indian Ocean Deep Water (IODW), are drawn back south by the Southern Ocean upwelling. As they move back in the Southern Ocean upwelling area, these deep waters rise and, in so doing, contribute to the formation of intermediate water.

As shown in Figure W10.1, AAIW has been subdivided into two types, an Upper Intermediate Water (UPIW) and a Lower Intermediate Water (LOIW). In Figure 4.16c, the Southern Ocean was also shown to be a site of extensive mode water formation with the most important form being Subantarctic Mode Water (SAMW). Since SAMW is less

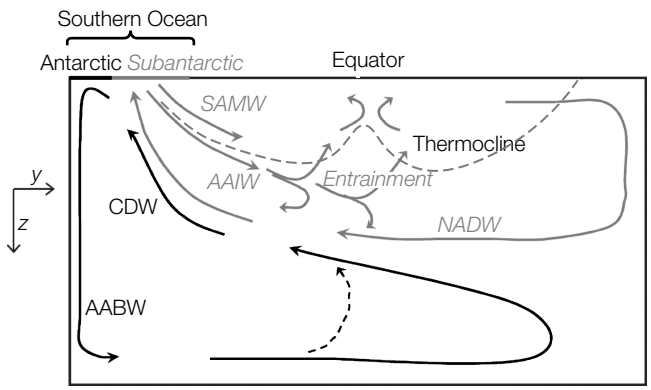


FIGURE W10.2

A longitudinal view of meridional overturning circulation in the Atlantic Ocean. NADW is produced only in the Atlantic Ocean. Otherwise similar intermediate water mass circulation patterns are observed in all the oceans. See Figure 10.3 for water mass abbreviations. *Source*: After Marinov, I., A. Gnanadesikan, J. R. Toggweiler, and J. L. Sarmiento (2006). The Southern Ocean Biogeochemical Divide, *Nature* 441, 964–967. (See companion website for color version.)

dense, it is found at shallower depths than the AAIWs. The roles of these intermediate waters in supplying waters to the thermocline are shown in Figure W10.2. These waters are drawn into the thermocline and toward the sea surface in the equatorial divergence zones, where the Trade Winds induce upwelling. Other intermediate waters shown in Figure 4.16b include North Pacific Intermediate Water (NPIW), Mediterranean Sea Water (MSW), and Labrador Sea Water (LSW). These water masses are of lesser importance and, hence, not included in the MOC model shown in Figure W10.1.

The intermediate waters formed in the Southern Ocean head northward into each of the oceans. As in the Atlantic, some of the intermediate water entering the Pacific and Indian oceans gets entrained in a deeper circulation loop. The remainder mixes with surface waters. The geostrophic currents then return these surface waters to the sites of deep and bottom water formation. For the surface waters in the Pacific Ocean, the first stage of their trip is the *Indonesian Throughflow*. This current moves surface waters from the Pacific into the Indian Ocean by flowing through passages between the Indonesian islands. The Indian Ocean surface waters are returned to the Atlantic by the Agulhas Current leakage. This flow carries surface waters around the southern tip of South Africa, thereby feeding the Benguela Current, which is the eastern boundary current of the South Atlantic Ocean. As shown in Figure 4.4b, the Benguela Current provides water to the Southern Equatorial Current. Some of this water is passed into the Northern Equatorial Current, which then feeds the Gulf Stream. In this way, surface water is returned to the site of NADW formation. Some return flow also appears to occur via leakage of North Pacific Intermediate Water through the Bering Straits and into the Arctic Ocean. This is termed the *Arctic Throughflow*.