ON THE INTERBASIN-SCALE THERMOHALINE CIRCULATION

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Abstract. The global-scale circulation has long been one of oceanography's most challenging and exciting research topics. A few features of the abyssal (near bottom) and deep circulation of the Atlantic Ocean have been known for over 50 years, and in the past decade or so there has been a developing focus on the world oceans' thermohaline circulation. The term thermohaline circulation as used here applies not only to a direct response to atmospheric buoyancy fluxes but also in the general sense of water mass modification or conversion, where mechanisms may be associated with internal mixing processes and even wind forcing (i.e., wind-induced upwelling or wind-driven mixing). The thermohaline circulation components reviewed and summarized in the following are associated with water mass conversion processes that are involved with interbasin exchange. Updated summary maps of the volume transports (in sverdrups; 1Sv = 10^6 m^3 s^{-1}) for the interbasin-scale pathways of the abyssal and deep thermohaline circulation and associated upper level compensating flows are developed for two to four vertical layers or potential density intervals, based primarily on a synthesis of published observational results. The cell(s) involving the largest worldwide exchange transport-wise (53 Sv) are associated with an interaction between various deep and bottom water components via Circumpolar Deep Water (CDW). The first major conversion step in the replacement path for the renewal (14 Sv) of North Atlantic Deep Water (NADW) is taken to be primarily to CDW. Bottom water in the Indian Ocean originates as lower CDW which recirculates while also moving equatorward in deep western boundary currents with eventual conversion to both deep and intermediate layer flows. Some of the intermediate water so formed in the Indian Ocean moves through the Agulhas Current system (ACS) and may "leak" into the Benguela Current regime (BCR), although probably primarily flowing through the ACS into the Subantarctic Frontal Zone (SFZ). It is modified throughout its transit in the SFZ south of the Indian Ocean, south of Australia, and across the South Pacific. Up to 10 Sv of the least dense brand of intermediate water flows through the northern sector of Drake Passage, becomes involved in a Malvinas Current–Brazil Current–Subtropical Gyre interaction, and then joins the BCR after perhaps also interacting with the ACS again. This compensating flow is warmed and becomes more saline in the South Atlantic and is later further modified and upwelled in the equatorial Atlantic, crossing the equator and moving through the Gulf Stream system to replace NADW. There is also an NADW replacement path of secondary importance westward around the tip of Africa (~4 out of 14 Sv) associated with an interbasin circulation pattern throughout the southern hemisphere oceans involving an $O(10$ Sv) Indonesian Throughflow.

BACKGROUND

The unique data base from the *Meteor* expedition led to the classical description of the abyssal and deep large-scale (or general) meridional circulation in the Atlantic Ocean [*Wüst*, 1935]. There are, however, earlier [*Brennecke*, 1921], more speculative results that resemble the *Meteor* summary in meridional section form (Figure 1), the canonical picture for the subthermocline thermohaline circulation in the Atlantic Ocean for many decades. *Gordon*'s [1967, 1971] meridional sections are analogous to Figure 1 but worldwide.

Figure 2, from *Stommel* [1957], contains a two-layer schematic of the combined wind-driven and thermodynamically driven Atlantic Ocean general circulation, simulating North Atlantic Deep Water (NADW) in the lower layer along with its compensation flow and the directly wind-forced response in the upper layer. Upwelling from the lower to upper layers is indicated (Figure 2) in both the Antarctic Circumpolar Current regime (ACCR) and to a lesser extent in the interior of the subtropical gyre of the North Atlantic. The sinking in the northern North Atlantic was presumed to be due to deep convection forced by atmospheric cooling there, and the upwelling shown in the interior is to balance diffusive heat loss there across the boundary between the two layers. The observational consistency of an upper layer cross-equatorial and tropical flow similar to that shown by *Stommel* [1957] in Figure 2 was demonstrated only recently [*Schmitz and Rich-*

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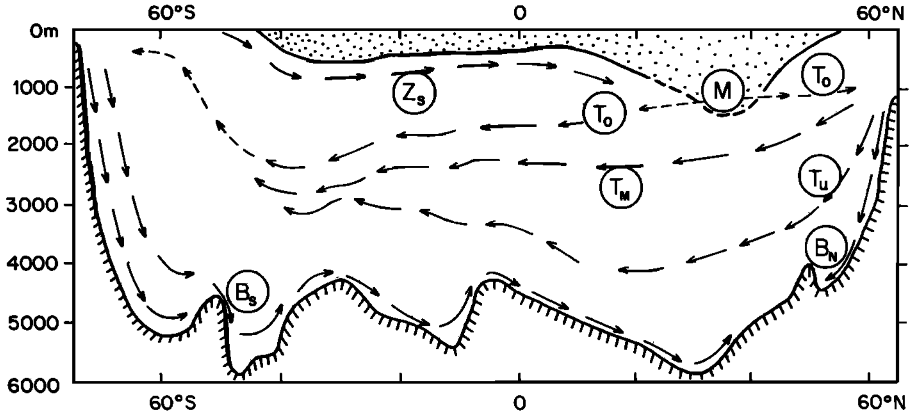


Figure 1. A meridional-vertical section of the subthermocline north-south general circulation in the Atlantic Ocean, simplified from *Wüst* [1935]. Z_S denotes Subantarctic Intermediate Water; B_S and B_N denote bottom water south and north; T_O, T_M, and T_U denote upper, middle, and lower deep water; and M denotes Mediterranean influence. The stippled layer is the warm water sphere.

ardson, 1991; *Schmitz et al.*, 1993; *Schmitz and McCartney*, 1993].

The upwelling in the ACCR shown in Figure 2 could be associated with the outcropping tendency of isopycnals there and perhaps schematically indicate water mass modification in other oceans. One possible outcropping linkage might be for NADW to be converted to intermediate water (maybe following *Sverdrup* [1933]) after many circuits in the ACCR, with this intermediate water entering the South Atlantic through Drake Passage and eventually the North Atlantic after further water mass conversion. However, the presence of NADW characteristics in Circumpolar Deep Water (CDW) and its penetration into the Pacific and Indian Oceans [*Lynn and Reid*, 1968; *Reid and Lynn*, 1971; *Mantyla and Reid*, 1983] implies that at least that amount of NADW is not converted directly to intermediate or upper layer water. The coupled NADW-CDW abyssal-deep thermohaline cells in the Pacific and Indian Oceans that occur as interbasin exchanges require more than a two-layer representation for NADW renewal and will be an essential part of this review (where the ACCR is considered as a basin separate from the southern hemisphere ocean basins). The penetration of NADW influence into the Indian Ocean was noted early on by *Clowes and Deacon* [1935]. A new description [*Mauritzen*, 1993] of the initial formation of NADW has also been developed (where deep convection in the Greenland-Norwegian Seas, and perhaps the Labrador Sea, is not the critical

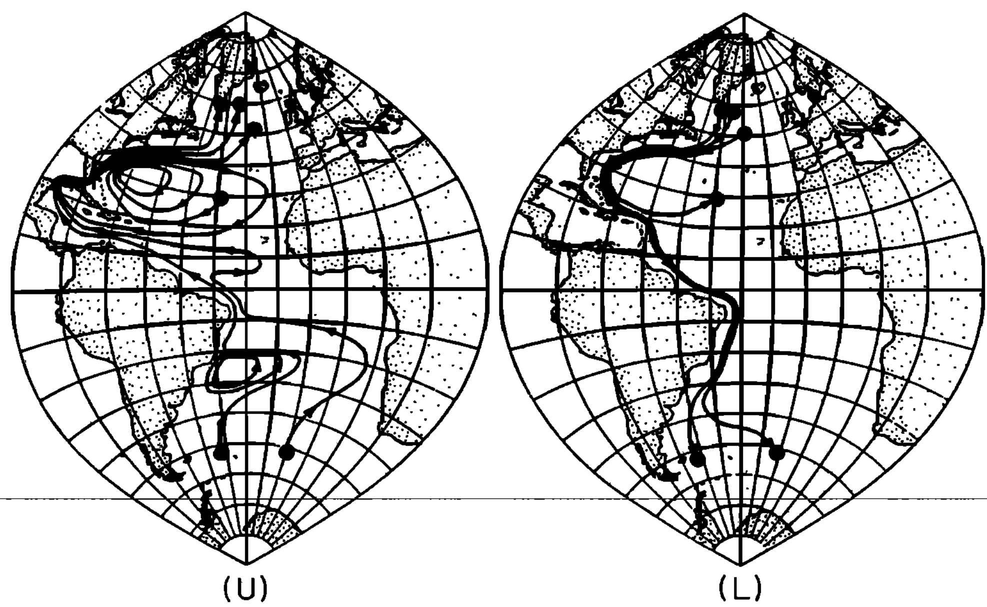


Figure 2. A two-layer schematic transport streamline field taken from *Stommel* [1957]; U denotes upper layer and L denotes lower. Solid circles indicate the sinking of North Atlantic Deep Water (NADW) in the northern North Atlantic and upwelling elsewhere.

process). Along-path cooling in the polar sea, with an entrainment scheme for the initial NADW path segments in the northern North Atlantic [*Dickson et al.*, 1990; *Dickson and Brown*, 1994; *Price and Baringer*, 1994], is a composite mechanism that could replace the idea that the extent of NADW formation is dominated by open ocean convection.

A comparatively recent major reformulation of the global picture of the thermohaline circulation involves the scheme for replacing NADW developed by *Gordon* [1986]. His map emphasizing a link between the upper layer compensation for NADW with upwelling and an upper layer circulation in the Indian and Pacific Oceans is shown here in Plate 1 (adapted from *Gordon* [1986, Figure 7]); see also Plate 2 (adapted from *Broecker* [1987, 1991], who introduced the conveyor belt terminology). Plates 1 and 2 are plotted on the standard base map for this review, which is also shown in Plate 3 with the 4000-m isobath and a few feature names. Plates 1 and 2 are to some extent geographically expanded versions of the thermohaline compensation associated with the ACCR in Figure 2, but with the Pacific and Indian Oceans providing most of the upwelling and renewal flow for NADW. The transfer of water from the Indian Ocean to the South Atlantic along the inshore edge of the ACS was first suggested by *Clowes* [1950] for potential density horizons of 26.5, 26.75, and 27.25 kg m^{-3}. *Clowes*'s [1950] work appears to be a very informative and perhaps undernoticed contribution, in which the major differences between intermediate waters in the South Atlantic and South Indian Oceans were also first described. The influence of the Indonesian through flow on the Indian Ocean circulation had also been previously emphasized by *Godfrey and Golding* [1981] and discussed even earlier by *Wyrtki* [1971] and *Gentilli* [1972]. A significant Indonesian passage through flow might also be needed to explain the origin of (at least part of) *McCartney*'s [1977, 1982] Subantarctic Mode Water (SAMW) flowing south of Australia and across and into the South Pacific.

In Plate 1, *Gordon* [1986] attributes more or less all (13.5 Sv, a controversial choice to say the least) of the upper layer compensation for NADW to a flow from the south Indian Ocean into the South and then North Atlantic. In *Gordon*'s [1986] text, however, there was noted a possible small (25% of NADW renewal, so 3–4 Sv) contribution of cold, fresh subantarctic water through Drake Passage (the heavily dashed green line in Plate 1), the so-called cold water path. This is "intermediate water" but, as it will turn out, its least dense brand. Another idea with respect to path for NADW renewal is related to previous suggestions concerning the transfer of intermediate water from the ACS (Indian Ocean) to the South Atlantic Ocean [*Clowes*, 1950; *Shannon and Hunter*, 1988; *Taft*, 1963] (see also *Gordon et al.* [1992] and *Talley* [1995]). The latest and most definitive field program in the Benguela Current (S. L. Garzoli and A. L. Gordon, Origins and variability of the Benguela Current, submitted to *Journal of Geophysical Research*, 1995, hereinafter referred to as Garzoli and Gordon, 1995) has the *Gordon* [1986] transport estimates reversed, that is, $O(10$ Sv) from the South Atlantic and 2–5 Sv from the south Indian Ocean.

In Plate 1, 8.5 Sv flows through the Indonesian archipelago and then joins 5 Sv upwelled water in the Indian Ocean which flow around Africa into the South Atlantic subtropical gyre circulation and eventually enter the North Atlantic. My interpretation is that roughly 5 Sv of upwelling from NADW to the thermocline layer in each of the Atlantic and Indian Oceans is implied by Plate 1, as is 10 Sv upwelling in the ACCR and Pacific Ocean (8.5 Sv through flow, 1.5 Sv as the Pacific to Atlantic flow through the Arctic Ocean, the latter not further considered in this review). Plate 4, adapted from *Broecker* [1991], may be thought of as an updated version of Plates 1 and 2. But how are the sites for the upwelling chosen in Plates 1, 2, and 4? The transport partition between cold water (10 Sv) and warm water (5 Sv) paths for NADW renewal as depicted by *Broecker* [1991] in Plate 4 is almost identical to that preferred in this review. It may be a bit early, but it seems to me that the general advective transport amplitude of Indian Ocean Water in the BCS has recently been rather thoroughly sorted out observationally (2–5 Sv (Garzoli and Gordon, 1995)). But regardless of further detail on the path partition issue, it is necessary at some point to determine how NADW gets converted to $O(10$ Sv) intermediate water flowing through Drake Passage and ~2–5 Sv upper layer plus intermediate water flowing west around the tip of Africa, and this is the least well documented issue at this time.

For present purposes, the ideas contained in Plates 1, 2, and 4 (plus many following investigations; see below) will be taken in this review to indicate the existence of an interbasin-scale circulation pattern that couples all three southern hemisphere oceans and also has a linkage to NADW renewal. Such a pattern includes some intermediate as well as upper layer flow. A generalized upper layer circulation pattern involving through flow and interbasin exchange, including a contribution to NADW renewal and a guess at the origin of this compensation, is outlined in Plate 5. In Plate 1, *Gordon* [1986] has the through flow circulating through Mozambique Channel only. In light of *Sætre and da Silva* [1984] and other studies, the dominant flow into the Agulhas Current system in Plate 5 occurs either from east of Madagascar and then south or toward the west across the ridge south of Madagascar, with only a minor input, perhaps primarily intermediate water, through the Mozambique Channel. IT denotes the flow through the Indonesian archipelago (Indonesian Throughflow), L denotes the Leeuwin Current [*Church et al.*, 1989], and IB denotes the interbasin exchange between the South Indian and South Atlantic Oceans. SC denotes a short circuit from the ACS to the Subtropical and Subantarctic Frontal Zones and R is a recirculation from these frontal zones back to the Agulhas. SC should be drawn through the Agulhas retroflection, but this could make Plate 5 difficult to read. N is the advective interaction of this entire process with NADW replacement, keeping in mind the possibility of a mixing interaction as well (which would presumably be a part of IB in Plate 5).

The important point for now is that the upper level interbasin exchange associated with the Indonesian Throughflow in Plate 5 is a complex process with lots of options, most yet to be determined with precision. IT probably plays only a minor advective role in NADW replacement but the major role in the upper layer southern hemisphere interbasin exchange. For example, the warm water flowing south of Australia (IB + SC − R + L in Plate 5) that appears in *McCartney*'s [1977] Subantarctic Mode Water figures probably requires a significant IT and SC. Another possibility would be that IT contributes to a diffusive modification of the subtropical gyre in the South Atlantic that influences intermediate water mass (from Drake Passage) modification. The hardest questions are to determine where NADW is converted to water with the characteristics of IT, and then how IT is converted to other water types, particularly Benguela Current Water, along with the origin and path of IT in the Pacific. In Plate 5, N Sv are advectively transported to the North Atlantic in the upper layer of a global interbasin exchange flow pattern, replaced by upwelling or modification of intermediate water in the Peru and Pacific equatorial current systems, with this N Sv of intermediate water originating as NADW in the southern oceans, schematically shown in Plate 5 to occur the eastern South Pacific. I suggest in Plate 5 the possibility of a small (~4 Sv) conversion of NADW to intermediate water, which may be converted to upper layer water in the Peru [*Wyrtki*, 1963] and Equatorial Current systems and exit from the Pacific through the Indonesian archipelago.

The flow patterns developed in the following are based primarily on a synthesis of a variety of published observational results as opposed to any dominant single point of view. However, it seems clear that authors will tend to emphasize those issues that seem interesting to them. In this review there is one major departure from published interpretation. I am suggesting, to my knowledge for the first time, that the $O(10$ Sv$)$ CDW converted to intermediate water (see the appendix) in the Indian Ocean (as first reported by *Toole and Warren* [1993] and verified by *Macdonald* [1993]) is a source, perhaps the most important source, for NADW compensation via interbasin exchange east along the Subantarctic Frontal Zone (SFZ) and out through Drake Passage. Large-amplitude flows in the intermediate water σ_θ range in the ACS were noticed long ago by *Clowes* [1950], *Harris* [1972], and *Visser and Van Niekerk* [1965]. It has been known for some time that the characteristics of intermediate water vary globally along the SFZ and in particular that Indian Ocean Intermediate Water is notably saltier than the brand of intermediate water found in the South Atlantic [*Clowes*, 1950] or South Pacific [*Piola and Georgi*, 1982]. *Burling* [1961] noticed early on that there were two types of intermediate or subantarctic water south of New Zealand: the "typical" fresh southern circumpolar variety and a salty "Australasian" variety that he felt originated in the Indian Ocean sector. Perhaps it is noteworthy in this context that *McCartney* [1977] attributes the initial formation of the denser SAMW to winter convective overturning of somewhat warmer and saltier waters advecting into the South Pacific from the west in the SFZ.

Some of the observationally based references that have turned out to be crucial to this review are entered on a standard global map (Plate 6). The reader should be aware that this investigation is concerned only with those intermediate layer and upper ocean flows that are part of the interbasin-scale replacement paths for the formation of deep and bottom water and is definitely not an account, for example, of intermediate water formation and circulation. Also, important upper layer thermohaline-related (thermocline) processes such as thermostad formation, ventilation of upper portions of the subtropical gyre, and mixed layer development are not examined. Because of the complex nature of the intermediate water component of the NADW renewal path, this topic is included as an appendix. In this review the focus is on volume transport amplitudes and pathways (as in Plates 1–4) and neither on flow details nor on heat nor freshwater budgets. Time variability is not considered for the sake of length and simplicity, not because it is not of considerable interest. Long-term fluctuations in the flow patterns described here are an important component of ocean climate.

The emphasis in this review is on water layers rather than water masses. Four layers are required to represent the range of global interbasin exchange, and two- (and three-) layer summaries should be a condensation of the four-layer picture, all with explicit representations of transformations between layers. The need for a minimum of four vertical layers in describing the ocean circulation was clearly articulated much earlier by *Reid* [1981]. The global conveyor belt notion (Plates 1, 2, and 4) is a very stimulating, basically two-layer idea, centered around NADW compensation, but does not adequately consider the essential role of intermediate water in NADW renewal or an abyssal or deep water linkage of global scale, specifically the important role that CDW plays [*Mantyla and Reid*, 1983]. Indeed, the existence of NADW characteristics in the Pacific and Indian Ocean bottom and deep cells means that these cells cannot be ignored in

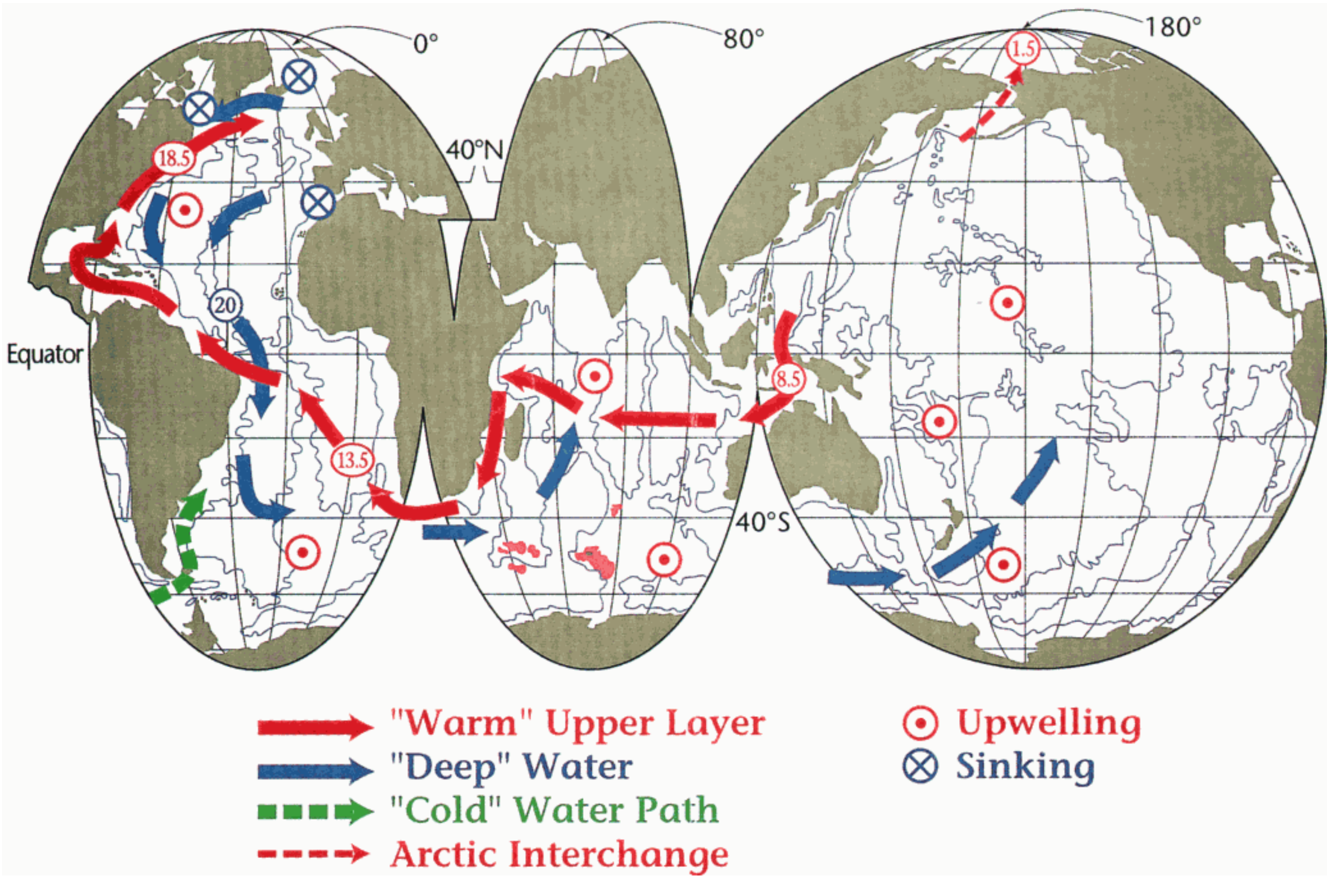


Plate 1. A map of the pathways and transports for NADW formation and renewal, adapted and modified from *Gordon* [1986]. Transports in circles are in sverdrups.

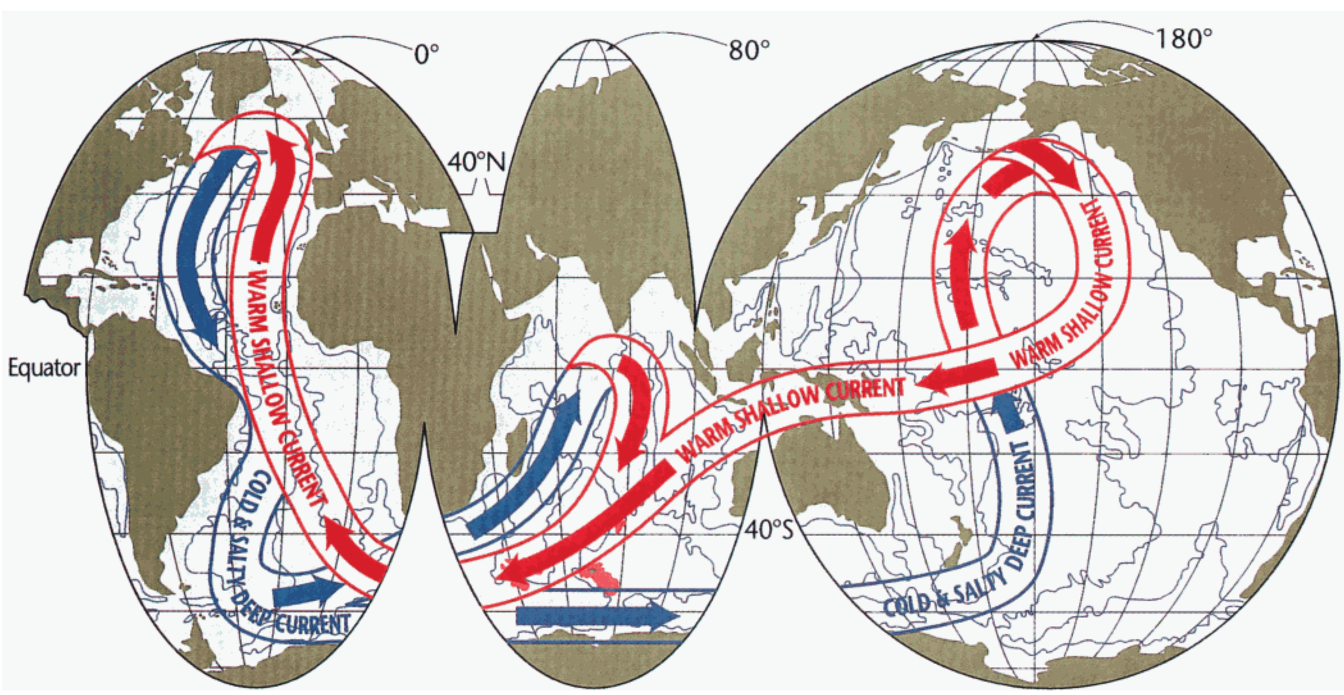


Plate 2. The two-layer thermohaline conveyor belt summary taken schematically from *Broecker* [1987, 1991], plotted on a different base map.

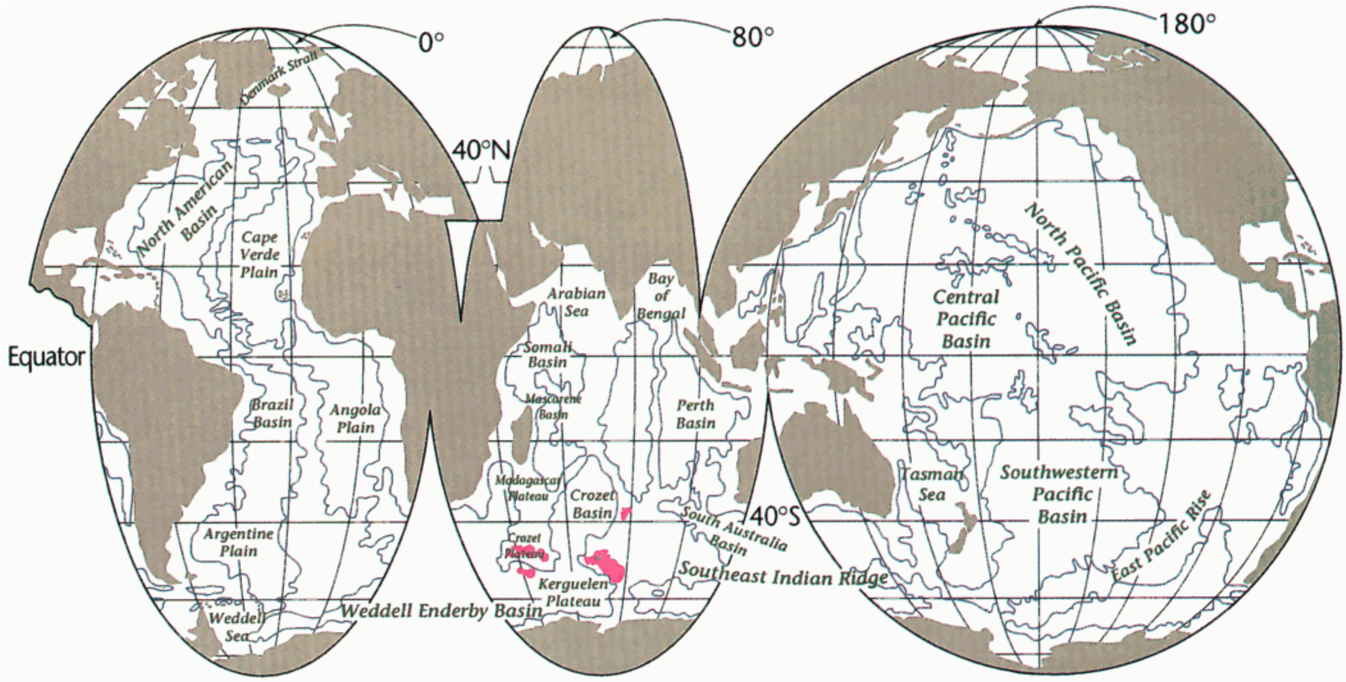


Plate 3. The standard base map used in this review with the 4000-m isobath and topographic feature names.

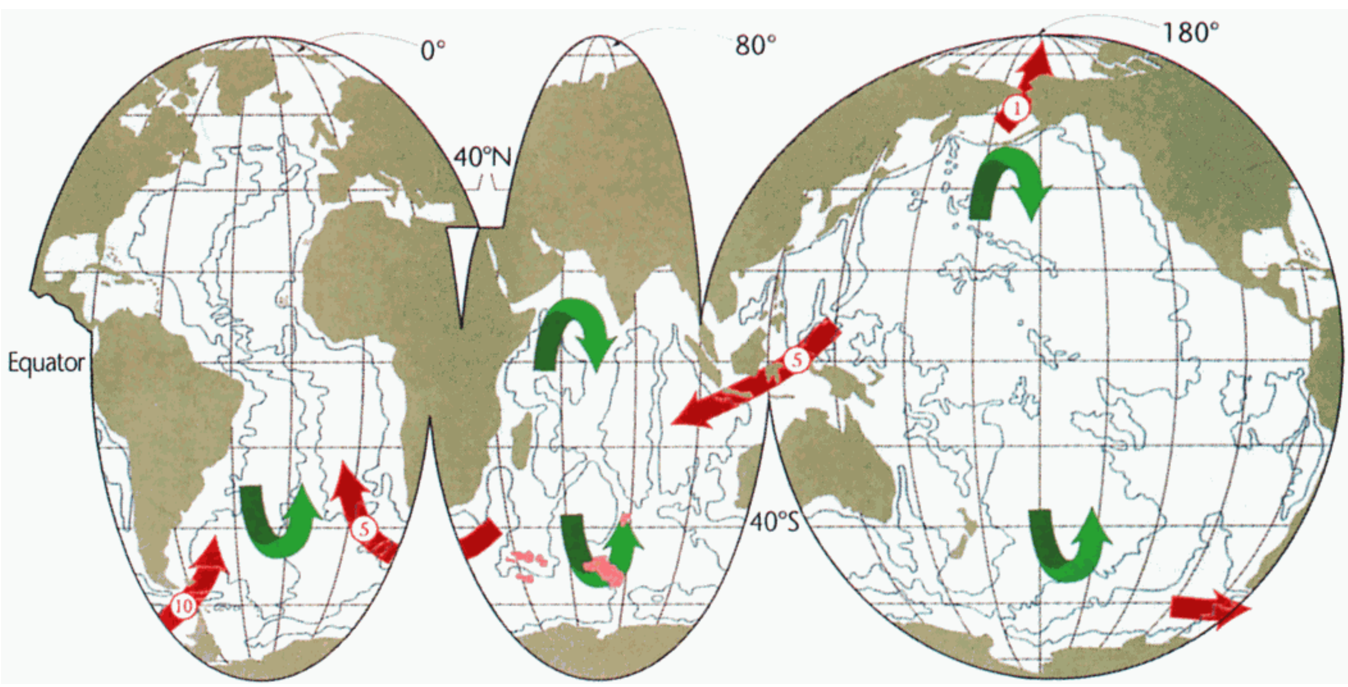


Plate 4. An updated two-layer thermohaline flow scheme depicting the location of upwelling (green arrows) and the NADW renewal flow paths, adapted from *Broecker* [1991, Figure 4]. The critical path segments for the "upper layer" NADW compensation are shown in red with transports (in sverdrups; 1 Sv = 10^6 m^3 s^{-1}) circled (also true for Pacific to Atlantic exchange through the Arctic).

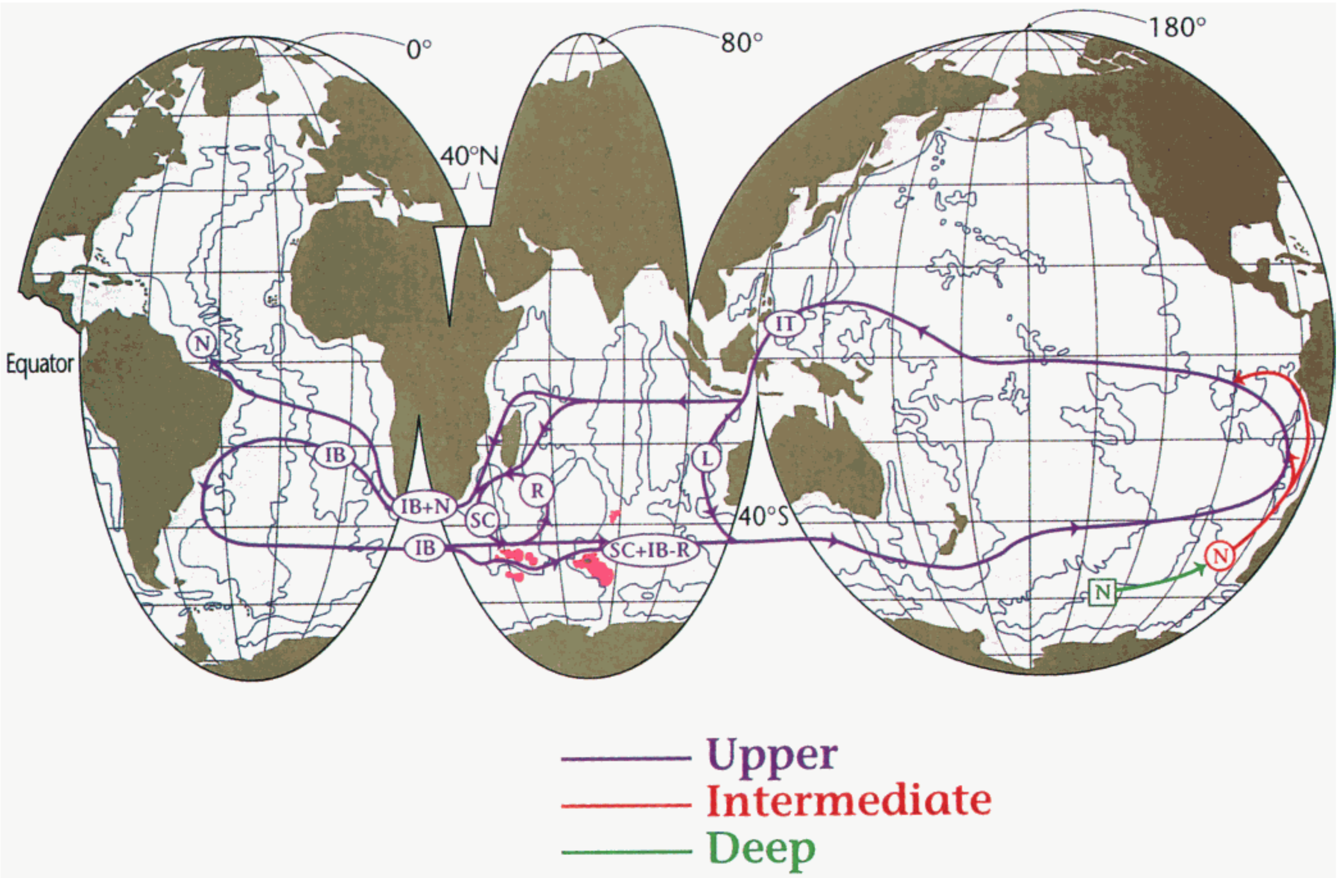


Plate 5. A map of the transport pathways for an upper layer interbasin exchange flow pattern. IT denotes the flow through the Indonesian archipelago (Indonesian Throughflow), L is the Leeuwin Current, IB is the interbasin exchange between the south Indian and South Atlantic Oceans, SC is the short circuit from the Agulhas Current system to the Subtropical and Subantarctic Frontal Zones. R is a recirculation within the Agulhas Current system, and N is the "leakage" to the North Atlantic.

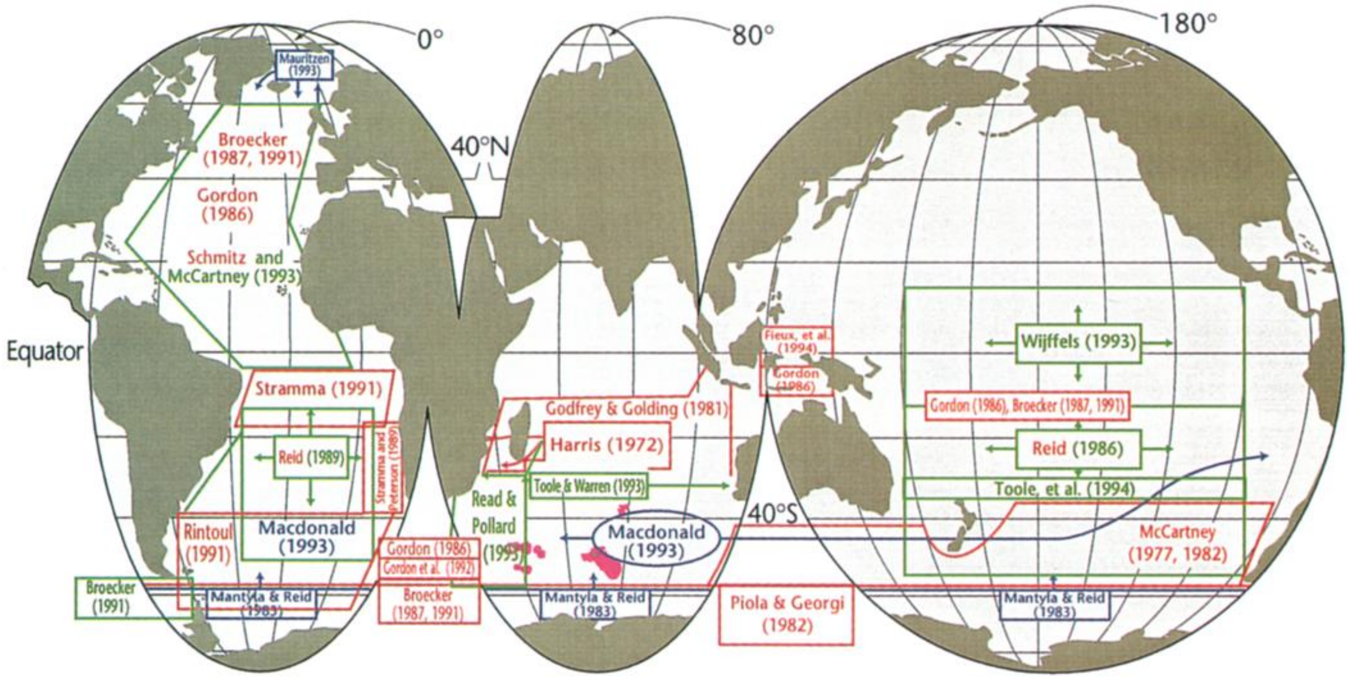


Plate 6. The standard base map with some critical references shown.

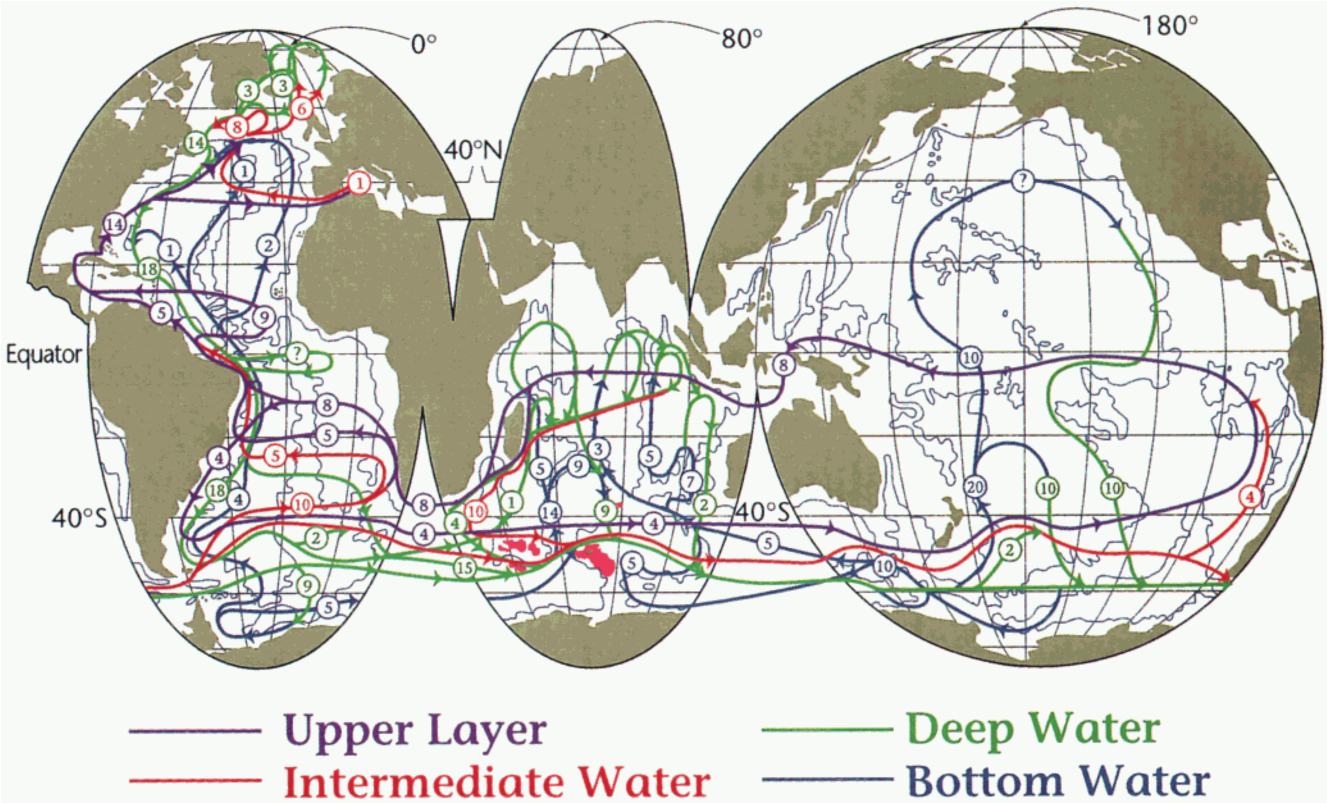


Plate 7. A four-layer version of the deep and abyssal global thermohaline circulation and its upper level compensation flows. Bottom water is shown by a blue line, and deep water is shown by a green line; a red line is used for intermediate depth flows, and purple denotes the uppermost layer. Volume transport estimates (in sverdrups) are in circles associated with the key path segments, and color changes indicate water mass conversion. The characteristics of these flows, which may vary with location, are discussed in the text.

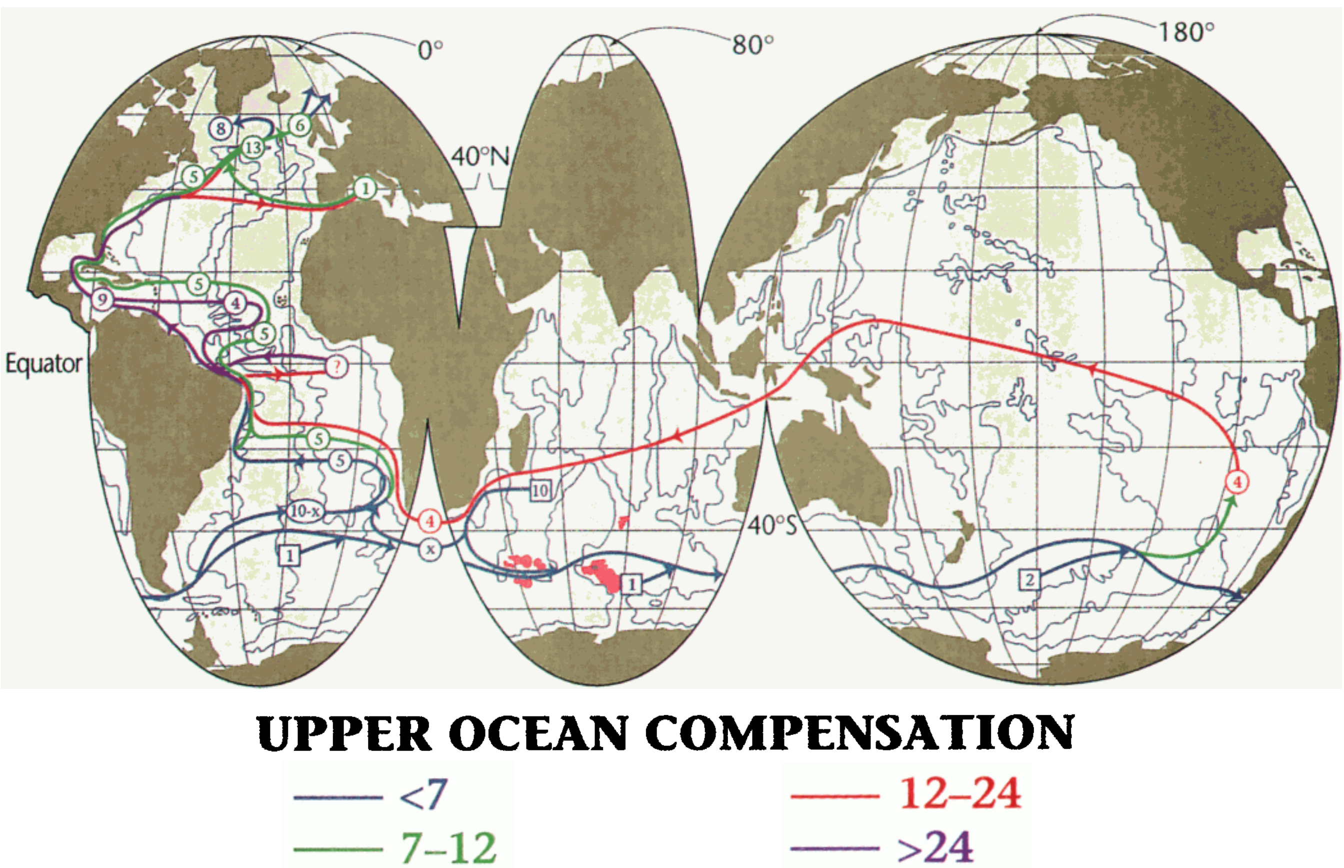


Plate 8. Global map of a four-layer breakdown of the renewal flow for the abyssal and deep circulation in Plate 7. Intermediate layer water is shown as a blue line, flow in the temperature interval 7°–12°C is shown by a green line, 12°–24°C flow is shown by a red line, and flow for temperatures >24°C by a purple line. The cross denotes the intermediate layer flow from the south Indian to the South Atlantic Ocean. Transports in sverdrups are in circles.

the context of NADW replacement, as is the case in Plates 1, 2, and 4.

In the following a variety of maps for the interbasin-scale deep and bottom thermohaline transports are presented, including the necessary compensating or renewal flows, with pathways that are as geographically explicit as possible. Bottom and intermediate layer flows are considered, as are those for deep and uppermost layer water. Four-level maps are described and summarized in two color plates and a table. After this, new simplified outline or summary maps for two and three vertical levels are briefly described. Then there is a discussion, followed by closing remarks. In the most general terms, looking at about 10 to 20 key numbers, the interbasin-scale pathways and transports summarized by *Roemmich and McCallister* [1989] are similar to what is found in this review, with a few exceptions.

GLOSSARY

Geostrophic flow: the simplest possible large-scale, very low frequency (or approximately steady state) dynamical balance between Coriolis and pressure gradient forces, similar to the situation in the atmosphere. The vertical current shear is proportional to the horizontal density gradient across the flow axis as a good first approximation ($\sim\pm10\%$) for large-scale, low-frequency ocean currents. Higher-order dynamics may be used to account for spatial variability along the flow axis, particularly in special regions, often boundary layers and/or boundary currents. To determine volume transport (volume-integrated currents) from estimates of geostrophic vertical current shear requires measurement of the transport at some pressure or the absolute pressure at some level or an estimate of location of a zero-velocity surface (a reference level). These are comparatively routine atmospheric observations but typically quite difficult oceanographically, where there also may be critical temporal and spatial sampling considerations. Since long-term direct current measurements are sparse, indirect methods are normally used to reference hydrographic sections (see below).

Potential temperature or density: the effective temperature or density of a parcel of water after removing the heat associated solely with compression. The use of various density parameters to study the deep and abyssal circulation was pioneered by *Lynn and Reid* [1968] and *Reid and Lynn* [1971]. They used the conventional definition that potential temperature θ is the temperature a water parcel would have if raised adiabatically to the sea surface (where pressure is assumed to be 1 atm), with an analogous definition for potential density σ_θ. *Lynn and Reid*'s [1968] introduction of the use of density parameters σ_p for any desired pressure p (they emphasized 4000 dbar, σ_4) is now routine.

Recirculating currents or gyres: boundary currents, like the Gulf Stream or Agulhas in the upper ocean and the deep western boundary currents (DWBCs) in the lower ocean, in many places have adjacent subbasin-scale opposing flow elements or countercurrents. Such currents or countercurrents tend to be recirculations or recirculating gyres of some similar water masses, and they can impact the choice of reference level for hydrographic sections because water with similar properties can be moving in opposite directions.

Reference level: direct measurement or estimate of currents or transports at some depth, pressure, or density horizon; possibly a zero-velocity surface (see geostrophic flow, and recirculating currents, above). The two main indirect methods currently used typically appeal to various mass (volume transport) conservation constraints and/or to the notion that water mass characteristics indicate flow direction [e.g., *Macdonald*, 1993; *Reid*, 1986, 1989, 1994; *Rintoul*, 1991; *Toole and Warren*, 1993].

Thermohaline circulation: buoyancy-driven flow field associated with water cooled (or heated) by contact with cold (warm) air, or modified by sources and sinks of fresh water. May also include flows whose characteristics are significantly altered by upwelling and/or by mixing. Water sinking at high latitudes tends to return equatorward in relatively strong, narrow currents called DWBCs.

Water mass characteristics: property ranges by which water masses can be identified and "tracked." The most basic are temperature T, potential temperature θ, salinity S, potential density σ_θ, and/or density parameter at a particular pressure p, σ_p (see above). Other valuable characteristics include concentrations of oxygen, nitrate, phosphate, silicate, chlorofluorocarbon, carbon 14 and tritium.

A FOUR-LAYER DESCRIPTION

A four-layer transport cartoon (Plate 7) for the abyssal and deep interbasin-scale thermohaline circulation, including intermediate and upper layer compensation flows, has been developed primarily on the basis of published observational results. Several key references and their areas of influence are indicated on Plate 6. In Plate 7, bottom water is shown by a blue line, and deep water is shown by a green line; a red line is used for intermediate layer flows, and purple denotes the upper layer pathways. Volume transport estimates (in sverdrups) are in circles associated with path segments. The pathways in Plate 7 are obviously nonunique simplifications, although I have tried to be as accurate as possible. Nevertheless, Plate 7 is still complicated. There is general but not complete agreement in the observational literature concerning the intensities and patterns of volume transport depicted in Plate 7. The most open questions are associated with the Indian and Pacific Oceans, especially the flows associated with vertical exchange, the least well established features of the ocean circulation anywhere.

The upper layer will typically contain water with potential density anomaly less than 26.8 kg m^{-3} (σ_θ units hereinafter are understood). In the following, intermediate water will normally be defined in the most general sense as having a potential density range σ_θ = 26.8–27.5, say, with water in the range σ_θ = 26.8–27.2 referred to as "upper" intermediate water. Note that this differs somewhat from the view of intermediate water as that associated with a salinity minimum, typically having $\sigma_\theta \sim$ 27.2–27.3 at midlatitudes. *Taft* [1963] described some time ago the properties of intermediate water in the σ_θ range 26.8–27.5 in the southern hemisphere oceans (plus the northern Indian Ocean). Bottom water and lower deep water, which may be at the bottom over some areas, exhibit σ_θ in the range 27.8–28.1 [*Lynn and Reid*, 1968, Figures 3 and 4], so upper deep water has σ_θ of 27.6–27.7. *Talley* [1995] describes intermediate water on surfaces of σ_1 from 31.6 to 32.0. *Mantyla and Reid* [1995] use σ_4 values in the abyssal Indian Ocean of 45.8–46.1 and characterize the deep flow on a σ_3 surface of ~41.5. Most recently, *Lozier et al.* [1995] have described the climatology of the North Atlantic on eight σ_p surfaces from σ_θ or σ_0 of 26.5 and 27.0 through σ_1 of ~32.0, σ_3 near 41.5, and σ_4 = 45.9. Other property ranges for these layers are discussed below as needed. Layers outcrop at high latitudes, but typical depth ranges in nonpolar areas are as follows: abyssal water, 4000 m to the bottom; for deep water, 1500 m to 4000 m; intermediate water, 800 to 1500 m; and upper layer, 0 to 800 m, the latter generally having potential temperature greater than 7°C at lower latitudes.

The nature and extent of Indian Ocean and/or Indonesian Throughflow influence on NADW compensation in the South Atlantic in Plates 1, 2, and 4 were challenged by *Rintoul* [1991] and others [i.e., *Schmitz and McCartney*, 1993; *Toggweiler and Samuels*, 1993a, b]. The data-based estimate by *Gordon et al.* [1992, Figure 1] is 3.9 Sv net excess upper layer water advecting around Africa into the South Atlantic rather than the 13.5 Sv shown by *Gordon* [1986]. There could be a mixing as well as an advective influence, for example, the transport of Indian Ocean water and properties into the South Atlantic by cut-off Agulhas retroflection rings [*McCartney et al.*, 1991], which could involve intermediate as well as upper layer exchange. *Gordon et al.* [1992] state in their abstract that 10 Sv of Indian Ocean water exists within the Benguela Current regime (BCR), enhanced by transports associated with Agulhas retroflection rings. *Stramma and Peterson* [1989] found 8 Sv of water of Indian Ocean origin in the BCR. The most recent observational picture of the upper 1000 m of the BCR has 2–5 Sv as the advective component from the Indian Ocean sector (Garzoli and Gordon, 1995); the mean is 3–4 as adopted here. *Toole and Warren* [1993] identify a net southward flow of 7 Sv along 32°S in the Indian Ocean for their choice of reference levels. *Godfrey and Golding* [1981] originally suggested a through flow of 7–14 Sv. IT = 7–8 Sv and N = 3–4 Sv appear to be the centroid of published mean values and are adopted here. This could be consistent with a possible Agulhas eddy transport (in IB) of roughly the same size as N (~3–4 Sv) around Africa into the South Atlantic [*McCartney and Woodgate-Jones*, 1991; *Gordon et al.*, 1992]. The results presented by *Macdonald* [1993] for an Indonesian Throughflow of 10 Sv yield transport values similar to those described in this review except in a few locations.

Recently, *Fieux et al.* [1994] have observed a comparatively high IT (15–20 Sv), raising the possibility of large-amplitude temporal variability on a variety of scales (tidal, seasonal, interannual). The bulk of their through flow transport is in the upper 200-m depth range at $\sigma_\theta < 26.0$, $T \sim 23$°C, and $S \sim 34.2$ psu (practical salinity units, hereinafter understood). How is this very light, warm, and fresh IT water modified into BCR water? Is it possible that a large fraction of IT joins the coalescence (the SC route in Plate 5) of the ACS and subtropical front and perhaps even enters the SFZ and flows across the Indian Ocean and south of Australia, participating in the SAMW modification process [*McCartney*, 1977, 1982] and recirculating in the South Pacific Ocean? The advective part of all of this is handled in Plate 7 approximately as indicated in Plate 5, except that SC, L, and R have not been put in Plate 7 for simplicity. Also a "direct" conversion of 4 Sv of NADW to intermediate water in the ACCR is shown schematically in two steps of 2 Sv each, as opposed to the one 4-Sv step shown in Plate 5. For Plate 7 (and 5) I have adopted the prevailing picture [*Gordon*, 1986; *Rintoul*, 1991] for only two types of replacement paths for NADW renewal. A third possibility, an intermediate water flow or "leakage" from the southern Indian Ocean into the South Atlantic (as described long ago by *Clowes* [1950] and *Taft* [1963] and more recently by *Shannon and Hunter* [1988]), is discussed further below. The recent measurements by Garzoli and Gordon (1995) would appear to limit this intermediate water interaction to $O(1$ Sv) above 1000-m depth.

Some features of the circulation patterns in Plate 7 will now be described by proceeding along path segments, typically from deep to shallow, south to north, and west to east, starting with the Atlantic Ocean. Key transport estimates that determine interbasin-scale exchanges are summarized in Table 1. No attempt will be made to depict with precision the circulation path(s)

TABLE 1. Key Sectional Thermohaline Component Transports for Plate 7

Location	*Upper Layer*	*Intermediate Layer*	*Deep Layer*	*Bottom Layer*
Drake Passage (E, W)	...	10	9	...
Atlantic at 32°S (N, S)	10	4	−18	4
Atlantic at 24°N (N, S)	14	...	−18	4
Atlantic at latitude just south of polar seas (N, S)	6	8	−10	−4
South of Africa (E, W)	−4	2	16	5
Indian at 32°S (N, S)	−8	−10	−5	15
Indian at 18°S West of Madagascar (N, S)	−8	−8	−5	13
Mozambique Channel (N, S)	...	−2	...	...
South and North of Australia (E, W)	−4	12	21	−10
Pacific at 32°S (N, S)	4	4	−20	20
Indonesian Throughflow (E, W)	−8	...	...	...
Pacific at 10°N (N, S)	...	...	−10	10

All transports are in sverdrups (10^6 m^3 s^{-1}). Positive transports indicate eastward or northward flow (axis orientation is indicated in parentheses).

associated with the Polar and Subantarctic Frontal Zones (PFZ and SFZ, shown by the green and red lines, respectively, around Antarctica in Plate 7) that here constitute the ACCR. However, the mass balance of the additions to and away from the SFZ or PFZ is closed. For example, in Plate 7, CDW in the vicinity of the PFZ is shown to gain and lose 55 Sv (Table 2), and intermediate water (the circumpolar red line in Plate 7) in the vicinity of the SFZ gains and loses 14 Sv. The path of CDW in the PFZ is shown crudely by a green

TABLE 2. Volume Transport Budget for CDW in Plate 7

	Transport, Sv	*Sector of ACCR*
	Joining CDW	
From NADW	15	South Atlantic and western south Indian Oceans
From Weddell Sea	5	south of western south Indian
From DW	4	western south Indian
From Crozet (Recirc.)	6	
From IODW	3	
From DW	2	eastern south Indian
From NPDW	10	South Pacific
From PDW (Recirc.)	10	South Pacific
Total	55	
	Leaving CDW	
To Weddell Sea	9	South Atlantic
To IOBW	14	western south Indian
To IOBW	10	south of Australia
To PBW	20	South Pacific
To Intermediate Water	2	South Pacific
Total	55	

Abbreviations are CDW, Circumpolar Deep Water, ACCR, Antarctic Circumpolar Current regime; NADW, North Atlantic Deep Water; DW, generic deep water; IODW, Indian Ocean Deep Water; NPDW, North Pacific Deep Water; IOBW, Indian Ocean Bottom Water; PBW, Pacific Bottom Water; Recirc., recirculation.

line across the bottom of the map just north of 60°S, being at about this latitude in Drake Passage and bulging north of 60°S in other locations. A few but not all of these excursions such as near the Crozet Basin are shown explicitly (for reasons noted below [see *Park et al.*, 1993]). Here, CDW is taken to be a mixture of deep and bottom waters (including NADW along with deep waters from the Indian and Pacific Oceans plus a possible variety of Antarctic "continental"-related components) homogenized within the ACCR. As lower CDW leaves the ACCR to become bottom water, a blue line is used.

Water from the Weddell Sea, a mixture of CDW from Drake Passage and water formed on the Antarctic continental shelf nearby, is often called Antarctic Bottom Water (AABW) as it flows into the South Atlantic [*Reid and Lynn*, 1971; *Reid*, 1989]. This is indicated by a blue line cyclonic gyre in the Weddell Sea with a branch that moves north along the coast of South America as a DWBC just offshore of the 4000-m depth contour. In the initial stages of its path, AABW has temperature-salinity characteristics of about −0.8°C and 34.66 [*Mantyla and Reid*, 1983], warming to about 1.9°C in the North Atlantic. Antarctic Bottom Water shown joining CDW in the PFZ by flowing into the Southern Ocean sector south of the south Indian Ocean from the Weddell Sea with an intensity of 5 Sv is taken from *Rintoul* [1991, Figure 5].

The flow of AABW in the latitude range of the Brazil Basin has recently been examined again by *Speer and Zenk* [1993] and *Speer et al.* [1992]. They identify roughly 7 Sv of AABW flowing north in this area; here the throughput is taken to be 4 Sv [*Hogg et al.*, 1982], possibly indicating a conversion of ~3 Sv (N. Hogg, personal communication, 1995) to lower NADW in the interior of the Brazil Basin (not shown in Plate 7). *Macdonald* [1993] has a net export of 7.5 Sv AABW north across 30°S and 15°S (her net deep plus abyssal water flowing southward is 21.5 − 7.5 = 14 Sv, as found by most authors, including this writer). The flow of AABW north of the Brazil Basin in Plate 7 is taken from *McCartney and Curry* [1993], and the general path of this water mass in the North Atlantic is taken from *Schmitz and McCartney* [1993]. This current is shown to shift from the western continental boundary to the western flank of the Mid-Atlantic Ridge near the equator and continue as such into the North Atlantic. A branch of AABW, being continuously modified in its properties, flows through the Vema Fracture Zone near 11°N and up to high latitudes, where it joins the subpolar circulation of NADW in the northern North Atlantic [*McCartney et al.*, 1991]. Another branch joins the DWBC along the east coast of the United States. Details of this complex path are not shown in Plate 7, but the net rounded-off transport shown is taken from *Schmitz and McCartney* [1993].

Even though NADW formation has been studied extensively, there is an exciting new possibility concerning its development in the polar and Arctic seas [*Mauritzen*, 1993], as shown very schematically in Plate 7. When this is taken jointly with recent ideas about overflows developed by *Price and Baringer* [1994] along with observational results of *Dickson et al.* [1990] and *Dickson and Brown* [1994], a new picture of NADW formation might be forthcoming. For example, the combined overflows of 5–6 Sv through the Denmark Strait and Iceland-Faroe Channel could simply be a cooled and slightly freshened 5–6 Sv from the North Atlantic Current in the polar sea that entrains 5–6 Sv from the "ambient" subpolar (cyclonic) gyre (see a similar earlier suggestion by *Reid and Lynn* [1971]) in the depth and water property range over which the overflows plunge (from ~1000 to 4000 m) to their natural level, leading to a net flow of 10–12 Sv NADW. Perhaps intermediate and/or deep convection in the subpolar gyre acts primarily to inject Labrador Sea Water characteristics into the cyclonic subpolar gyre [*McCartney and Talley*, 1984], where they are entrained, rather than as an essential volume transport control. So the 8 Sv shown sinking to form Labrador Sea Water in Plate 7 might represent 2 Sv deep convection plus 6 Sv water mass modification of a "deep" branch of the North Atlantic Current into "subpolar gyre water" which is then entrained into the 6-Sv overflows, leading to a total of 14 Sv of NADW formation. NADW is not shown as a blue line in the northernmost North Atlantic for the sake of clarity, but a guess at the bottom-deep partitioning is contained in Table 1. *Dickson and Brown* [1994] have clearly outlined the extent of the remarkable general support for a comparatively steady ~12–15 Sv overall NADW formation, and there is general agreement that this is the transport exported to the South Atlantic and to the ACCR [*Macdonald*, 1993; *Rintoul*, 1991; *Schmitz and McCartney*, 1993].

The highly idealized DWBC path for NADW for the Atlantic in Plate 7 is basically along the 4000-m depth contour. The possibility of an excursion of NADW along the equator [*Richardson and Schmitz*, 1993] is indicated by a green line zonal loop with a question mark transport in the vicinity of the equator in Plate 7. The transequatorial path of NADW in Plate 7 could also indicate some upwelling of lower NADW to middle NADW [*Friedrichs et al.*, 1994]. Similar phenomena, that is, zonal paths at the equator possibly associated with upwelling, could also characterize [*Warner and Weiss*, 1992] intermediate water (not shown in Plate 7 for simplicity). The equator may turn out to be a prominent oceanic upwelling site for deep and intermediate flows as well as for the upper ocean, possibly with some connection to the existence of deep equatorial jets [*Eriksen*, 1982; *Luyten and Swallow*, 1976]. The path of NADW in the South Atlantic is to a large extent taken schematically from *Reid* [1989, 1994], although many elements of the zonality of the southward flow of NADW [*Reid*, 1989, 1994; *Tsuchiya et al.*, 1994] in the South Atlantic cannot be shown without cluttering up Plate 7 even more. In the southwestern Atlantic the Malvinas (Falkland) Current excursion could be confusing in Plate 7, but it should be kept in mind that the interaction between intermediate water and the subtropical gyre in this regime could be important to the NADW renewal process.

The transport of intermediate water from Drake Passage into the South Atlantic as compensation for NADW is taken from *Rintoul* [1991]. It should be emphasized that "upper" intermediate water (σ_θ range of 26.8–27.2), *Rintoul*'s [1991] layer 3, is where his net loss of intermediate water between Drake Passage and 30°E occurs. That is, "upper" intermediate water is *Rintoul*'s [1991] primary source for the replacement of NADW. Denser varieties, essentially Antarctic Intermediate Water (AAIW) near the salinity minimum at lower latitudes [*Talley*, 1995; *Tsuchiya*, 1989], are layer 4 (plus perhaps 5) for *Rintoul*'s [1991] calculations. His layer 4 loses less than 1 Sv to the north as it moves from Drake Passage to 30°E, whereas layer 3 loses 10.6 Sv. This does not mean that denser AAIW does not get north of the SFZ in the Atlantic but rather that its northward and return southward transports balance across 32°S, with less than 1 Sv net north-south transport, and therefore are not a critical factor in NADW renewal. That is, the "cold water path" water is cold and fresh but comparatively light and not necessarily in the conventional salinity minimum density range of AAIW at lower latitudes. All of *Rintoul*'s [1991] net northward flow across 32°S occurs in the Benguela Current system, that is, in the last seven or eight station pairs on the eastern side of his 32°S section [*Rintoul*, 1988], with the 10 Sv of "upper" intermediate water (layer 3) exiting north across 32°S as 4 Sv of layer 3 water and 6 Sv of layer 2 or "thermocline" water (σ_θ = 26.2–26.8). This conversion of layer 3 to layer 2 water is probably the least convincing part of *Rintoul*'s [1991] scheme for NADW renewal. The preceding examination of Rintoul's results is new with this review.

It is essentially upper intermediate water in the σ_θ interval 26.8–27.2 (with $7° \leq T \leq 12°C$ and $S =$ 34.9–35.0 in the Straits of Florida) that was found by *Schmitz and Richardson* [1991] and *Schmitz et al.* [1993] to be moving from the South Atlantic into the Caribbean Sea and out of the Straits of Florida onto the Blake Plateau. Denser varieties of AAIW exist in the Caribbean [*Morrison and Nowlin*, 1982] and Gulf of Mexico (and the Straits of Florida where depths of 850 m and more occur). *Morrison and Nowlin* [1982, Table 1] identify a water mass with typical $\sigma_\theta = 27.15$, a depth range of 400–700 m (the deepest water exiting the northern Straits of Florida), and low oxygen values. Significant transport can occur from the northern straits only at temperatures of 7°C and higher, even though 6°–7°C water exists off Miami and Key West, presumably because the depth shoals to ~700–725 m across the Fort Pierce section. The probable subantarctic origin of this water in the Florida Current above the Blake Plateau was noted early on by *Iselin* [1936]; see also *Atkinson* [1983] and *Richardson* [1977]. The penetration of the comparatively low salinity and high silicate that characterize the 7°–12°C water in the Straits of Florida into the Gulf Stream and North Atlantic Current was clearly shown by *Tsuchiya* [1989]. The increase in salinity of this water as it moves from the Straits of Florida to its entrance into polar seas off England occurs more or less continuously along its path [*Tsuchiya*, 1989, Figure 2], apparently interacting with Mediterranean Water to do so [*Reid*, 1994], and the route that this water takes is best defined by the silicate distribution [*Tsuchiya*, 1989, Figure 3].

In the South Atlantic the upper layer flow (purple line) is taken from *Reid* [1989], *Peterson and Stramma* [1991], *Stramma* [1991], and *Stramma and Peterson* [1989, 1990]. The upper layer compensating flow for NADW in the North Atlantic is taken from *Schmitz and McCartney* [1993]. This water has two distinct temperature-salinity-depth ranges [*Schmitz et al.*, 1993], $T > 24°C$ and $S =$ 34.9–35.2 in the upper 50–75 m of the water column, and a layer of "upper intermediate" water with $7° \leq T \leq 12°C$ and $S =$ 34.8–35.0 in the depth range 400–800 m, referred to as upper layer water as it proceeds through the Caribbean and Straits of Florida [*Schmitz and Richardson*, 1991]. The salinity range of the water entering the polar seas of the North Atlantic to replace NADW [e.g., *Fuglister*, 1960, pp. 84–85] is 35.0–35.5 with a temperature range of 5°–12°C (the maximum depending on season), possibly the result of some salinity enhancement by Mediterranean Water [*Reid*, 1994] (see also *Tsuchiya* [1989]).

The flow of bottom water (lower CDW) from the circumpolar region into the south Indian Ocean is taken from *Kolla et al.* [1976], *Mantyla and Reid* [1983, 1995], *Speer and Forbes* [1994], and *Toole and Warren* [1993]. The northward flow of this water into the Crozet Basin (14 Sv according to *Toole and Warren* [1993] or 9 Sv according to *Park et al.* [1993]) starts at potential temperatures near 0.0°C and reaches 0.5°C with a salinity near 34.70 psu in the basin. The flow into the Perth Basin (10 Sv according to *Toole and Warren* [1993]) starts with lower CDW now having Ross Sea and Adélie Coast components at 0°C and reaches 0.5°C in the Indian Ocean at a salinity near 34.71 [*Mantyla and Reid*, 1983, 1995].

The bottom and deep compensating flows for the southern Indian Ocean in Plate 7 are partly adapted from *Toole and Warren* [1993], but the recirculation (that I infer from the maps by *Mantyla and Reid* [1995]) of the deep and/or bottom water in the Crozet Basin is taken to be 9 instead of 4 Sv per *Toole and Warren* [1993]. The point of view taken here is to some extent consistent with *Park et al.* [1993], who have a net northward flow of 6 Sv (9 Sv north and 3 south, the latter comparatively high silicate North Indian Ocean Deep Water) in the Crozet Basin. I also choose 2 Sv deep water return instead of 1 in the Perth Basin, leading to a net bottom and deep water inflow below 2000 m north across 32°S of 14 Sv. The NADW (taken to be 1 Sv here, possibly larger) flowing directly into the Madagascar and Mascarene Basins is adapted from *Mantyla and Reid* [1995]. *Macdonald* [1993, Table 9] finds a net bottom and deep water (below $\sigma_2 = 36.8$, located at roughly 2000-m depth at 32°S) transport north through the 32°S section of 13 Sv (for an IT of 10 Sv), very close to the value (~15 Sv) chosen (independently) here. The bottom water (blue line) flowing into the central Indian Basin may be composed of more deep water than is shown in Plate 7, and in general there may be more younger NADW moving north in the southern Indian Ocean than is indicated in Plate 7 (A. Mantyla, personal communication, 1995).

Toole and Warren [1993] focused on transports above and below 2000 m, but there is a layer of water between 1500 and 2000 m which is here taken as "upper" deep water (~4 Sv of the green line flow in Plate 7). *Toole and Warren* [1993, Figure 5 and associated text] have a net excess of roughly 10 Sv of southward transport in the Agulhas Current across 32°S (see the appendix) in the intermediate water potential density range 27.0–27.5. This is comparatively high salinity (~34.5–34.6) and low oxygen (~4 mL L^{-1}) intermediate water, sharply distinct, for example, from the brand of intermediate water found in the Atlantic [*Clowes*, 1950; *Piola and Georgi*, 1982]. *Macdonald* [1993] finds a net excess southward transport of 9 Sv in the intermediate water density range through the 32°S Indian Ocean section, essentially identical to the analogous result by *Toole and Warren* [1993] but using a much different method of calculation, and this estimate is approximately independent of IT. The Indian Ocean pathway summarized by *Roemmich and McCallister* [1989, Figure 7 and associated discussion] has an $O(10$ Sv) thermohaline cell in the Indian Ocean but from deep to intermediate and upper layer flow, as opposed to bottom to deep and intermediate.

In Plate 7 the net 14 Sv of northward flowing bottom water at 32°S is eventually modified to become both deep water below 2000-m depth (2 Sv) and "upper" deep water (at 1500–2000 m nominal depth range, 3 Sv associated with the ACS along with 1 Sv directly upwelled NADW for a total of 4 Sv in the ACS) as well as intermediate water (700–1500 m nominal depth range). The latter is shown to flow south in the Agulhas Current system and join the SFZ (red line, 10 Sv) southeast of the southern tip of Africa in the Crozet Basin where the three fronts (Polar, Subantarctic and Subtropical) are typically seen to merge [*Park et al.*, 1993]. In Plate 7 the path of the upwelled intermediate water is taken to be south of Madagascar into the ACS. However, it may be that a few sverdrups of intermediate water enters the Agulhas through Mozambique Channel from the north. The nature of this "upwelling" or water mass modification is unknown, a crucial area for future study. Perhaps the equatorial or low-latitude segment of the north Indian Ocean is important in this regard, and/or the eastern south Indian Ocean off the coast of Australia. No attempt is made in Plate 7 to depict the conversion of bottom to deep water in the north Indian Ocean in the interest of simplicity. It is clear that the Indian Ocean itself needs a more detailed and thorough examination.

It is also possible that some of the intermediate water formed from CDW in the Indian Ocean flows directly into the South Atlantic through the ACS and into the BCR [*Clowes*, 1950; *Taft*, 1963; *Shannon and Hunter*, 1988]. However, *Rintoul* [1991, Figures 3, 4, and 5, Table 2] shows that the 10-Sv loss of intermediate water from the ACCR (or SFZ) between Drake Passage and the south Indian Ocean sector mostly occurs by 0°E, possibly before Africa is reached. *Rintoul* [1991] also has only 4 Sv of layer 3 water flowing north across 32°S, so modification of ~6 Sv of layer 3 to layer 2 water is needed. This is why all of the intermediate water in Plate 7 flows into the South Atlantic through Drake Passage and not around Africa (see the appendix). But it could be that some intermediate layer water flows from the ACS into the South Atlantic south of 32°S, say, X Sv, and the actual loss of Drake Passage Intermediate Water in the same σ_θ range would be, say, $(10 - X)$ Sv. One reason for suspecting a direct flow of layer 3 water from the Indian Ocean to the South Atlantic might be the "spatially rapid" warming and salinization of layer 3 from Drake Passage to 32°N (and 0°E, 30°E). On the other hand, *Rintoul* [1988] does outline an "upwelling mechanism" for these changes within the South Atlantic sector south of 32°S. And, of course, whatever layer 3 water enters the Benguela Current from the ACS would also need to undergo similar modification to layer 2 to be consistent with *Rintoul*'s [1991] requirement for 6 Sv layer 2 and 4 Sv layer 3 water moving north in the Benguela Current at 32°S. In any event, the recent results by Garzoli and Gordon (1995) would seem to limit X to $O(1$ Sv) above 1000 m. A net transport of 3–4 Sv of Indian Ocean water into the South Atlantic by cut-off Agulhas Retroflection rings as noted above could of course also contain significant intermediate water (increased X).

The flow of bottom water (lower CDW modified along its path) at potential temperatures near 0.8°C and salinities near 34.72 from the circumpolar region into the South Pacific and north is taken from a combination of *Roemmich and McCallister* [1989], *McCartney and Baringer* [1993], and *Toole et al.* [1994b] and is approximately consistent with *Reid* [1986]. However, regardless of details, there is general agreement that 10–20 Sv of bottom water enters the South Pacific and 10–20 Sv returns to CDW as deep water. There is also agreement that about 10 Sv of bottom water enters the North Pacific and returns as silicate-rich deep water [*Roemmich and McCallister*, 1989; *Wijffels*, 1993]. The tropical Pacific portions of Plate 7 are based on *Wijffels* [1993], who has approximately 10 Sv of lower CDW crossing 10°N from the south below $\theta = 1.2$°C (consistent with *Roemmich and McCallister* [1989]) and a 10-Sv return flow south along topography in the eastern Pacific. The southward flow with potential temperatures between 1.2° and 2°C is North Pacific Deep Water (NPDW), a water mass defined by a silicate maximum. In Plate 7 the bottom thermohaline flow and its compensation as NPDW are shown in dramatically simple form. For the sake of simplicity, no attempt is made to depict the complex and possibly controversial flow [*Warren and Owens*, 1985; *Roemmich and McCallister*, 1989] of bottom and deep water in the North Pacific, characterized by a question mark north of ~20°N in Plate 7. This is done because the details of the flow of bottom and deep water within the North Pacific are not critical to the global picture of interbasin exchange.

The upper and intermediate layer renewal flows associated with Plate 7 have been mapped in Plate 8 into four vertical layers. Intermediate water (blue line) is the deepest with $T \leq 7$°C. Lower thermocline layer or upper intermediate layer water ($7° \leq T \leq 12$°C) is denoted by a green line, thermocline layer water ($12° \leq T \leq 24$°C) is shown by a red line, and a comparatively thin and tropically trapped mixed layer water with temperatures greater than 24°C is shown by a purple line. These temperature ranges are chosen to match the characteristics of the cross-equatorial flow into the North Atlantic through the Caribbean and Straits of Florida according to *Schmitz and Richardson* [1991] and vary slightly in σ_θ ranges from Plate 7.

Plate 8 shows (10 − X) Sv of intermediate water from the Indian Ocean joining the flow associated with the SFZ in the Crozet Basin, with an additional 4 Sv (in arbitrary increments of 1, 1, and 2 Sv) joining south of the SFZ; (10 − X) Sv of the least dense brand of intermediate water in Drake Passage, with σ_θ = 26.8–27.2, joins the South Atlantic subtropical gyre in the Benguela Current Region. A new feature of Plate 8 relative to Plate 7 is that X Sv of intermediate water is tranferred directly from the ACS to the BCR. The intermediate water at $T \leq 7°C$ that is not modified to the 7°–12°C layer in the Benguela Current (but at the equator) is shown to flow with the subtropical gyre to the coast of South America where it proceeds north as a boundary current. The 5 Sv that is warmed to 7°–12°C in the Benguela Current is joined by 4 Sv of upper layer water from the Indian Ocean, and both are upwelled to very warm ($T > 24°C$) tropical water in the equatorial current system. The layer that is upwelled or modified to the 7°–12°C range in the equatorial current system retroflects as a subthermocline countercurrent and moves into the Caribbean and out through the Straits of Florida [*Schmitz and Richardson*, 1991; *Schmitz et al.*, 1993; *Warner and Weiss*, 1992]. The ultimate fate of the 14 Sv of cross-equatorial flow in the Florida Current is here taken to be as described by *Schmitz and McCartney* [1993] except for modifications associated with previously noted more recent ideas (in this regard, see *Lozier et al.* [1995]).

TWO- AND THREE-LAYER INTERBASIN THERMOHALINE FLOW OUTLINES

The essential interbasin-scale transport estimates used in Plate 7 were summarized in Tables 1 and 2. Since Plate 7 is busy and complicated, attempts at simplified two- and three-layer schemes are presented. My version of a simplified, two-layer, conveyor-belt type of summary is contained in Plate 9, a condensation and simplification of Plate 7. In Plate 9 the red layer contains both intermediate water and the upper layer flows, and blue denotes both deep and bottom water. These are referred to in the figure as the upper level current (warm) and the deep current (cold). Plate 9 differs in some characteristics from Plate 2 in every ocean basin but is also similar to some features of an updated circulation pattern by *Broecker* [1991, Figure 4], as presented in modified form in Plate 4. *Gordon*'s [1986] path for upper layer compensation for NADW (Plate 1) is through the Gulf Stream System in agreement with *Schmitz and Richardson* [1991] and *Schmitz and McCartney* [1993], but *Broecker* [1987, 1991] does not follow this route in Plate 2, even though his pathways are otherwise more explicit than *Gordon*'s [1986]. Color transformations along paths represent water mass conversion. The least well established features of Plate 9 are associated with the vertical exchange processes in the Indian and Pacific Oceans. The flow of deep water in the Indian Ocean is so strongly correlated with complex topography that it cannot be adequately shown in the type of summary used in Plate 9. The deep flows in the North Atlantic and North Pacific are also deliberately oversimplified.

Plate 9 is the simplest possible schematic for the major deep and abyssal water mass conversion processes in the global ocean. Fourteen Sverdrups of upper and intermediate level water is converted to deep water (NADW) in the northern North Atlantic (lower NADW is also at the bottom there) and flows south across the equator and join the Circumpolar Current. Ten sverdrups of the needed upper level compensation enters the South Atlantic through Drake Passage, and 4 Sv enters from the Indonesian Throughflow across the Indian Ocean and around Africa. Twenty-four sverdrups of cold water enters the Indian Ocean from the ACCR, with 14 returning as cold water and 10 being transformed to upper level water. This 10 Sv of upper level water flows south of Australia, across the South Pacific, and out through Drake Passage into the BCR in the South Atlantic. This water joins 4 Sv of Indonesian Throughflow water, crosses the equator, and flows with the Gulf Stream system into the northern North Atlantic to replace NADW. Twenty sverdrups of deep water enters the South Pacific and returns to the ACCR as (less) cold water, after roughly 10 Sv also traverses the North Pacific.

A three-layer summary is shown in Plate 10, again a condensation of Plate 7. In Plate 10 the red line (as in Plate 9) contains both upper and intermediate layer water, but the blue line in Plate 9 has been split into deep (green) and bottom (blue) flows. Here the large-amplitude (in terms of volume transport exchange with CDW) bottom-deep water interactions can be shown more explicitly, relative to the maps with two layers. In Plate 10, 48 Sv of bottom water starts as lower CDW, and 38 Sv is returned after modification to less dense deep water. The 5 Sv of AABW formed in the Weddell Sea that rejoins the ACCR south of the Indian Ocean (per *Rintoul* [1991]) is not shown for simplicity. The 14-Sv NADW cell is essentially as depicted in Plate 9.

DISCUSSION

Several recent numerical simulations can be related to the observational summary presented here. *England* [1992] identified a version of the *McCartney* [1977, 1982] SAMW mechanism, where the low-salinity tongues formed at the surface just north of the SFZ subduct both in the eastern South Pacific and in the Atlantic just north of Drake Passage, as responsible for AAIW formation, relative to the classical notion of

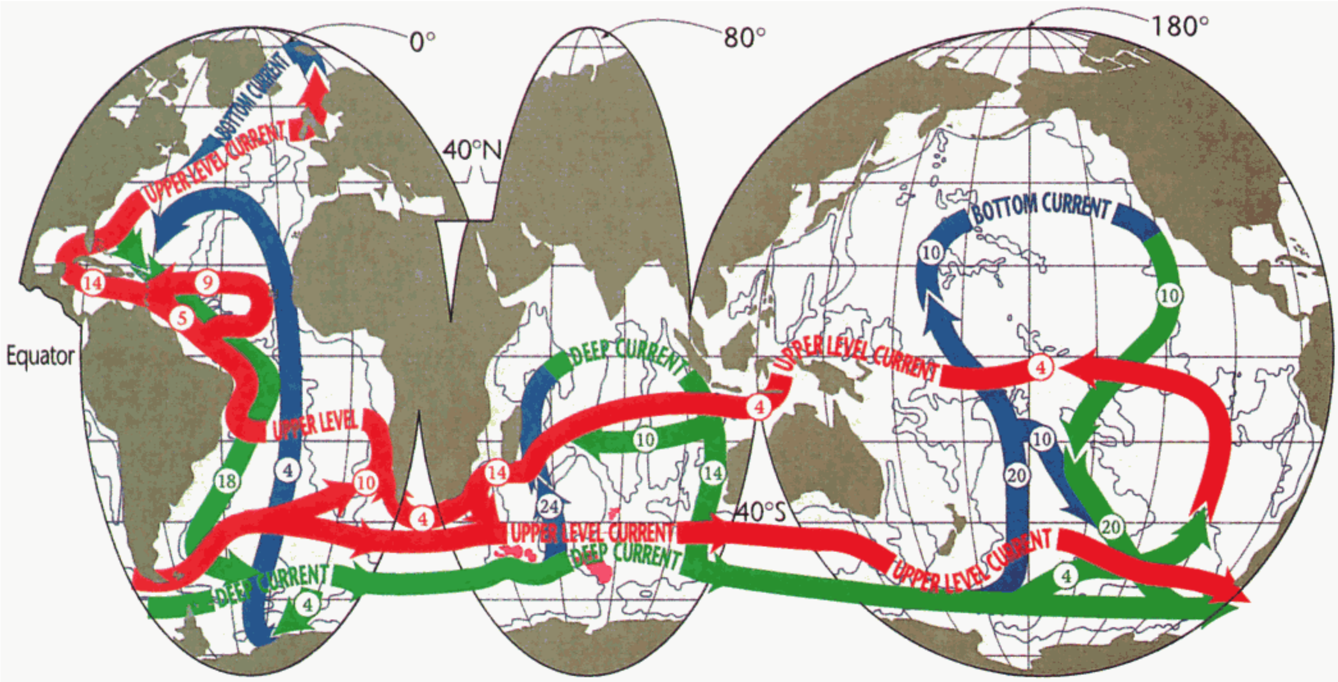


Plate 9. A two-layer thermohaline conveyor belt based on a condensation of the four-layer picture developed in detail in preceding sections of this review. Blue denotes abyssal water (deep and bottom layers), and red denotes uppermost layer flow (thermocline and intermediate water); transports in sverdrups are in circles. This is my replacement for Plates 1, 2, and 4.

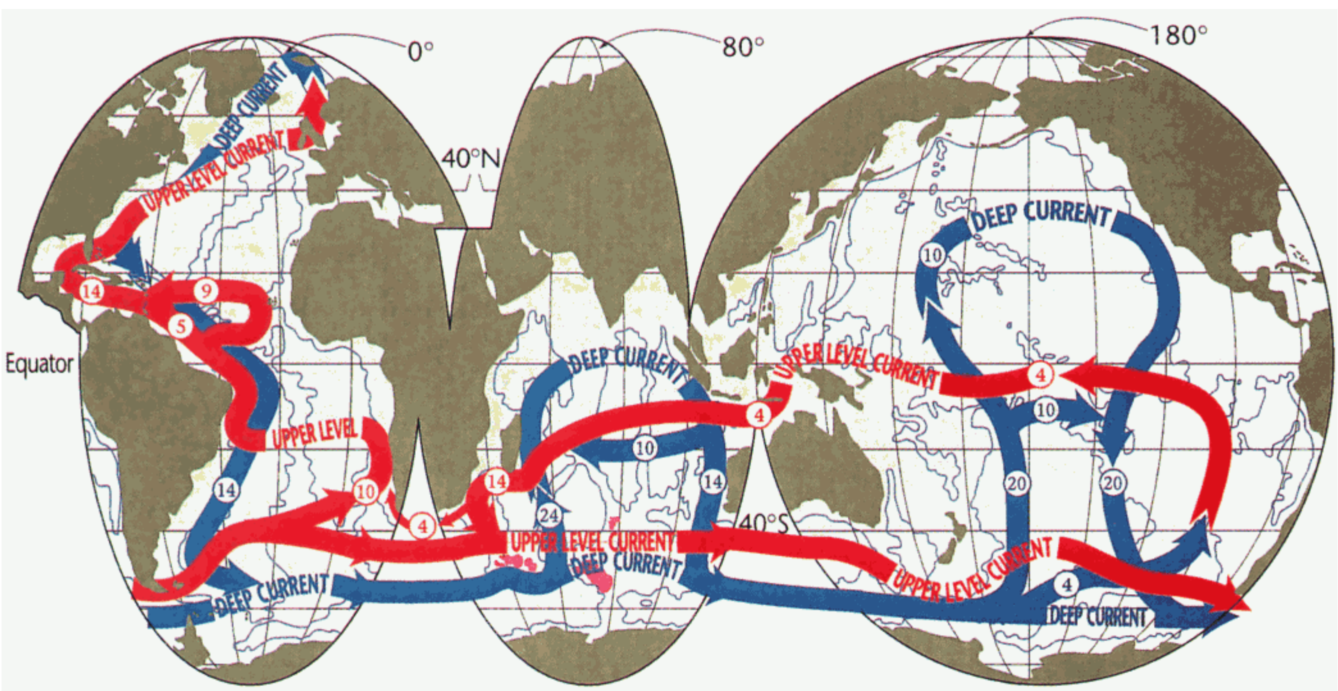


Plate 10. A three-layer thermohaline conveyor belt based on a condensation of the four-layer picture developed in detail in preceding sections of this review. Here red lines denote the thermocline and intermediate layers, green lines denote deep flow, and blue lines denote bottom circulation. This is my extension of Plates 1, 2, 4, and 9.

circumpolar subduction of surface water at the polar front. His model results required winter surface salinities in the Weddell and Ross Seas in order to get both realistic bottom water and intermediate water. I feel (appendix) that the mechanism(s) described by *McCartney* [1977, 1982] and *Talley* [1995] is important in determining the *T-S* properties, but not necessarily all of the transport of the South Pacific and South Atlantic brands of "upper" intermediate water that influence NADW renewal (*Rintoul*'s [1991] layer 3, σ_θ = 26.8–27.2).

A variety of model results appear to be generally in line with the overall intensity of observed NADW formation described here [*England and Garcon*, 1994; *Holland and Bryan*, 1994, Table 1; *Maier-Reimer et al.*, 1993, Figure 1]. However, the export of NADW south across the equator in these models may vary with the mixing parameterization chosen (see also *Toggweiler* [1994]), with, for example, only 10.6 Sv (formation 16 Sv) flowing into the South Atlantic in the England and Garcon formulation. *England and Garcon* [1994] find 2–3 Sv from the Indian Ocean acting as an upper layer advective replacement for NADW, consistent with the values chosen here. This 2–3 Sv is part of an "Agulhas leakage" into the South Atlantic of 8–9 Sv, with a return to the South Indian Ocean of ~6 Sv. *England and Garcon* [1994] have a net loss of ~10 Sv from Drake Passage to 0°E, which also upwells from intermediate water to upper layer water in the vicinity of the BCS, very reminiscent of *Rintoul* [1991] and this review. They have in addition a 6-Sv leakage of intermediate water directly from the ACS to the BCS, ~1.5 Sv of which replaces NADW, all much as found in this review from data alone (Plates 5, 7, and 8).

Toggweiler and Samuels [1993a, b] question the possibility of significant upwelling from the abyss through the thermocline in the Pacific Ocean, throwing in doubt the Pacific limb of the conveyor belt diagrams by *Gordon* [1986] and *Broecker* [1987, 1991]. *Toggweiler and Samuels* [1993a, b] also present an exceptionally clear discussion of the issues involved in explaining (and describing to some extent) the global thermohaline circulation, especially the absence of evidence for the dominance of large-scale, large-amplitude, diapycnal-mixing-driven, deep-to-shallow upwelling across the thermocline in subtropical gyres. They suggest a "reconfigured conveyor belt," which is part of what I have attempted in this review, but based primarily on observational summaries relative to numerical simulations. The "into and/or through the thermocline" upwelling that I have described here (e.g., Plate 5) occurs primarily near the equator, roughly consistent in the Pacific with *Toggweiler and Samuels* [1993a, b] and with *Semtner and Chervin* [1992] (see especially their Figure 2d).

The choice of 3–4 Sv as the contribution to NADW renewal (out of a total 14-Sv NADW replacement) associated with the Indonesian Throughflow is not seriously inconsistent with *Rintoul* [1991], who shows an uppermost layer flow of 1–2 Sv from the Indian Ocean to the South Atlantic to go along with his net northward transfer (loss) of ~10 Sv of intermediate water (defined to be water with $\sigma_\theta = 26.8 \rightarrow \sigma_1 = 32.36$) between Drake Passage and the Greenwich meridian. This loss occurs primarily in the least dense class (layer 3, σ_θ = 26.8–27.2). These density parameter classes show very large increases in salinity relative to Drake Passage for both 0°E and 32°S [*Rintoul*, 1991, Table 2], before reaching Africa, converting 6–7 Sv of intermediate water to upper layer water by 32°S, a conversion process needing more examination.

CLOSING REMARKS

The deep and bottom interbasin thermohaline transports in the world's ocean and the replacement of NADW by intermediate and upper layer flows have been summarized by several new maps and tables. Although most of the features of these maps are determined by piecing together published results, a few new ideas or speculations were presented, and possible deficiencies in our knowledge or interpretation were discussed.

The net transport of the deep and bottom water cells is about 50 Sv, with roughly 20 Sv associated with transfers between the ACCR (via CDW) and the southern hemisphere oceans and the other 30 Sv executing cross-equatorial paths in their transformation from bottom to deep (or, later, intermediate) water. The estimate of 14 Sv for the renewal and export of NADW now appears to have almost overwhelming support [*Dickson and Brown*, 1994; *Macdonald*, 1993; *Rintoul*, 1991; *Schmitz and Richardson*, 1991; *Schmitz and McCartney*, 1993]. The principal pathway (~10 Sv) for NADW compensation was here taken to be to CDW to bottom and deep water in the Indian Ocean to intermediate water in the southern hemisphere oceans to upper layer water in the low-latitude Atlantic. It is possible that some of this intermediate water formed by modification of CDW in the Indian Ocean flows into the South Atlantic through the Agulhas Current system. It is probable that low-density intermediate water flowing through the Drake Passage is a major component of NADW renewal. There is also an advective contribution of 2–4 Sv around the tip of Africa from the Indian Ocean upper layer, connected to an *O*(10 Sv) Indonesian Throughflow. There is possibly a diffusive exchange between the South Indian and South Atlantic Oceans involving the shedding of rings in the Agulhas retroflection of around the same amount as the advective change (~4 Sv). This exchange could influence the properties of the least dense intermediate water in the South Atlantic and therefore impact NADW renewal. The cold water–warm water path partitioning adopted here is essentially the same as adopted by *Broecker* [1991]. The results presented here are also remarkably consistent in many respects with *Rintoul* [1991], *Roemmich and McCallister* [1989], and *Macdonald* [1993]. The recent results by Garzoli and Gordon (1995) should end the community's preoccupation with the approximate strength of the cold versus warm water path partitioning, and perhaps we can now focus on how "converted NADW" gets to both areas.

A general characteristic of the results described here is that modifications to the thermohaline cells occur geographically, in a variety of areas and in "small" steps, that is, mostly layer to layer as opposed to straight up from the abyss through the thermocline. Significant large-scale and uniform upwelling from the abyss through the thermocline to an upper layer above the thermocline in the interior of most subtropical gyres is not required, but there is a lot of piecewise water mass conversion and modification along long horizontal paths from bottom to deep and deep to intermediate flows and then from intermediate to upper layers in particular regions. Although the results presented in this review are based on piecing together diverse published results on the large-scale circulation, the sentences earlier in this paragraph are at least partially consistent with other types of measurement entirely, that is, those of small-scale diapycnal mixing in and below the thermocline in the interior of subtropical gyres. For example, *Toole et al.* [1994a] observe diapycnal diffusivities that are too low by an order of magnitude to be driving the return flow of NADW by upwelling through the thermocline in ocean interior regimes.

It seems clear, however, that the bottom-to-deep cells are directly associated with diapycnal mixing over very long space and time scales, although the bottom cells originating as CDW return about 40% of their flow to the ACCR over comparatively short distances with only minor modification. *Reid and Lynn* [1971] long ago identified the North Pacific and north Indian Oceans as probable general locii of the bottom to deep conversions. Observations of truly abyssal mixing should be considered, with the data collected where the modification of bottom to deep water might occur, perhaps in the presence of the abyssal boundary currents themselves or near variable topography, not at arbitrarily situated "ocean interior locations."

The principal locations for "conventional" upper ocean upwelling (i.e., into and through the thermocline) might be in regimes like the Peru and Benguela Current systems and, perhaps most significantly to NADW renewal, in equatorial current systems, not only in the Atlantic but also in the Indian and Pacific Oceans. Perhaps the deeper (below the undercurrent) equatorial zone upwelling could be associated with the subundercurrent zonal jets observed there, and in any event, this region, that is, at depth near the equator, seems like a good place to carry out new field programs. The overall vertical exchange process in the Indian Ocean is a critical area for future study. If indeed, as extracted from *Toole and Warren* [1993] and *Macdonald* [1993] and suggested in this review, there is a net conversion of about 10 Sv of bottom and deep water to intermediate water north of 32°S in the Indian Ocean, then where and how does this happen?

APPENDIX: THE ROLE OF INTERMEDIATE WATER IN NADW RENEWAL

A spectrum of water types in the intermediate water σ_θ range 26.8–27.5 flow out through Drake Passage, but it is the least dense intermediate water in the σ_θ range 26.8–27.2 that enters the South Atlantic but does not leave it south of Africa according to *Rintoul*'s [1991] layer breakdowns (kindly made available by S. Rintoul (personal communication, 1994)). The reader interested in more information on the characteristics of intermediate water in the Atlantic should consult *Piola and Gordon* [1989] and *Talley* [1995]. Deeper, more dense brands of intermediate water basically recirculate in the Atlantic Ocean according to *Rintoul* [1991] and/or continue on in the SFZ south of Africa, and are not part of the NADW renewal process (no net transport north). That is, the loss of intermediate water between Drake Passage and 0° or 30°E occurs primarily in *Rintoul*'s [1991] layer 3, above the σ_θ associated with the AAIW salinity minimum at lower latitudes. A potential density of ~ 27.0 with $7° \leq T \leq 12°C$ and $34.88 \leq S \leq 35.1$ is the type of water identified by *Schmitz and Richardson* [1991] as leaving the Straits of Florida after having arrived from the South Atlantic.

Of course, layer 3 water could also be flowing into the South Atlantic from the south Indian Ocean, and there is a need in the *Rintoul* [1991] scheme to "upwell" ~5–6 Sv of layer 3 water into layer 2 water in the South Atlantic south of 32°S. But with the most recent results from Garzoli and Gordon (1995) the case for 5–10 Sv of upper intermediate water (σ_θ of 26.8–27.2, *Rintoul*'s [1991] layer 3) flowing from Drake Passage into the BCS is convincing. Layer 3 is the least dense intermediate water with σ_θ = 26.8–27.2, average θ and S of 4.18°C and 34.14 at Drake Passage, and average θ and S of 5.85°C and 34.33 at 0°E. As it exits north at 32°S, layer 3 has average θ and S of 6.73°C and 35.23. But there could of course be some interaction between IB water (Plate 5) and Drake Passage water in the Malvinas Current as well as transfer by cut-off Agulhas retroflection rings.

The Indian Ocean brand of intermediate water in the Agulhas as characterized by the 34.5 salinity contour [*Clowes*, 1950] is present in all of the relevant north-south sections in the Indian Ocean atlas [*Wyrtki*, 1971], including the section (section 8 in the atlas)

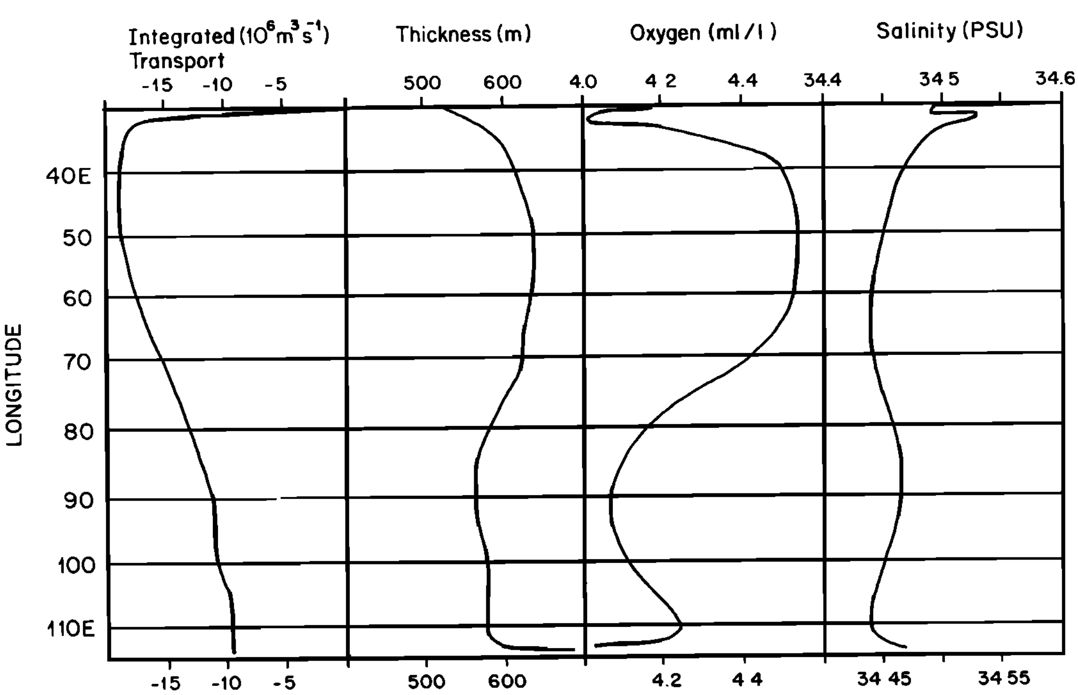


Figure A1. The characteristics and transport along 32°S in the Indian Ocean for intermediate water, defined as the layer of potential density range 27.0–27.5, adapted in smooth form from *Toole and Warren* [1993, Figure 5].

south of Australia from Bass Strait to Antarctica. Indian Ocean Intermediate Water is clearly present at 40°E [*Read and Pollard*, 1993] and possibly at 0°E [*Whitworth and Nowlin*, 1987, Figure 2]. So some of the "upper" intermediate water in the σ_θ range 26.8–27.2 could enter the Benguela Current directly from the ACS as well as from Drake Passage, but this was not shown in Plate 7 for the sake of simplicity. This possibility is shown, however, in Plate 8. A flow of intermediate water from the ACS into the South Atlantic was suggested by *Clowes* [1950], *Shannon and Hunter* [1988, Figure 8], and *Taft* [1963].

An excess southward transport of 10 Sv of intermediate water across 32° in the South Indian Ocean [*Toole and Warren*, 1993] is potentially the most important new observational result I know of for the global thermohaline circulation. Significantly for this review, this result is corroborated by the essentially identical net transport excess for intermediate water at 32°S that was found by *Macdonald* [1993] regardless of the transport of the Indonesian Throughflow, using the *Toole and Warren* [1993] data set but a much different method of referencing. This 10-Sv excess is a result of 19 Sv flowing south in the Agulhas Current and 9 Sv flowing north in the Agulhas recirculation and in the rest of the interior of the South Indian Ocean, as shown in Figure A1, a smooth version of Figure 5 from *Toole and Warren* [1993]. Roughly 4–5 Sv recirculates in the southwestern Indian Ocean, possibly consistent with the ventilated properties described by *Fine* [1993]. The other 4–5 Sv flows north on basin scale east of ~60°E (Figure A1), possibly more "conventional" intermediate water [*Talley*, 1995].

In Figure A1 the intermediate water flowing south in the Agulhas has an average salinity of 34.55, whereas the average salinity of the intermediate water flowing north in the interior of the south Indian Ocean is 34.45. Observations indicating a large transport (~13 Sv for the σ_θ range 27.0–27.5; ~20 Sv for 26.8–27.5) of intermediate water (Figure A2) by the Agulhas Current off Durban were first published by *Harris* [1972]. The origin of this intermediate layer flow was

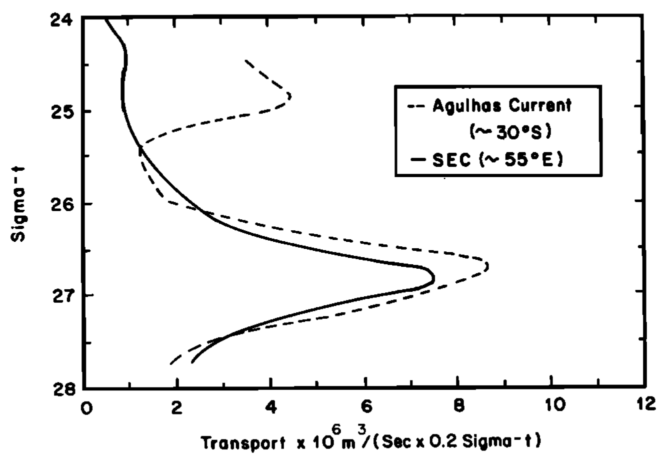


Figure A2. The transport per unit $0.2\sigma_t$ interval for the Agulhas Current (dashed line) off Durban and for the South Equatorial Current (SEC, solid line) along 55°E as a function of σ_t, partially taken from *Harris* [1972].

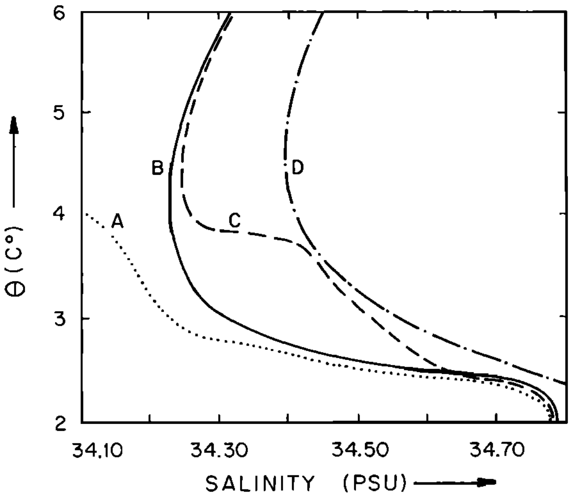


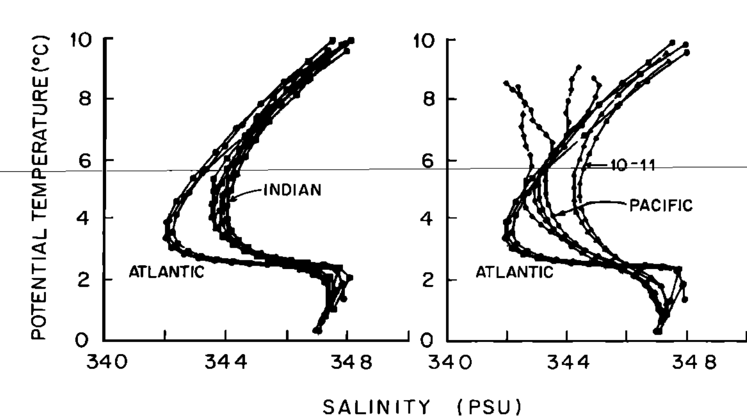
Figure A3. Potential temperature–salinity (θ–S) profiles for intermediate water across the Agulhas return flow and the Southern Ocean, adapted in smooth form from *Read and Pollard* [1993, Figure 7]. Antarctic Surface Water is depicted in curve A, Antarctic Intermediate Water (AAIW) from the south in curve B, intermediate water from the north in curve D, and interleaving between AAIW and intermediate water in curve C.

mostly from the South Equatorial Current across 55° and 65°E, but including ~2 Sv through Mozambique Channel (approximately as was found by *Macdonald* [1993]) with a Red Sea influence. Strong flows into the Agulhas Current system from the east across the Madagascar Ridge in the intermediate water σ_t range 27.2–27.6 and depth range 1000–2000 m were established even earlier by *Visser and Van Niekerk* [1965] (see also *Clowes* [1950]). These authors also show flow diagrams suggesting a comparatively short horizontal scale recirculation into the Agulhas of perhaps an additional few sverdrups of intermediate water (much as suggested by *Toole and Warren* [1993] and *Fine* [1993] and noted above), but *Visser and Van Niekerk* [1965] did not discuss volume transports.

The nearly 10 Sv of excess (possibly upwelled) intermediate water with comparatively high salinity (~34.5) and low oxygen in the Agulhas are sharply distinct from the ~34.25 core of the South Atlantic brand of AAIW (Figure A3, adapted from *Read and Pollard* [1993, Figure 7]) along the Subantarctic Front. It has been known for some time that the characteristics of intermediate water vary globally [*Taft*, 1963] and in particular that Indian Ocean Intermediate Water is notably saltier than the brand of intermediate water found in the South Atlantic [*Clowes*, 1950] or South Pacific (Figure A4, adapted from *Piola and Georgi* [1982, Figure 8]). *Burling* [1961] noticed long ago that there were two types of intermediate or subantarctic water south of New Zealand: a fresh southern circumpolar variety and a salty "Australasian" variety that he felt originated in the Indian Ocean sector.

Read and Pollard [1993] convincingly show that along their section south of Africa there is a southern (fresh) and a northern (salty) intermediate water (Figure A3). All of this is also possibly consistent with the transfer of comparatively warm intermediate water to the Circumpolar Current system south of the Indian Ocean as found by *Georgi and Toole* [1982]. That is, the intermediate water in the Agulhas system may be transferred to the SFZ, where everything seems to merge owing to topographic constraints near the Kerguelen and the Crozet Basin passages and plateaus [*Park et al.*, 1993]. This intermediate water joining the SFZ could be modified along its path in the SFZ into other brands of intermediate water, especially in the South Pacific as was described by *McCartney* [1977, 1982]. The longitudinal sequence of latitudinally averaged (over 30°–45°S) T-S curves in Figure A4 suggests that the Pacific Ocean T-S curves in the intermediate water range are basically freshened Indian Ocean T-S curves (and vice versa for South Atlantic versus south Indian [*Clowes*, 1950]). That is, the "initial" transport of the water that is later strongly modified in T-S properties by convection just north of the SFZ into the "least dense" mode water that gets into Drake Passage and then the BCR may be provided by a thermohaline cell in the Indian Ocean that converts bottom and deep water into intermediate water. The warmest

Figure A4. Potential temperature–salinity (θ–S) diagrams for intermediate water in the southern hemispheric oceans, adapted from *Piola and Georgi* [1982, Figure 8]. Each θ–S curve is from a zonal sector of the Antarctic Circumpolar Current regime, grouped by ocean basin except that curves labeled 10 and 11 are south of Australia.



mode water may recirculate through the Indian and South Pacific subtropical gyres.

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