

distinctly nonsteady character of the ocean circulation. Ocean currents are remarkably variable. Variability on much shorter time scales of weeks and months, and length scales of tens and hundreds of kilometers, often dominates the larger-scale flows discussed in this article. Thus, it is not appropriate to think of the ocean circulation as sluggish, linear, and steady. Instead, it is more appropriate to think of the ocean as a complex turbulent environment with its own analogs of unpredictable atmospheric weather systems and climate variability. Nevertheless, the simplified theories of steady circulation illustrate important mechanisms that govern the time-averaged flows.

In closing, two ocean regions deserve special mention: the equatorial ocean and the extreme southern ocean. Equatorial regions have substantially different dynamics compared with models discussed above because Coriolis accelerations are negligible on the Equator, where $f = 0$. The wind-related processes that govern El Niño and the Southern Oscillation, for example, depend critically on this fact. The southern ocean distinguishes itself as the only region without a western (or eastern) continental boundary. This absence of boundaries produces a circulation characteristic of the atmosphere, with intense zonal flows that extend around the globe. They represent some of the most intense large-scale currents in the world, and

derive much of their energy from the wind. So they, too, represent an important part of the surface/wind-driven circulation.

See also

Air–Sea Interaction: Momentum, Heat and Vapor Fluxes. **Boundary Layers:** Ocean Mixed Layer. **Ocean Circulation:** General Processes.

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Thermohaline Circulation

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Introduction

The circulation of the ocean is usually divided into two parts, a wind-driven circulation that dominates in the upper few hundred meters, and a density-driven circulation that dominates below. The latter is called the ‘thermohaline’ circulation because of the role of heating, cooling, freshening, and salinification in producing regional density differences within the ocean. The thermohaline circulation, for the most part, is an ‘overturning’ circulation in which warm water flows poleward near the surface and is subsequently converted into cold water that sinks and flows equatorward in the interior. Radiocarbon measurements show that the thermohaline circulation turns

over all the deep water in the ocean every 600 years or so.

The most spectacular features of the thermohaline circulation are seen in the sinking phase, in the formation of new deep water in the North Atlantic and the Southern Ocean. Large volumes of cold polar water can readily be observed spilling over sills, mixing violently with warmer ambient water, and otherwise descending to abyssal depths. The main features of the upwelling phase are less obvious. Most of the gaps in our knowledge about the thermohaline circulation are due to uncertainty about where the upwelling occurs and how upwelled deep water returns to the areas of deep water formation. The main new development in studies of the thermohaline circulation is the role of Drake Passage and the Antarctic Circumpolar Current (ACC) in the upwelling phase.

The thermohaline circulation is an important factor in the Earth’s climate because it transports roughly 10^{15} W of heat poleward into high latitudes, about

one-fourth of the total heat transport of the ocean–atmosphere circulation system. The upwelling branch of the thermohaline circulation is important for the ocean’s biota as it brings nutrient-rich deep water up to the surface. The thermohaline circulation is thought to be vulnerable to the warming and freshening of the Earth’s polar regions associated with global warming.

The Cooling Phase — Deep Water Formation

The most vigorous thermohaline circulation in the ocean today is in the Atlantic Ocean, where the overturning is often likened to a giant conveyor belt. The upper part of the conveyor carries warm, upper-ocean water through the tropics and subtropics toward the north, while the deep part carries cold, dense polar water southward through the Atlantic, around the tip of Africa, and into the ocean beyond. The Atlantic thermohaline circulation converts roughly $15 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ of upper ocean water into deep water. (Oceanographers designate a flow rate of $1 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ to be 1 Sverdrup, or 1 Sv. All the world’s rivers combined deliver about 1 Sv of fresh water to the ocean.) Most of the 15 Sv flow of the upper part of the Atlantic thermohaline circulation passes through the Florida Straits and up the east coast of North America as part of the Gulf Stream. The path of the conveyor cuts eastward across the Atlantic and continues northward along the coast of Europe. The warm water flowing northward in the northern North Atlantic gives up roughly 50 W of heat per square meter of ocean surface to the atmosphere. This heat flux is comparable to the solar energy reaching the lowest layers of the atmosphere during the winter months and is a significant factor in the climate of northern Europe.

As the upper part of the Atlantic thermohaline circulation moves northward through the tropical and subtropical North Atlantic, it spans a depth range from the surface down to ~ 800 m and has a mean temperature of some 15–20°C. During its transit through the tropics and subtropics, the flow becomes saltier owing to the excess of evaporation over precipitation in this region. It also becomes warmer and saltier by mixing with the salty outflow from the Mediterranean Sea. By the time the flow has crossed the 50° N parallel into the subpolar North Atlantic, it has cooled to an average temperature of 11.5°C. Roughly half of the water carried northward by the thermohaline circulation flows into the Norwegian Sea between Iceland and Norway. Part of the conveyor flow extends into the Arctic Ocean.

The final stages of the cooling process make the salty North Atlantic water dense enough to sink. Sinking is

known to occur in three main places. The densest sinking water in the North Atlantic is formed in the Barents Sea north of Norway, where salty water from the Norwegian Current is exposed to the atmosphere on the shallow ice-free Barents Shelf. Roughly 2 Sv of water from the Norwegian Current crosses the shelf and sinks into the Arctic basin after being cooled to 0°C. This water eventually flows out of the Arctic along the coast of Greenland at a depth of 600–1000 m. The volume of this flow is increased by additional sinking and open-ocean convection in the Greenland Sea north of Iceland. A mixture of these two water masses flows into the North Atlantic over the sill between Iceland and Greenland (Denmark Strait) at 600 m.

As water at 0°C from the Arctic and Greenland Seas passes through Denmark Strait it mixes with Atlantic water at 6°C beyond the sill and descends the Greenland continental slope down to a depth of 3000 m. It flows southward around the southern tip of Greenland into the Labrador Sea as part of a deep boundary current that follows the perimeter of the subpolar North Atlantic. A slightly warmer water mass is formed by open-ocean convection within the Labrador Sea. The deep water formed in the Labrador Sea increases the volume flow of the boundary current that exits the subpolar North Atlantic beyond the eastern tip of Newfoundland.

Newly formed water masses are easy to track by their distinct temperature and salinity signatures, high oxygen, and anthropogenic tracer concentrations. The southward flow of North Atlantic Deep Water (NADW) is a prime example. NADW is identified as a water mass with a narrow spread of temperatures and salinities between 2.0 and 3.5°C and 34.9 and 35.0 psu. NADW quickly ventilates the Atlantic Ocean. **Figure 1** illustrates an oceanographic section between the southern tip of Greenland and the coast of Labrador, showing recent ventilation by chlorofluorocarbon 11 (CFC-11, or Freon 11). High-CFC water with concentrations in excess of 3.0 units ($3.0 \times 10^{-15} \text{ pmol kg}^{-1}$) tags the overflow water from Denmark Strait that flows around the tip of Greenland along the sloping bottom on the right into the Labrador Sea. Deep water with a slightly lower CFC concentration flows out of the Labrador Sea at the same depth on the left. High-CFC water in the center of the basin (3.5–4.0 units) tags Labrador Sea Water that has been ventilated by winter convection down to 2000 m. There is presently no water in the North Atlantic north of 30° N that is uncontaminated with CFCs.

NADW flows southward along the coasts of North and South America until it reaches the circumpolar region south of the tip of Africa. **Figure 2** shows the

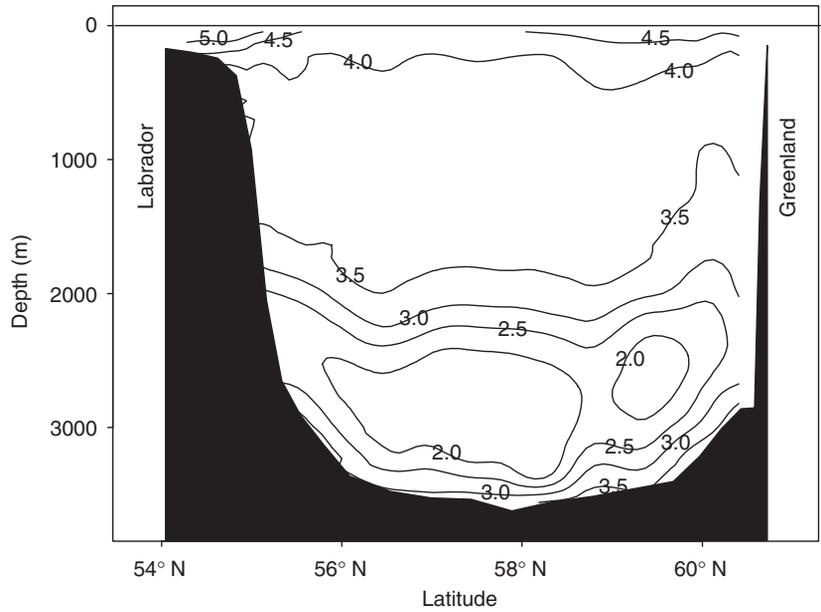


Figure 1 Section of CFC-11 (chlorofluorocarbon 11, or Freon 11) concentration between the southern tip of Greenland and the coast of Labrador (WOCE section A1W) illustrating the recent ventilation of the deep North Atlantic by the main components of North Atlantic Deep Water. CFC concentrations are given in units of $10^{-15} \text{ mol kg}^{-1}$, or pmol kg^{-1} . (Measurements courtesy of R. Gershey of BDR Research, collected during Hudson Cruise 95011 6/95–7/95.)

distribution of salinity in the western Atlantic along the path of the flow. Newly formed NADW salinity ($S > 34.9 \text{ psu}$) is easily distinguished from the relatively fresh intermediate water above ($S < 34.6 \text{ psu}$) and the Antarctic water below ($S < 34.7 \text{ psu}$). NADW exits the Atlantic south of Africa between 35° and 45° S and

joins the eastward flow of the ACC. Traces of NADW re-enter the Atlantic Ocean through Drake Passage (55° – 65° S) with a salinity in excess of 34.7 psu after flowing all the way around the globe.

The other major site of deep-water formation is the coast of Antarctica. The surface waters around

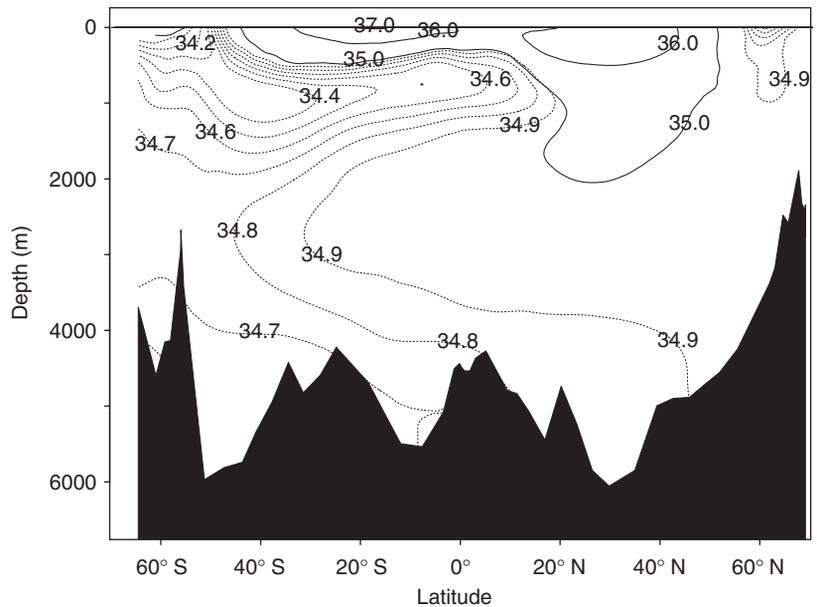


Figure 2 North–south section of salinity down the western Atlantic from Iceland to Drake Passage. The salinity distribution has been contoured every 0.1 psu between 34.0 and 35.0 psu to highlight North Atlantic Deep Water (34.9–35.0 psu).

Antarctica, like those over most of the Arctic Ocean, are ice covered during winter and are too fresh to sink. Deep water below 500 m around Antarctica, on the other hand, is relatively warm (1.5°C) and fairly salty (34.70–34.75 psu). This water mass, known as Circumpolar Deep Water (CDW), penetrates onto the relatively deep continental shelves around Antarctica, where it is cooled to the freezing point. Rejection of brine in the formation of new sea ice maintains fairly high salinities on the shelf despite the freshening effects of precipitation and the input of glacial meltwater. Supercooled shelf water is observed to flow out from under floating ice shelves where contact with glacier ice cools shelf water to temperatures below the freezing point. Very cold, salty shelf water (-1°C , 34.6–34.7 psu) is observed descending the continental slope to the bottom in the Weddell Sea. Bottom water is also observed to form off the Adelie Coast south of Australia ($\sim 140^{\circ}\text{E}$).

The volume of new deep water formed on the Antarctic shelves is not very large in relation to the volume of deep water formed in the North Atlantic, perhaps 3–4 Sv in total. However, the deep water formed around Antarctica is denser and is able to sink below NADW in the south. The deep water formed around Antarctica does not readily ventilate the Southern Ocean. It is diluted many times by mixing with the weakly ventilated water offshore. **Figure 3** shows CFC-11 concentrations along a transect at 140°E that begins on the Antarctic continental shelf on the left. This section was occupied at roughly the

same time as the North Atlantic section in **Figure 1**. In contrast to **Figure 1**, water with more than 3.0 units of CFC-11 is limited to near-surface waters and the continental shelf. A small amount of recently ventilated water (>1.0 units) is seen descending to the bottom along the continental slope. The mass of old CFC-free water that fills the interior is CDW. The mixture of Antarctic shelf water and CDW descending the slope is Antarctic Bottom Water (AABW). AABW occupies the deepest parts of the ocean and is observed penetrating northward into the Atlantic, Indian, and Pacific Oceans through deep passages in the midocean ridge system.

Small quantities of deep water are also observed to form in evaporative seas like the Mediterranean and Red Seas. These water masses are dense because of their high salinities. They tend to form intermediate-depth water masses in relation to the colder deep and bottom waters from the North Atlantic and Antarctica.

The Warming Phase — Upwelling and the Return Flow

The upwelling of deep water back to the ocean's surface was thought at one time to be widely distributed over the whole ocean. This variety of upwelling was linked to turbulent mixing processes that were hypothesized to be active throughout the interior. Mixing was thought to be slowly heating the deep

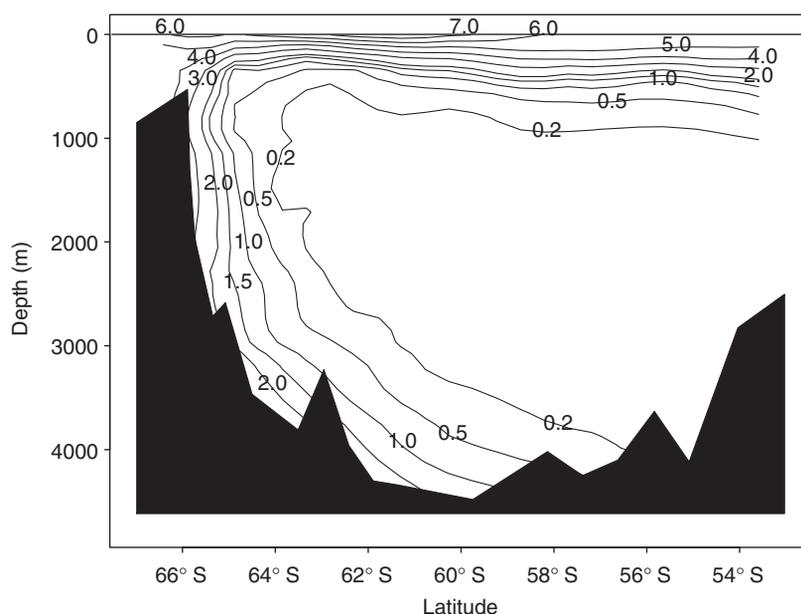


Figure 3 Section of CFC-11 concentration (units of pmol kg^{-1}) extending northward from the coast of Antarctica along 140°E (WOCE section SR3) illustrating the penetration of CFCs into the Southern Ocean. (Measurements courtesy of J. Bullister of NOAA-PMEL, collected during Aurora Australis cruise AU9404 12/94–1/95.)

ocean, making the old deep water in the interior progressively less dense so that it could be displaced upward by the colder and saltier deep waters forming near the poles. Since the main areas of deep water formation are located at either end of the Atlantic, and since most of the ocean's area is found in the Indian and Pacific Oceans, it stood to reason that the warming of the return flow should be widely distributed across the Indian and Pacific. Schematic diagrams often depict the closure of the conveyor circulation as a flow of warm upper-ocean water that passes from the North Pacific through Indonesia, across the Indian Ocean, and then around the tip of Africa into the Atlantic.

Observations made over the last 30 years have failed to support the idea of a broad, diffuse upwelling. Attempts to directly measure turbulent mixing rates in the interior have shown that the actual mixing rates are generally only about 10% or 20% of the amount required. There is no indication that any deep water is actually upwelling to the surface in the warm parts of the Indian and Pacific Oceans. Mixing does seem to be effective in warming the deepest part of the ocean, however. Modern circulation reconstructions show AABW flowing northward into the Indian, Pacific, and Atlantic basins at 0°C , upwelling across 3500 m, and exiting back to the south at less than 2°C between 2000 and 3500 m. This indicates that the circulation and heat transport associated with mixing in the ocean is quite weak and is limited to the volume of ocean ventilated by AABW.

It now appears that most, if not all, of the deep water sinking in the North Atlantic upwells back to the surface in the Southern Ocean south of the ACC. The upwelling in this case seems to occur within the channel of open water that circles the globe in the latitude band of Drake Passage (55° – 65°S). Drake Passage lies within the belt of midlatitude westerlies. The flow in the surface Ekman layer is directed northward and is divergent (upwelling favorable) within the channel. A key dynamical factor in this problem is the lack of meridional barriers in the upper 1500 m of the Drake Passage channel. Without meridional barriers, there can be no net geostrophically balanced flow into the channel above 1500 m to balance the northward flow in the surface Ekman layer. This means that the winds, in driving surface waters northward out of the open channel, tend to draw up old deep water to the surface from depths near 1500 m.

The deep water upwelled to the surface and driven northward out of the Drake Passage channel is forced down into the thermocline on the north side of the ACC where the flow in the surface Ekman layer is convergent. Numerical experiments with ocean gen-

eral circulation models show that much of the water forced down into the thermocline all around the circumpolar belt eventually makes its way into the Atlantic Ocean, where it is converted into deep water in the northern North Atlantic. The action of the winds in the channel, in drawing up deep water from the ocean's interior, has been shown to actively enhance the formation of deep water in the North Atlantic.

The deep water drawn up to the surface by the winds in Drake Passage is quite cold. As this cold water comes into contact with the atmosphere and is carried northward, it takes up solar heat that otherwise would be available to warm the Southern Ocean and Antarctica. The Atlantic conveyor carries this southern heat across the Equator into the high latitudes of the Northern Hemisphere, where it is released to the atmosphere when new deep water is formed in the north. The thermohaline circulation thereby warms the North Atlantic at the expense of a colder Southern Ocean and colder Antarctica. Indeed, sea surface temperatures at 60°N in the North Atlantic are on average about 6°C warmer than sea surface temperatures at 60°S .

If the warming phase of the thermohaline circulation involved a downward mixing of heat through the thermocline in low and middle latitudes, as once thought, the thermohaline circulation would carry tropical heat poleward into high latitudes. The warming phase now seems to take place in the far south where the warming is associated with an equatorward transport of heat. This means that the heat transport by the thermohaline circulation is opposed to the heat transport of the atmosphere in the Southern Hemisphere. The net effect is a weakening of the overall heat transport in the Southern Hemisphere and a strengthening of the heat transport in the Northern Hemisphere.

General Theory for the Thermohaline Circulation

Figure 4 is a north–south section showing the distribution of density through the Atlantic Ocean. The main thermocline in this diagram lies close to the surface, between the 34.0 ($\sim 20^{\circ}\text{C}$) and 36.0 ($\sim 8^{\circ}\text{C}$) g kg^{-1} isopycnals. The northward flow of the Atlantic thermohaline circulation takes place largely within this part of the density field. The northward flow in the far south starts off a bit denser and colder, as low as 36.6 g kg^{-1} . The southward flow of NADW is located, for the most part, below the 37.0 g kg^{-1} isopycnal.

The isopycnals at the base of the thermocline in Figure 4 are basically flat north of 40°S but rise up to the surface between 40° and 60°S . The rise of these

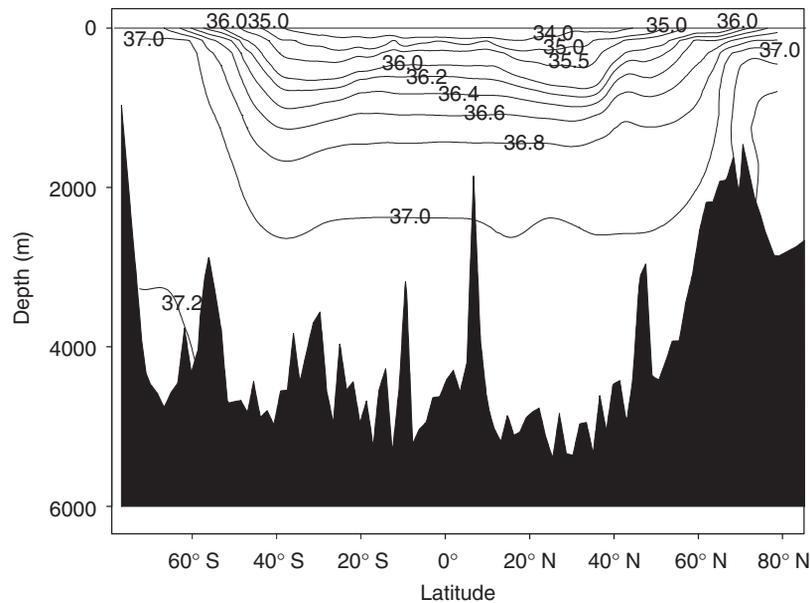


Figure 4 Density structure of the Atlantic thermocline. Sea water density is referenced to a depth of 2000 m and has been zonally averaged across the Atlantic basin (units g kg^{-1}). Contours have been chosen to highlight the lower part of the thermocline. The zonally averaged topography fails to capture the height of the sills in the Greenland–Scotland Ridge (65°N), which are closer to 600 m.

isopycnals in the south is a reflection of the ACC, which flows to the east across the section (out of the page): i.e., the north–south density gradient between 40° and 60°S is in thermal wind balance with an eastward flow that increases toward the surface. The relatively deep and flat position of the isopycnals at the base of the thermocline reflect, to a large extent, the mechanical work done by the winds that drive the ACC. The convergent surface flow generated by the winds pushes down relatively light water north of the ACC in relation to the cold, dense water being lifted up by the winds south of the ACC.

The position of the 36.0 and 36.4 g kg^{-1} isopycnals at depths near 1000 m is important because it signals the presence of relatively warm water adjacent to the sills in the north where new NADW spills into the deep North Atlantic. It is the contrast between the cold water behind the sills and relatively warm water beyond the sills that provides the density gradient that drives the flow of dense water into the deep Atlantic. Numerical experiments carried out in ocean GCMs suggest that all the warm isopycnals in the lower thermocline would be squeezed up into the main thermocline if Drake Passage were to be closed up and the ACC eliminated.

Gnanadesikan has described a general theory for the thermohaline circulation that relates the thickness of the thermocline, as illustrated in **Figure 4**, with the intensity of the Atlantic conveyor. When deep water formation occurs in the North Atlantic, it converts

relatively low-density water within the thermocline into new deep water. It thereby removes mass from the thermocline, allowing it to be squeezed upward. When water is upwelled from the deep ocean and pumped into the thermocline in the south, it adds mass to the thermocline, causing it to thicken downward. In this way the thermocline thickness reflects a balance between the addition of mass to the thermocline via winds in the south, the addition of mass via upwelling from below (presumably minor), and the loss of mass by deep water formation in the north. Gnanadesikan also includes the potentially important effect of eddies in the ACC, which tend to drain mass from the thermocline in opposition to the wind effect. The strength of the conveyor in Gnanadesikan's scheme is reduced to a simple function of the thermocline thickness and the density difference between thermocline water and deep water.

Instability of the Thermohaline Circulation

Cooling of the ocean in high latitudes makes polar surface waters denser in relation to warmer waters at lower latitudes. Thus cooling contributes to a stronger thermohaline circulation. The salinity section through the Atlantic Ocean in **Figure 1** gives one a superficial impression that haline forces also make a positive contribution to the thermohaline circulation. This is actually not true. The cycling of fresh water between

the ocean and atmosphere (the hydrological cycle) results in a net addition of fresh water to high latitudes that reduces the density of polar surface waters. Thus, the haline contribution to the thermohaline circulation is nearly always in opposition to the thermal forcing. The Earth's hydrological cycle is expected to become more vigorous in the future with global warming. This is expected to weaken the thermohaline circulation in a way that could be fairly abrupt and unpredictable.

North Atlantic Deep Water is salty because the water in the upper part of the conveyor flows through zones of intense evaporation in the tropics and subtropics. If the rate at which new deep water is forming is relatively high, as it seems to be at the present time, the sinking water removes much of the fresh water added in high latitudes and carries it into the interior. The added fresh water in this case dilutes the salty water being carried into the deep water formation areas but does not erase the effect of evaporation in low latitudes. Thus, NADW remains fairly salty and is able to export fresh water from the Atlantic basin. (The key factor here is that NADW at depth is actually a bit fresher than the water flowing northward.)

If the rate of deep water formation is relatively low, however, or the hydrological cycle is fairly strong, the export of fresh water via NADW is reduced and the fresh water added in high latitudes tends to accumulate. There seems to be a critical threshold of fresh water input for maintaining the Atlantic conveyor. If the fresh water input is close to the threshold, the overturning becomes unstable and may oscillate over time. If the fresh water input exceeds the threshold, the haline effect overwhelms the thermal effect and the thermohaline circulation stops dead.

Manabe and Stouffer have projected that a fourfold increase in atmospheric CO₂ would increase the hydrological cycle sufficiently that the Atlantic conveyor might collapse. This would lead to a substantially deeper thermocline and a shift in the heat exchange between the hemispheres. It would also lead to a drastic reduction in the rate at which nutrients are supplied to the upper ocean biota and a reduction in the oxygen content of deep water.

See also

General Circulation: Models; Overview. **Ocean Circulation:** General Processes; Surface-Wind Driven Circulation; Water Types and Water Masses.

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