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Information Report

Is There a Global Scale Ocean Circulation?

PAGES 109, 110

The word "global" is the "in" word in today's oceanography. We have already had "ecology" and "environment," and perhaps even the recent "climate" buzz word giving way to the more general designation of "global." We are faced with the Tropical Ocean and Global Atmosphere program (TOGA), the World Ocean Circulation Experiment (WOCE), and the Global Flux Experiment; AGU has entered the "global" stage with a new journal called *Global Biogeochemical Cycles* (which covers it all), and there was the well-attended Earth System Science: New Views and Plans symposium at the 1985 AGU Fall meeting in San Francisco, Calif., last December.

Why all the interest in the global scale? It's safe to say that the important present concerns of the earth sciences, such as climate stability and the ocean's continued potential to absorb civilization's chemical wastes, are global issues and must be viewed in that context if we are to address them properly. Another factor is that for the first time, through satellite technology, we have the capability of gathering global scale data on a truly synoptic basis. So, as in the past, application of new technology allows us to define new horizons and address a new range of research questions. In addition to these factors, there is also the historical evolution of oceanography, which makes the global prospective particularly appealing at this time.

The scientific exploration of the ocean in the late 19th and early 20th century was dominated by great national expeditions that gave us the first glimpse of vast areas of the ocean. As the most general picture of the ocean's large-scale structure emerged, attention was directed towards specific regions of the ocean, such as the Gulf Stream, upwelling regimes, etc., the field of regional oceanography evolved. Now armed with a reasonably good picture of the regions and with the necessary technology to view the global in its entirety, we are guided toward the important global scientific concerns of today. It's time to put the regional pieces of the jigsaw puzzle together to determine how they interact with one another and with the atmosphere in es-

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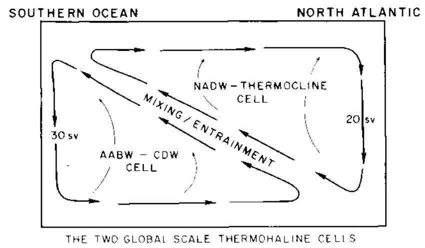

Fig. 1. Schematic representation of the two dominant global scale thermohaline circulation cells along a meridional plane. The magnitude of the formation rates of Antarctic Bottom water and North Atlantic Deep water are "ballpark" values.

tablishing the climate system, its stability and variability, and the delicate balance of the global biogeochemical system.

With all this interest about the global scale, it's natural to ask: Is there really a global scale ocean circulation? How are the regional circulation cells linked together? While the regional systems are generally thought to be wind-driven features, the global scale circulation is of the more sluggish thermohaline circulation type, driven by large-scale buoyancy fluxes between ocean and atmosphere.

Perhaps the most influential global scale thermohaline circulation theory is that for the abyssal circulation, proposed by *Stommel and Arons* [1960]. This enduring yet simple concept, in which strong meridional flow within the western boundaries of the ocean is balanced in both mass and vorticity by the sluggish interior flow, has been well verified by observations. It has been extended, using more realistic ocean bathymetry, and its validity to ocean basin–ridge scale has been established (due largely to the work of Bruce Warren of Woods Hole Oceanographic Institution, Woods Hole, Mass.).

The global prospective is often taken in study of the southern ocean, where the major oceans are linked by the deep reaching circumantarctic belt in the 50°–60° S range. Within this belt is the eastward flowing Antarctic Circumpolar Current. Perhaps it's unfair to call this a global current, since it encircles the longitudes at high latitudes, but it should be noted that with its path of 24,000 km and transport of 125 Sv (Sv = 10^6 m^3/s) it is the strongest, most dominant current of the world ocean. It is the most important factor in diminishing the differences between oceans. However, this is probably because it is the thermohaline part of the southern ocean that has the greatest impact at the global scale. Intense water mass alteration around Antarctica occurs as the relatively warm Circumpolar Deep water upwells to interact with the polar atmosphere, the sea, and the glacial ice to form dense Antarctic Bottom water. This water mass creeps northward, reaching well into the northern hemisphere. It has been said (in partial jest, of course) that the Atlantic, Pacific, and Indian oceans are mere esturaries of the southern ocean.

However, the global spread of Antarctic Bottom water is not the only thermohaline "show in town." There are two global scale circulation cells (Figure 1), one composed of Antarctic Bottom water, compensated by return to the southern ocean as the somewhat warmer saltier Circumpolar Deep water, and the other driven by North Atlantic events, as upper layer or thermocline water is converted to North Atlantic Deep water (NADW). The full extent of the NADW/thermocline thermohaline cell has not really been explored in the literature, although the global spreading of the salinity maximum of NADW [*Reid and Lynn,* 1971] is firmly part of introductory courses of Physical Oceanography.

As NADW spreads throughout the ocean, slow upwelling returns water to the upper layer (à la *Stommel and Arons* [1960]) which initially fed the initial production of NADW. Naturally, the upper layer water must flow back to the North Atlantic to balance the export of deep water. This thermohaline cell is so well developed that it is clearly seen in the inverse solutions for North Atlantic transport along the meridional plane [*Roemmich and Wunsch,* 1985]: upper layer water within the thermocline flows northward to balance approximately 17 Sv of southward transport within the deep water. This feature must be part of a global system; however, the path of the return flow has not been identified. A clue exists within the South Atlantic: oceanic heat flux across 30° S is directed toward the equator (talk about taking coals to Newcastle)! According to *Hastenrath* [1982] at a rate of 69 × 10^{13} W. Since it is not likely that this heat is introduced to the Atlantic from the atmosphere south of 30°S, where does it come from? I believe it comes from the Indian Ocean thermocline and is part of the global scale NADW/thermocline circulation cell.

If realistic values for NADW temperature and volume flux (2°C and 17 Sv, respectively) and for the Brazil Current flow across 30°S (18°C and 10 Sv, respectively; see *Gordon* [1986]) are used, it can be seen that the northward flowing upper layer water must have an average temperature of 12°–14° C, far too warm to be derived from the Drake Passage. It can only be derived from the Indian Ocean. An Indian Ocean thermocline source for this upper layer flow is supported by recent observations that indicate leakage of the Agulhas Current (within the warmer upper layers) to the South Atlantic subtropical gyre [*Gordon,* 1985], although most (80–

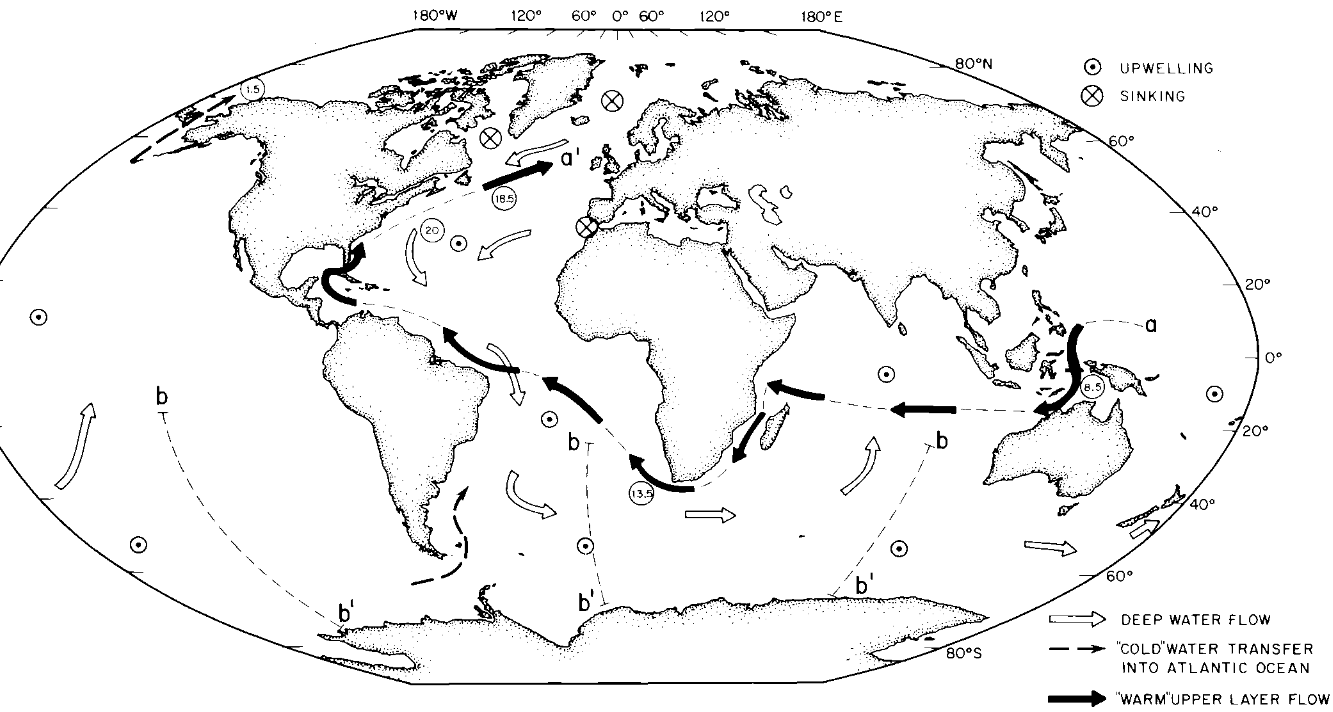

Fig. 2. Map view of the North Atlantic Deep water thermocline circulation cell [*Gordon,* 1986]. The circled values refer to transport in Sverdrup units required to match globally uniform upwelling of a 20-Sv production of NADW.

90%) of the Agulhas flow curls back into the Indian Ocean as part of the Agulhas Retroflection. The subtropical gyre of the South Atlantic is most unique in that there is a heat source at its poleward-eastern corner and as *Olson and Evans* [1986] point out, the Agulhas connection also may supply significant amount of anticyclonic vorticity into the South Atlantic.

With an Indian-Atlantic thermocline link in mind, a global pattern for the NADW thermocline circulation cell is proposed (Figure 2; See also *Gordon* [1986]): NADW spreads into each ocean, where it is eventually introduced into the thermocline (it is likely that the upwelling around Antarctica and the production of Antarctic intermediate water plays an important role), and the thermocline water begins its long trip back to the North Atlantic to complete the cycle.

The NADW, entering the Pacific thermocline, feeds westward flow into the Indian Ocean through the Indonesian seas. Estimates of the volume flux reported in the literature have an order to magnitude range: 1.5 Sv [*Wyrtki*, 1961] to 14 Sv [*Poila and Gordon*, 1984]. During transit of the Indonesian seas there is evidence of anomalously high vertical mixing within the thermocline: the surface water temperature deceases despite strong atmosphere to ocean heat flux. The North Pacific subsurface salinity maximum is annihilated during passage, and the vertical nutrient gradient across the thermocline is greatly reduced. The Pacific to Indian transfer of tropical water and the strong vertical mixing within the Indonesian seas should have some important larger-scale effects on the heat, fresh water, and nutrient budgets.

The spread of the low-salinity Pacific water across the entire Indian Ocean along 10° S is clearly seen in the various thermocline maps presented by *Wyrtki* [1971]. The similarity of the thermocline within the Indian Ocean north of 10° S in regard to the low vertical salinity gradient and high near-surface nutrient concentrations suggests some connection with the Indonesian flow-through and mixing event. However, the Pacific-derived water in the tropical Indian Ocean eventually slips southward through the Mozambique Channel to feed (as a minor component) the Agulhas Current, which in turn introduces Indian Ocean thermocline water into the South Atlantic. While the poleward flux within the Mozambique Channel is suggested by the water mass characteristics, there is no strong evidence that there is a poleward mass flux at the approximately 10-Sv level, as required by the global scale pattern.

Once in the Atlantic, the upper layer thermocline water passes to the north within the subtropical gyre and crosses the equator, probably on the western side, although some involvement with the complex vertical and zonal equatorial circulation is possible. The Caribbean and Gulf Stream features carry the thermocline water further north into the NADW production regions.

The proposed NADW/thermocline cell involves much of the thermocline circulation. The efficiency of the system, and perhaps the vigor of NADW production itself, may depend upon the ability of the system to pass thermocline water between ocean basins. These links may be vulnerable to variations due to the wind-driven circulation. The Pacific Ocean to Indian Ocean sea level difference across the Indonesian seas might vary as the large-scale wind fields over the tropical Pacific and Indian oceans change, perhaps in response to Southern Oscillation events. The leakage of Indian Ocean thermocline water into the South Atlantic is effected by the local wind: models show that the leakage grows larger as the maximum westerlies shift further to the south. Thus these two links may act as "choke" points, which upon responding to the wind affect the entire efficiency of the thermohaline cell. Climate variability at a variety of time scales may be related to the imposed wind drive efficiency of this cell and bears investigation. With a global prospective in mind, the oceanography of certain regions, while interesting in its own right, takes on new significance. In the scheme presented above, it is suggested that ventilation of specific thermoclines may not be successfully approached in isolation from neighboring thermoclines.

We are about to enter into a new phase of oceanography as we take on the global prospective. Armed with good knowledge of regional oceanography and with the technology available to us, I suspect that by the year 2000 we will be amazed to learn that all the things that we have been saying about the importance of the ocean to large-scale climate system are really true! Well, what's left for the 21st century? In addition to setting monitoring networks to keep tabs on the ocean, I guess we will go back and get the regional and process oceanography done right, and then there's always those other bodies in the solar system, with liquid and ice "oceans."

This work was presented at the AGU/American Society of Limnology and Oceanography Ocean Sciences Meeting Luncheon, New Orleans, La., January 15, 1986.

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This item was contributed by Arnold L. Gordon, *Lamont-Doherty Geological Observatory, Palisades, N.Y.*

News & Announcements

Ocean Sciences Award

PAGE 110

The Ocean Sciences Award is presented by the Ocean Sciences Section of AGU to an individual who has made outstanding and longstanding contributions to the ocean sciences. Previous recipients are

Eugene C. LaFond	1982
Richard C. Vetter	1983
Robert E. Wall	1983
Fennan D. Jennings	1984
Wayne V. Burt	1984
W. Stanley Wilson	1984
Curtis A. Collins	1985

Nominations are solicited for candidates for the Ocean Sciences Award in 1986. Letters of nomination should be sent to Arnold L. Gordon, President-Elect, Ocean Sciences Section, Lamont-Doherty Geological Observatory, Palisades, NY 10964. The deadline for nominations is May 1, 1986. Nominations may be accompanied by seconding nominations and a resume of the candidate.

Black Sea Cruise

PAGE 110

The National Expeditionary Planning Committee of the University-National Oceanographic Laboratory System (UNOLS) has designated the R/V *Knorr* to support oceanographic programs in the Black Sea during 1987. Researchers are invited to submit requests for ship time in 1987 and 1988 to support projects in the Black Sea, the Mediterranean Sea, the Red Sea, and the Indian Ocean. Proposals for the support of the scientific programs should be submitted in accordance with the funding agency deadlines.

Requests for ship use should be sent soon to J. D. Donnelly, Manager, Marine Operations, Woods Hole Oceanographic Institution, Woods Hole, MA 02543 (telephone: 617-548-1400, ext. 2736), or to W. D. Barbee, Executive Secretary, UNOLS Office, WB-15, School of Oceanography, University of Washington, Seattle, WA 98195 (telephone: 206-543-2283).

Meeting Report

Ocean Telemetry Workshop

PAGE 110

An informal workshop on ocean telemetry and platform location was held on January 15, 1986, during the AGU Ocean Sciences Meeting in New Orleans, La. Plans for the workshop grew from the realization that pre-

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