JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 91, NO. C4, PAGES 5037–5046, APRIL 15, 1986

Interocean Exchange of Thermocline Water

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Formation of North Atlantic Deep Water (NADW) represents a transfer of upper layer water to abyssal depths at a rate of 15 to 20 × 10^6 m^3/s. NADW spreads throughout the Atlantic Ocean and is exported to the Indian and Pacific Oceans by the Antarctic Circumpolar Current and deep western boundary currents. Naturally, there must be a compensating flow of upper layer water toward the northern North Atlantic to feed NADW production. It is proposed that this return flow is accomplished primarily within the ocean's warm water thermocline layer. In this way the main thermoclines of the ocean are linked as they participate in a thermohaline-driven global scale circulation cell associated with NADW formation. The path of the return flow of warm water is as follows: Pacific to Indian flow within the Indonesian Seas, advection across the Indian Ocean in the 10°–15°S latitude belt, southward transfer in the Mozambique Channel, entry into the South Atlantic by a branch of the Agulhas Current that does not complete the retroflection pattern, northward advection within the subtropical gyre of the South Atlantic (which on balance with the southward flux of colder North Atlantic Deep Water supports the northward oceanic heat flux characteristic of the South Atlantic), and cross-equatorial flow into the western North Atlantic. The magnitude of the return flow increases along its path as more NADW is incorporated into the upper layer of the ocean. Additionally, the water mass characteristics of the return flow are gradually altered by regional ocean-atmosphere interaction and mixing processes. Within the Indonesian seas there is evidence of strong vertical mixing across the thermocline. The cold water route, Pacific to Atlantic transport of Subantarctic water within the Drake Passage, is of secondary importance, amounting to perhaps 25% of the warm water route transport. The continuity or vigor of the warm water route is vulnerable to change not only as the thermohaline forcing in the northern North Atlantic varies but also as the larger-scale wind-driven criculation factors vary. The interocean links within the Indonesian seas and at the Agulhas retroflection may be particularly responsive to such variability. Changes in the warm water route continuity may in turn influence formation characteristics of NADW.

INTRODUCTION

Warm salty water spreads into the northern North Atlantic, where it is cooled primarily by evaporation. Ironically, this is a consequence of its anomalously high temperature relative to the atmosphere [*Warren*, 1983]. This in turn maintains relatively high salinity and density despite an abundance of precipitation. The cooled salty water sinks to the deep ocean, marking the formation of North Atlantic Deep Water (NADW) [*Warren*, 1981; *Killworth*, 1983]. The NADW from the two northern sites (Labrador Sea and the Greenland Sea–Norwegian Sea overflow), with a mean temperature and salinity of approximately 2°C and 34.93‰ (the northern component defined by *Broecker et al.*, [1976] and *Broecker and Peng* [1982]), spreads to the south within the deep western boundary current, being joined by the saltier outflow from the Mediterranean Sea. The NADW water mass influences most of the global ocean [*Reid and Lynn*, 1971]. *Warren* [1981], reviewing the estimates of NADW formation rate, arrives at a number of 14 Sv (1 Sv = 10^6 m^3/s). *Broecker* [1979], using radiocarbon data, suggests a formation rate of greater than 20 Sv. The two northern components account for over 90% of the NADW volume flux.

The process of NADW formation is self-perpetuating in that as the surface layer water sinks and is exported southward within the deep layer, more upper layer water is drawn into the northern North Atlantic. This in turn drives the high evaporation rates continuing the NADW formation process. Whether a random event initialized the circulation or whether it is a response to the changing distribution of the land masses and associated large-scale circulation remains a tantalizing problem in oceanography. The thermohaline circulation pattern in the meridional plane associated with the NADW formation is one of a negative estuary [*Stommel*, 1956; *Reid*, 1961; *Worthington*, 1981; *Gordon and Piola*, 1983]: upper layer water moves to the north, while deeper water moves to the south. This pattern is clearly seen in the results of the inverse solutions for the Atlantic Ocean using the International Geophysical Year (IGY) set of zonal hydrographic sections [*Roemmich*, 1980, 1983; *Fu*, 1981; *Wunsch*, 1984; *Roemmich and Wunsch*, 1985]. Comparison of the IGY data with recent data sets indicates the suspected stability of the thermohaline circulation, though the distribution of the transport within the various density strata does vary [*Roemmich and Wunsch* 1985].

The choice for the separation between the two layers varies, but only slightly, among authors. *Gordon and Piola* [1983], noting that the salty characteristic of NADW is incorporated into the Antarctic circumpolar belt below the σ_0 density of 27.6 [*Georgi*, 1981], place water less dense than that value within the upper layer (this includes the thermocline and intermediate water). The density interval from σ_0 of 27.7 to σ_2 of 36.82 divides the upper and lower layers in the inverse method approaches [*Roemmich*, 180; *Roemmich and Wunsch*, 1985]. *McCartney and Talley*'s [1984] separation between northward and southward flow falls near 4°C, which coincides more or less with the 27.7 σ_0.

Broecker and Peng [1982] in their discussion of the upper layer feed for NADW point out that the upper layer water must have about the same nutrient concentrations as NADW, since there is no significant source or sink of nutrients in the North Atlantic. In their Table 7-2 the nutrient concentrations for the various components of NADW are listed. Characteristic PO_4, NO_3, and SiO_2 concentrations are 1, 15, and 12 mol/kg, respectively. Inspection of the GEOSECS data [*Bainbridge*, 1981] indicates that within the central North Atlantic these values are associated with temperatures between 11° and 13°C and salinity of approximately 35.55‰, corresponding to

Paper number 6C0064.
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a σ_0 of 27.0. Thus the feed water is derived from within the main thermocline, well above the Antarctic Intermediate Water (AAIW) layer.

The magnitude of the thermohaline circulation for the Atlantic Ocean has been estimated by various means. The inverse method approach of *Roemmich and Wunsch* [1985] yields for the IGY and 1981 transatlantic sections at 24° and 36°N an average of 17 Sv for the northward flow of upper layer water (surface component of 11.3 Sv and intermediate water component of 5.8 Sv), which balances the southward flowing deep water (19.9 Sv, 2.9 Sv of which is returning Antarctic Bottom Water). This estimate is close to the 15- to 16-Sv values given by *Roemmich* [1980] and *Hall and Bryden* [1982]. These estimates do not take into account the Pacific to Atlantic transfer of about 1 Sv in the Bering Strait [*Coachman et al.*, 1975], so the southward deep flow is expected to be slightly above the northward upper layer flow. Box models based on temperature and salinity yield similar results. *Gordon and Piola* [1983] find that gradual increase in salinity of the northward flowing Atlantic Ocean upper layer water can be justified with the *Baumgartner and Reichel* [1975] estimates of fresh water exchange with the atmosphere if the magnitude of the thermohaline circulation cell is near 20 Sv. *McCartney and Talley* [1984] investigate the thermal field, finding southward flow across 50°N of 14.1 Sv of cold water. Their feed of upper layer water into the NADW formation region is about 11.5°C, similar to the temperature horizon necessary to meet the nutrient requirements.

As NADW spreads into the South Atlantic and then eastward with the Antarctic Circumpolar Current into the Indian and Pacific oceans, the negative estuary circulation pattern is expected to extend out of the North Atlantic into the rest of the world ocean [see *Broecker and Peng*, 1982, Figures 1–13; *Piola and Gordon*, 1984]. The objective of this paper is to explore the general form of this global scale thermohaline circulation cell and demonstrate support for the hypothesis that upper layer return flow is accomplished primarily within the main thermoclines of the ocean.

The NADW upwells within the world ocean, returning water to the upper layer within the Antarctic region and into the thermocline. Antarctic and thermocline upwelling may be coupled in that deep water upwelling around Antarctica contributes to the formation of Antarctic Intermediate Water, which then spreads below the thermocline and upwells into the thermocline. There are two routes by which the upper layer water can return to the Atlantic Ocean, though they are not mutually exclusive: the cold water route within the Drake Passage, in which AAIW and Subantarctic Mode Water (SAMW) pass into the South Atlantic [*Georgi*, 1979; *Piola and Georgi*, 1982; *McCartney*, 1977], and the warm water route, in which Indian Ocean thermocline water is introduced to the South Atlantic south of Africa (Gordon, 1985). It is proposed that the warm water route is the more important.

WARM WATER ROUTE

As was mentioned above, most of the northward flow within the upper layer in the North Atlantic resides in the warmer water above the intermediate stratum [*Broecker and Peng*, 1982; *Roemmich and Wunsch*, 1985]. A simple demonstration that this is also the case in the South Atlantic can be made on the basis of the equatorward oceanic heat flux characteristic of the South Atlantic. *Hastenrath* [1982] determines that 69×10^{13} W pass to the north across 30°S. Invoking the concept that the wind-driven Brazil Current within the thermocline is weakened by the thermohaline-driven circulation pattern [*Stommel*, 1957] as some South Atlantic thermocline water is transferred into the North Atlantic, it is possible to determine the mean temperature of the northward moving upper layer water across 30°S.

The mass and heat flux equation across 30°S are

Mass

$$V_i = [V_{bz} + V_n] - V_{bs} \tag{1a}$$

Heat

$$V_t T_t = [V_{bz} T_{bz} + V_n T_n] + Q_f \tag{1b}$$

where V_t is the mass flux of the northward moving water, with a temperature of T_i, within the interior of the South Atlantic; V_{bz} is the mass flux of the Brazil Current within the upper layer, with a transport averaged temperature of T_{bz}; V_n is the mass flux of NADW across 30°S, with a temperature of T_n; V_{bs} is the mass flux of water through the Bering Strait; and Q_f is the northward oceanic heat flux across 30°S.

A production rate of 20 Sv for NADW, with uniform upwelling north of 30°S, yields 16 Sv for V_n; T_n is taken as 2°C. V_{bs} is taken as 1.5 Sv [*Coachman et al.*, 1979]. The transport of the Brazil Current in the upper layer increases from approximately 6.5 Sv across 19°–23°S to 17.1 Sv across 38°S [*Gordon and Greengrove*, 1986]. An intermediate value of 10 Sv is taken for V_{bz}. The combined transport of the Brazil Current and NADW flow across 30°S is 26 Sv, which approximately balances the Sverdrup interior transport across 30°S, given as 30 Sv by *Hellerman and Rosenstein* [1983]. The value used for T_{bz} is 18°C, as was determined from the distribution of the meridional component of the volume transport in temperature-salinity space given by *Miranda and Castro Filho* [1981] for the Brazil Current at 19°S. Using the *Hastenrath* [1982] Q_f, 50% of Q_f, and 5% of Q_f, equations (1*a*) and (1*b*) are solved, resulting in a T_i of 15.4°C, 12.0°C and 9°C, respectively (Figure 1).

The warmest water in the Drake Passage is about 8°C [*Gordon and Molinelli*, 1982], and the volumetric mode of the AAIW/SAMW in the southwest Atlantic, which can be traced into the South Atlantic, is 3.5°C [*Georgi*, 1979]. Thus even in the extreme case in which the Hastenrath heat flux value is an order of magnitude too high, the cold water route cannot be the sole supplier of upper layer return to the NADW production region. Assuming that the Hastenrath Q_f is roughly correct, the bulk of the upper layer return flow must reside within the thermocline. The only source for such water south of 30°S is the Indian Ocean thermocline water within the Agulhas Current.

The proposed global scale warm water route associated with thermohaline-driven circulation cell is as follows (Figures 2*a*, 2*b*, and 2*c*): The upwelling NADW returns water to the thermocline which was lost during production of NADW. The primary site of upwelling is the southern ocean, where the upwelled NADW eventually flows below the thermocline and enters the thermocline as AAIW. The thermocline water is returned to the North Atlantic by the following route:

1. The NADW introduced into the Pacific Ocean is transferred as North Pacific Central (thermocline) Water to the Indian Ocean through the Indonesian seas.

2. The Pacific water crosses the Indian Ocean in the 10°–15°S latitude belt, incorporating the saltier Indian Ocean thermocline water.

3. The mix of Pacific Ocean and Indian Ocean water passes southward within the Mozambique Channel, supplying a small component of the Agulhas Current transport.

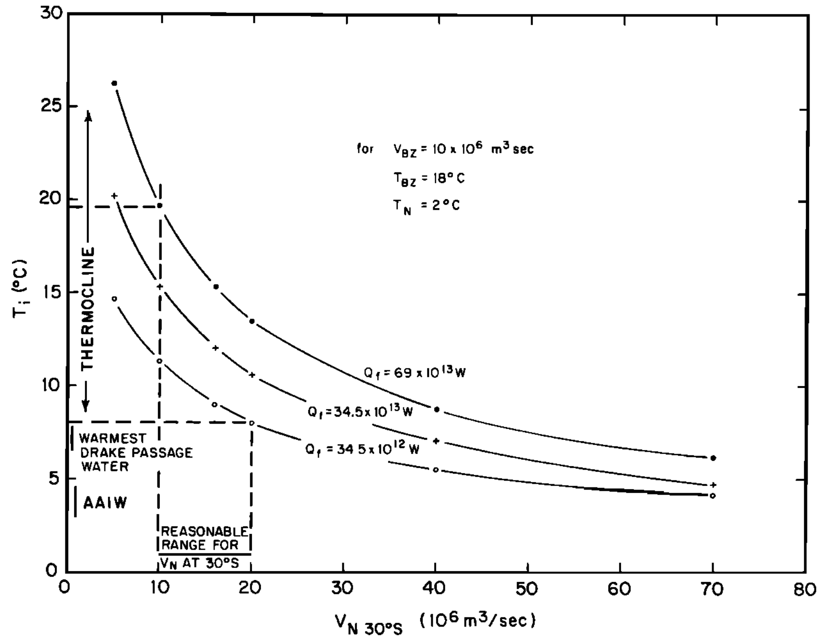

Fig. 1. Relationship of the temperature of the water flowing to the north across 30°S (T_i, see equation (1)) as is required to balance the component of NADW advected southward across 30°S (V_n, see equation (1)). The relation is given for three values of Q_f (the northward heat flux across 30°S): the value given by *Hastenrath* [1982], half of that value, and 5% of that value. See equations (1*a*) and (1*b*) for explanation of other values.

4. A branch of the Agulhas Current flows into the South Atlantic and does not participate in the Agulhas retroflection, which returns most of the Agulhas water to the Indian Ocean.
5. The warm water passes northward with the South Atlantic subtropical gyre, crossing the equator to enter the upper layer of the North Atlantic.

Assuming a 20-Sv production rate of NADW with uniform upwelling into the world ocean (thus the Pacific receives 50% of the deep water, with the Atlantic and Indian oceans splitting the rest equally [*Piola and Gordon*, 1984]) and assuming that the cold water route is insignificant, it is possible to place some numbers on the magnitude of the warm water route (Figure 2*a*). The assumption of uniform upwelling (introduced by *Stommel and Arons* [1960]) may not be strictly adhered to. For example, if a larger proportion of NADW upwells in the Atlantic, the transport values given for the Pacific-Indian and Indian-Atlantic transfer would be reduced. Hence these numbers are not overly significant, since the assumptions are not likely to be strictly followed, but they do provide some "ball park" estimates which can be compared with other, independent determinations.

The following section attempts to show supporting evidence for key links of the proposed interocean warm water route.

EVIDENCE FOR THE WARM WATER ROUTE

Indonesian Through Flow

The most comprehensive physical oceanographic work on the Indonesian seas is that of *Wyrtki* [1957, 1961]. On the basis of water mass analysis he shows that Pacific water spreads into the Indian Ocean down to depths of 1000 m. Replacement of the water filling the deep basin of the Banda Sea by sill overflow is an active feature within the Indonesian seas. The displaced deep water is responsible for the low-salinity Banda Intermediate Water of the Indian Ocean [*Rochford*, 1966]. Above the 1000-m flow, Wyrtki traces some eastward transfer, primarily by lateral mixing, of the Indian O_2 minimum layer into the Banda Sea. At depths shallower than approximately 500 m, flow is more substantial and is directed into the Indian Ocean. This water, derived from the Mindanao Current, contains subtropical salinity maximum and intermediate salinity minimum water masses of the North Pacific. "Thus in all layers with the exception of that of the oxygen minimum, movements from the Pacific to the Indian Ocean predominate" (page 114 of the *Wyrtki* [1961] study).

Water mass analysis using the gridded *Levitus* [1982] data set (Figures 3, 4, and 5), supports the results of *Wyrtki* [1961]: The water within the Banda Sea thermocline (10°–20°C layer) is similar to that of the North Pacific Central (thermocline) Water, with only minor requirements for additional fresh water (Figure 4). The Banda Sea thermocline water enters the Indian Ocean primarily in the passages adjacent to Timor island (Figure 3). The low-salinity thermocline within the eastern tropical Indian Ocean (Figure 3) is similar to the Banda Sea/North Pacific thermocline water (Figure 5). It spreads within the South Equatorial Current across the full width of the Indian Ocean, as will be discussed below. Furthermore, it is noted that within the 10°–20°C layer of the Indonesian seas, the vertical mixing (cross-isopycnal) coefficient must be large (greater than 3×10^{-4} m²/s) to account for the modification of the North Pacific thermocline temperature-salinity structure. The subtropical *S* maximum of the North Pacific thermocline is destroyed as an isohaline thermocline forms in the Banda Sea (Figure 4). The thermohaline structure is not conducive to salt finger activity. The mixing is more likely a product of interaction of the circulation with the irregular topography of the region.

Intense vertical mixing implies substantial downward heat flux within the Banda Sea thermocline. The vertical temperature gradient is 10°C in 150 m (area 23 on Plate 205 of *Wyrtki* [1971]); a vertical mixing coefficient of 4×10^{-4} m²/s yields downward heat flux of 110 W/m². The atmosphere to ocean heat exchange for the region is approximately 90 W/m² [*Talley*, 1984]. Thus as the water flows through the Indonesian seas, the upper layers of the thermocline would remain at the same temperature or perhaps cool slightly, even though

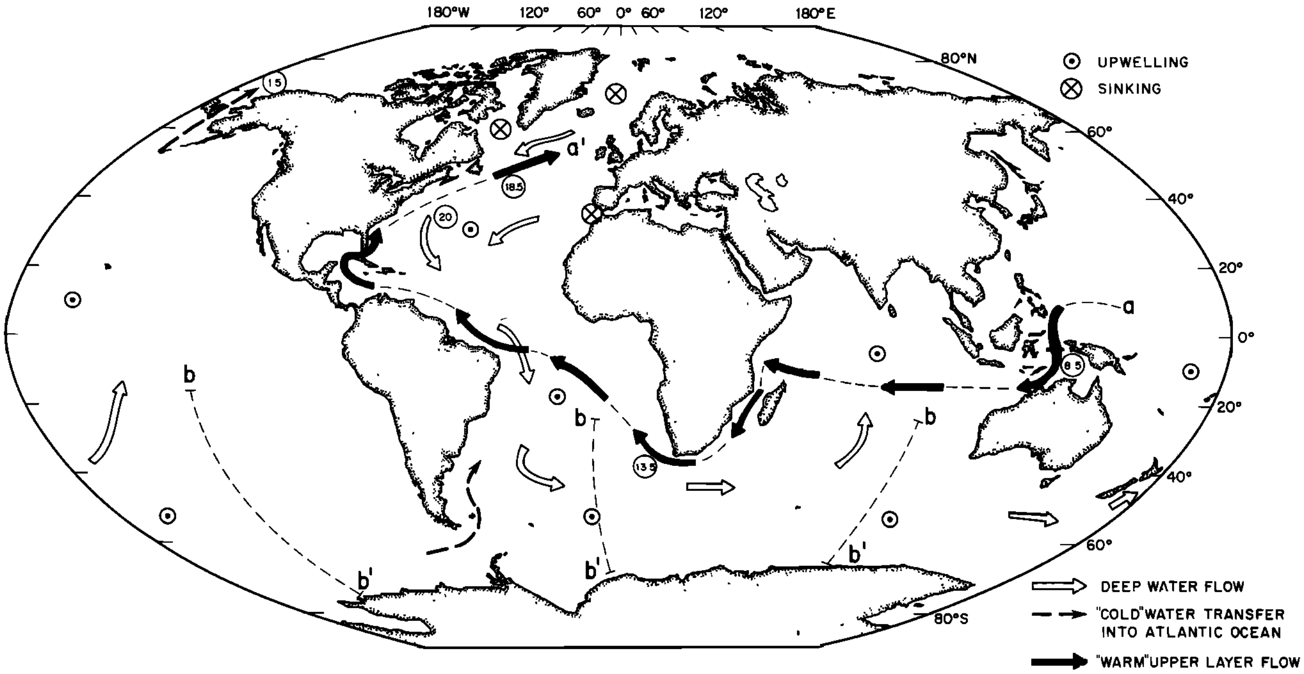

Fig. 2*a*. Global structure of the thermohaline circulation cell associated with NADW production. The warm water route, shown by the solid arrows, marks the proposed path for return of upper layer water to the northern North Atlantic as is required to maintain continuity with the formation and export of NADW. The circled values are volume flux in 10^6 m^3/s which are expected for uniform upwelling of NADW with a production rate of 20×10^6 m^3/s. These values assume that the return within the cold water route, via the Drake Passage, is of minor significance.

the atmosphere to ocean heat flux is large, while the lower thermocline would warm. This effect probably accounts for the decrease of surface water temperature from over 28°C in the western tropical Pacific to less than 28°C in the eastern tropical Indian Ocean receiving the through flow (for example, see the surface temperature maps of *Pickard and Emery* [1982]) despite strong atmospheric heating of the ocean.

Wyrtki [1971] shows that the nutrient concentrations in the Banda Sea on the $25.0\sigma_0$ surface (near the 18°C isotherm at 150 m) are 1.0, 15, and 23 mol/kg for PO_4, NO_3, and SiO_2, respectively. Closer to the base of the thermocline, at the $26.6\text{-}\sigma_0$ surface (near the 10°C isotherm at 350 m), nutrients are higher by somewhat less than a factor of 2: 1.8, 30, and 35 mol/kg for PO_4, NO_3, and SiO_2, respectively. Within the Pacific Ocean's North Equatorial Current, which is the source for the Mindanao Current [*Tsuchiya*, 1968] feeding the transfer to the Indian Ocean, there is a strong nutrient-cline across the 15° to 20°C layer [*Wyrtki and Kilonsky*, 1984]. Values of 0.5, 5, and 5 mol/kg near 18°C yield to 2.0, 25, 30 mol/kg near the 10°C isotherm for PO_4, NO_3, and SiO_2, respectively, a factor of 5 increase. The breakdown of the nutrient-cline and elevated nutrient concentrations in the upper layer of the Banda Sea thermocline is likely to be a consequence of the large vertical mixing coefficient within the Indonesian seas. The high nutrient levels characteristic of the Indian Ocean thermocline north of 15°S may be derived at least in part from the vigorous mixing within the Indonesian seas.

The North Pacific origin for the water flow into the Indian Ocean [*Wyrtki*, 1961] suggests that the NADW contribution to the North Pacific thermocline is the chief supplier for this link of the warm water route. The NADW entering the more saline South Pacific thermocline may add some water to the flow through, (associated with equatorial upwelling and advection) along the north coast of New Guinea (Figure 3), but it appears to have a secondary impact on the Banda Sea salinity. This leads to the question, where does most of the

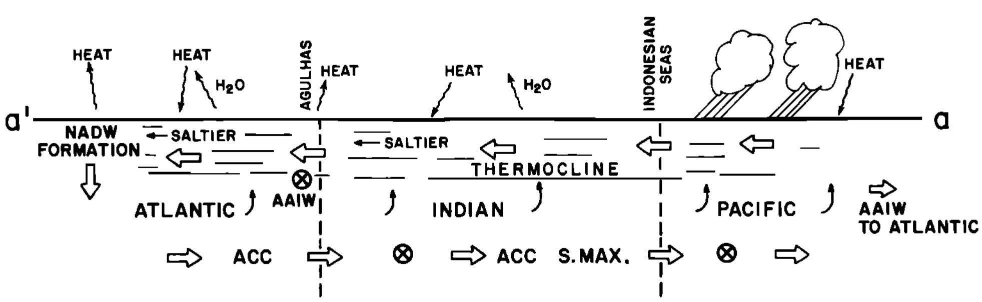

Fig. 2*b*. Schematic representation of the thermohaline circulation cell associated with NADW production and the warm water route along line *a-a'* shown in Figure 2*a*. The upper layer water within the main thermocline begins its passage to the North Atlantic in the Pacific as low-salinity water. It enters the Indian Ocean via the Indonesian seas, where its salinity and volume flux increase by excess evaporation and further upwelling of NADW, respectively. The thermocline water enters the Atlantic south of Africa and spreads to the northern Atlantic, continuing to increase in salinity and volume flux.

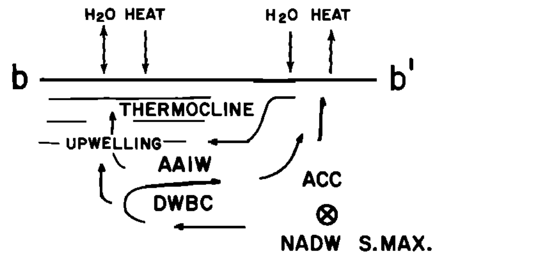

Fig. 2c. Schematic representation of the paths followed as NADW upwells, becoming incorporated into the thermocline, along line b-b' shown in Figure 2a. The main upwelling is expected to occur in the Antarctic region, with eventual transfer to the thermocline as Antarctic Intermediate Water.

NADW entering the South Pacific thermocline go? This is not the main topic of this paper, but it is suggested that it may feed the cold water route via the Drake Passage. Under the assumption of uniform NADW upwelling, this would account for a maximum of 25% of the total return flow into the North Atlantic Ocean.

There has been some work addressing the magnitude of the Pacific to Indian Ocean transfer. *Wyrtki* [1961] determines the current velocity from differences in dynamic heights. South of Timor Island (Timor Sea) a single station pair indicates a flux of 6.4 Sv. This flow is accomplished within the upper 300 m. However, in his summary of transports for the upper 150 to 200 m (his Table 12, p. 136), the resultant flow from the Indonesian waters to the Indian Ocean ranges from a low of 1 Sv in the December to February period to 2.5 Sv in August, with an annual average of 1.7 Sv.

Recently there have been a rash of estimates (based on a variety of methods) of the Pacific to Indian transfer of water, all of which are larger than Wyrtki's estimate (Table 1). The average of all estimates is 9.2 Sv into the Indian Ocean.

Clearly, there is agreement that the water flow is toward the Indian Ocean, but there is a wide range of estimates as to its magnitude. The value proposed in this paper (8.5 Sv, Figure 2*a*) is close to the average estimate. The values would be halved to about 4 Sv if the NADW entering the South Pacific thermocline returns to the Atlantic by way of the Drake Passage. However, there is likely to be additional Pacific to Indian transport which balances eastward transfer of (cooled) thermocline water south of Australia. The value presented in Figure 2*a* represents only that component involved in the global scale NADW-thermocline circulation cell.

Trans-Indian Ocean

The low-salinity thermocline within the westward flowing South Equatorial Current in the 10° to 15°S latitude belt of the Indian Ocean (Figure 3) has temperature-salinity characteristics similar to those of Banda Sea water emerging from the Timor Sea region (Figures 5 and 6; also see *Wyrtki* [1971], Plates 223, 231, and 237 for salinity on isopycnal surfaces within the thermocline and Plates 364 to 369 and 394 for dynamic topography), attesting to its Pacific origin. The characteristic of this feature stands in sharp contrast to the more saline thermocline of the south Indian Ocean and Arabian Sea; a lesser contrast is seen with the Bay of Bengal. Inspection of the evolution of the temperature-salinity relation in the downstream direction shows a steady increase of salinity above the 10°C isotherm (Figures 3 and 6). The salinity increases by approximately 0.5‰ throughout the thermocline before reaching the Somali Basin in the western Indian Ocean. It is likely that the salt is introduced by lateral (isopycnal) mixing with the neighboring thermoclines. The salinity levels within the neighboring thermoclines are maintained by the regional excess of evaporation over precipitation [*Baumgartner and Reichel*, 1975]. In addition, NADW incorporated into the Indian Ocean thermocline, via the AAIW route or directly (Figure 2*c*), would be expected to swell the transport of the warm water return flow during transit of the Indian Ocean.

The nutrient concentrations within the Indian Ocean thermocline north of 15°S are significantly above those within the south Indian Ocean thermocline [*Spencer et al.*, 1982]. As was mentioned above, similar levels are observed in the Banda Sea, and it is suspected that the intense vertical mixing within the Indonesian seas may, at least in part, be responsible. This may also be true for the more or less isohaline thermocline of the northern Indian Ocean. Thus it is possible that the Pacific

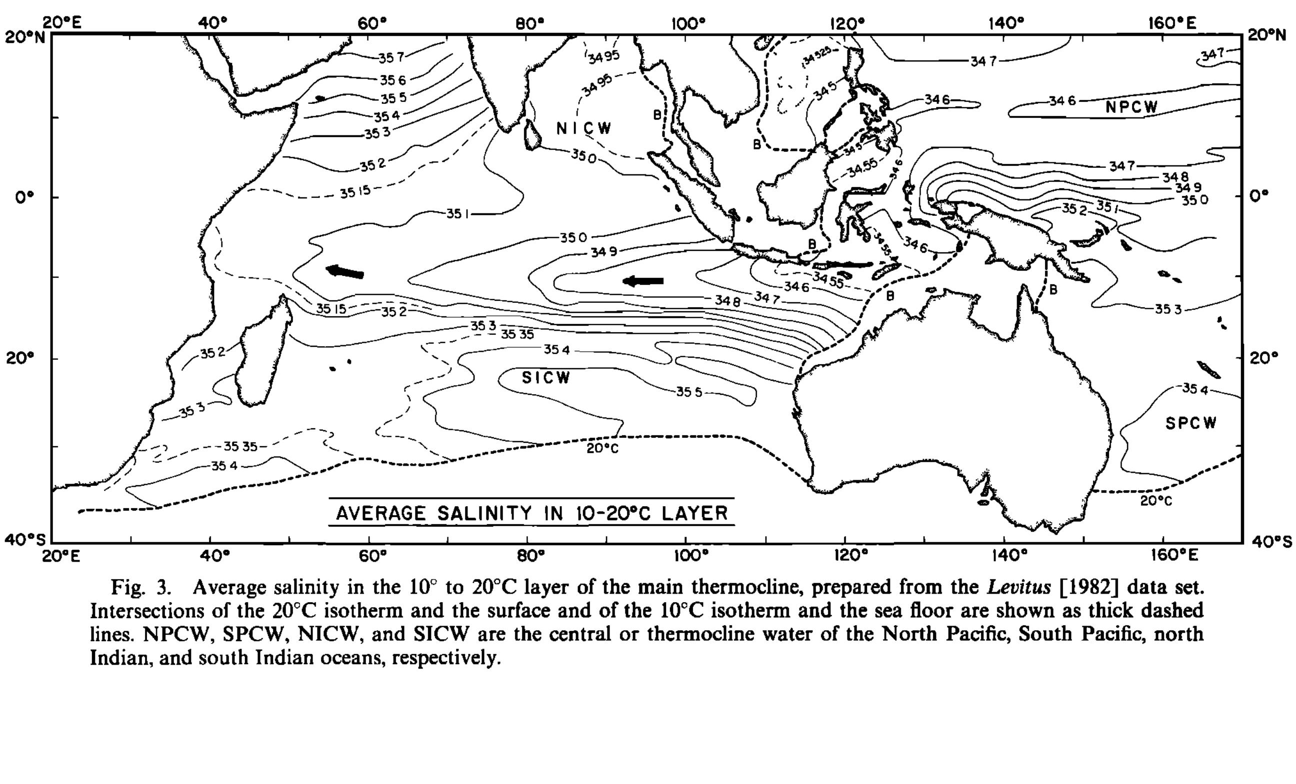

Fig. 3. Average salinity in the 10° to 20°C layer of the main thermocline, prepared from the *Levitus* [1982] data set. Intersections of the 20°C isotherm and the surface and of the 10°C isotherm and the sea floor are shown as thick dashed lines. NPCW, SPCW, NICW, and SICW are the central or thermocline water of the North Pacific, South Pacific, north Indian, and south Indian oceans, respectively.

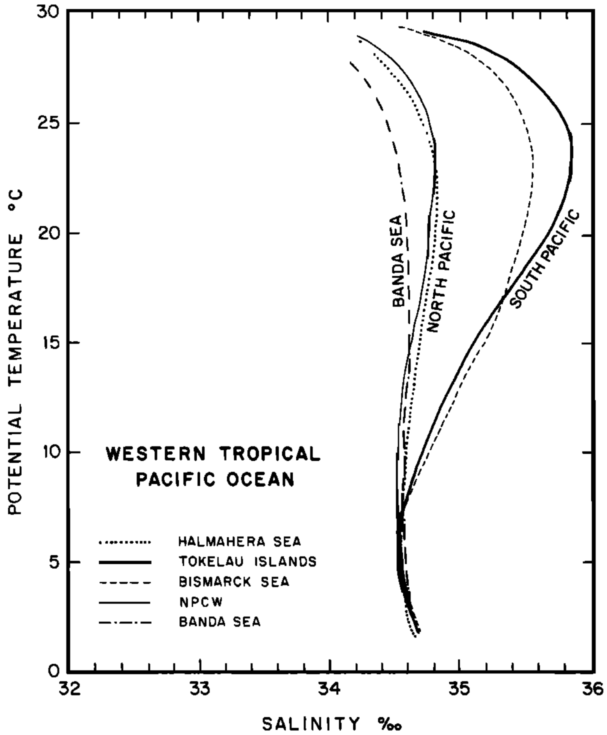

Fig. 4. The potential temperature–salinity relationship for various seas or regions of the western tropical Pacific Ocean and Banda Sea, from the Levitus data set. The Banda Sea curve is similar to the thermocline characteristics of the North Pacific. It is possible to "produce" the Banda Sea curve from the North Pacific curve with strong vertical (cross-isopycnal) mixing and with the addition of slight amount of fresh water (of the order of 10 cm). To produce the Banda Sea curve from South Pacific thermocline water requires far more vigorous mixing and the addition of nearly 10 m of fresh water, a condition believed improbably for realistic residence time of through flow water within the Indonesian seas.

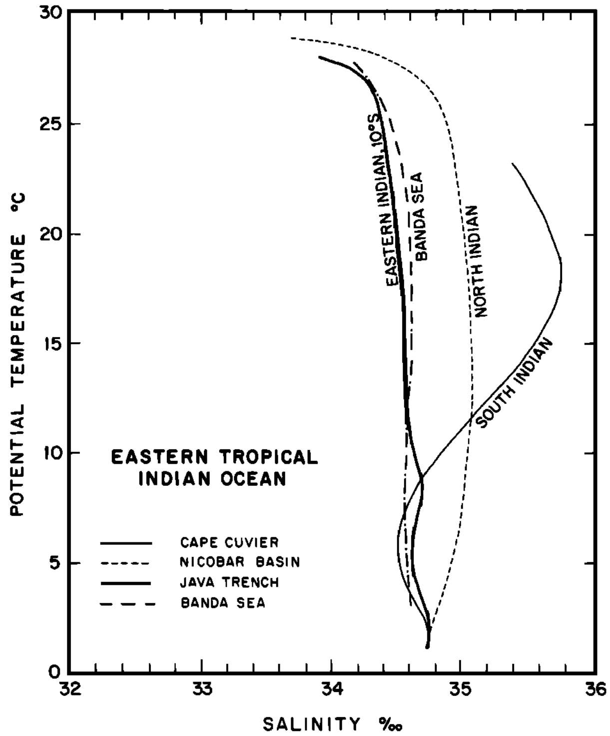

Fig. 5. The potential temperature–salinity relationship for various seas or regions of the eastern tropical Indian Ocean from the Levitus data set. The water within the low-salinity thermocline along the 10° to 15°S latitude belt (see Figure 3) is similar to that of the Banda Sea and is much more saline than that of the Indian Ocean to the south and north. This similarity supports the Banda Sea (North Pacific) origin of the low-salinity feature.

inflow to the Indian Ocean is an important determiner of the thermocline water properties of the northern Indian Ocean and that it feeds the southward flux via the Mozambique Channel.

Mozambique Channel

The low-salinity thermocline characteristic of the Somali Basin can be traced to spread southward within the Mozambique Channel (Figure 7; also see *Wyrtki* [1971, Plates 223, 231, and 237]), but the signal is weak. *Saetre and da Silva* [1984] conclude that the circulation within the Mozambique Channel is dominated by anticyclonic gyres with only minor through flow. They call into question the older concept that the Mozambique Channel is the main supplier of the Agulhas Current. Rather, the bulk of the Agulhas Current seems to be associated with a strong anticyclonic gyre situated west of 45°E within the 30° to 40°S belt of the Indian Ocean [*Wyrtki*, 1971, Plate 394]; however, some input from the Mozambique Channel and East Madagascar Current is likely [*Wyrtki*, 1971, Plates 364 to 369; *Harris*, 1972; *Lutjeharms*, 1976]. *Harris* [1972] estimates 10-Sv flows poleward through the Mozambique Channel. *Fu*'s [1986] inverse method solution for six hydrographic sections in the Indian Ocean indicates southward transport in the Mozambique Channel of 6 Sv, similar to his value for the Indonesian sea through flow (Table 1).

A hydrographic section adjacent to Durban obtained from the R/V *Meiring Naude* in October 1983 [*Grundlingh*, 1986; A. L. Gordon et al., manuscript in preparation, 1986] shows the inshore segment of the Agulhas Current is marked by reduced salinity within the thermocline at temperatures above 14°C. The temperature-salinity relationship of the feature is nearly identical to that found in the Mozambique Channel, while the temperaure-salinity curve, 10 to 20 km further offshore matches that of the East Madagascar Current (Figure 7). This low-salinity thermocline feature along the inshore side of the

TABLE 1. Estimates of Pacific to Indian Ocean Transport Within the Indonesian Seas

Who	What, Sv	How
Wyrtki [1961]	1.7	dynamic calculations
Cox [1975]	18	general circulation model (experiment III); pressure around Australia equated to zero
Godfrey and Golding [1981]	10	mass transport in the eastern Indian Ocean
Piola and Gordon [1984]	14	freshwater box model of the Pacific and Indian oceans
Fine [1985]	5.1	tritium box model (upper 300 m)
Fu [1986]	6.6	inverse method applied to six Indian Ocean sections

1 Sv = 10^6 m^3/s.

Agulhas Current is also seen in the 1973 *Meiring Naude* section off Durban used by *Pearce* [1977]. Thus the water mass composition indicates that the low-salinity Mozambique Channel input is confined to the inshore segment of the Agulhas (this is also seen in the *Wyrtki* [1971] plates). Sections of the 1983 *Meiring Naude* data set further to the south, and those of the R/V *Knorr* obtained in November and December 1983 in the Agulhas retroflection [*Gordon*, 1985; *Huber et al.*, 1985; A. L. Gordon et al., manuscript in preparation, 1986] reveal that the Mozambique Channel signature can be traced to the south, but it becomes more diffuse as mixing with the more saline offshore components occurs.

Grundlingh [1984] reports the presence of an intrusion of Red Sea water of 5°C near 1400 m in the southern end of the Mozambique Channel. He concludes that the Mozambique Channel closure below the 27.5-σ_t surface as suggested by *Lutjeharms* [1976] is not complete.

It is suggested that the Mozambique Channel water, while a minor component of the Agulhas Current volume flux, does inject specific water mass characteristics derived from the Somali Basin into the Agulhas, and it is feasible that the level of transport required by the warm water route (Figure 2*a*) can be supported.

Agulhas Leakage

The Agulhas Current is the most energetic western boundary current of the southern hemisphere; volume transport estimates vary from 44 Sv [*Toole and Raymer*, 1985] to the range 62–75 Sv [*Grundlingh*, 1980] as the current passes adjacent to Durban, with 80% occurring in the upper 1000 m [*Grundlingh*, 1980].

The Agulhas Current turns westward as its path follows the southern terminus of the African continent, separating from the margin near 22°E. After separation it executes an abrupt anticyclonic turn to the east in what is referred to as the Agulhas retroflection [*Bang*, 1970]. The dynamics of the retroflection are addressed by *de Ruijter* [1982] and *Ou and de Ruijter* [1985]. Not all of the Agulhas water participates in the retroflection. Using the *Knorr* November–December 1983 hydrographic data set, *Gordon* [1985] on the basis of water mass characteristics and geostrophic flow shows the presence of isolated rings of Agulhas water west of the retroflection (also see *Duncan* [1968] and *Olson and Evans* [1985]). Between the ring centers and the African mainland, is an Agulhas Current branch, carrying 14 Sv, directed into the South Atlantic Ocean. The 1983 situation is remarkably similar to that found in Mach 1969, when a synoptic data set indicates that 5 Sv of Agülhas water enters the South Atlantic [*Harris and Van Foreest*, 1978], and to the pattern shown by *Dietrich* [1935]. Model studies also depict linkage between the subtropical gyres of the South Atlantic and Indian oceans [*Veronis*, 1973; *de Ruijter and Boudra*, 1985].

The Mozambique Channel input to the Agulhas system carries the high-nutrient characteristic of the Indian Ocean north of 15°S. This is seen in density surface maps of *Wyrtki* [1971] as nutrient rich water spreads poleward along the western boundary. The hydrographic data obtained within the Agulhas Current axis south of Africa from aboard the *Knorr* in November and December 1983 [*Huber et al.*, 1985] reveal nutrient levels similar to the level required to match the feed

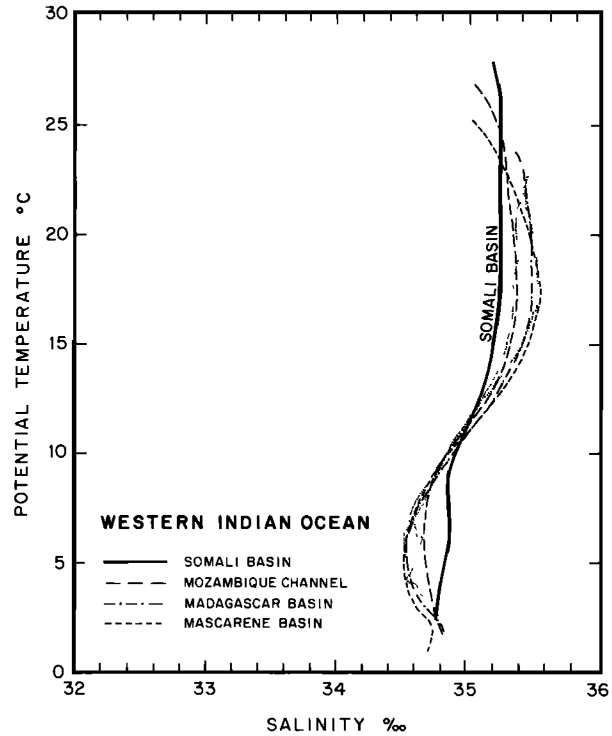

Fig. 7. The potential temperature–salinity relationship along the western South Indian Ocean, from the Levitus data set. The Madagascar Basin represents the East Madagascar Current regime, and the Mascarene Basin represents the anticyclonic circulation gyre of the southwest Indian Ocean. The two fine dotted lines are from stations within the Agulhas Current (data were obtained from the R/V *Meiring Naude* in October 1983) adjacent to Durban. The station from the inshore segment of the current is nearly identical to the water within the Mozambique Channel, whereas the characteristics of the outer segment of the Agulhas Current are closer to those of the East Madagascar Current, suggesting that the Mozambique input is confined to the inshore side of the Agulhas Current.

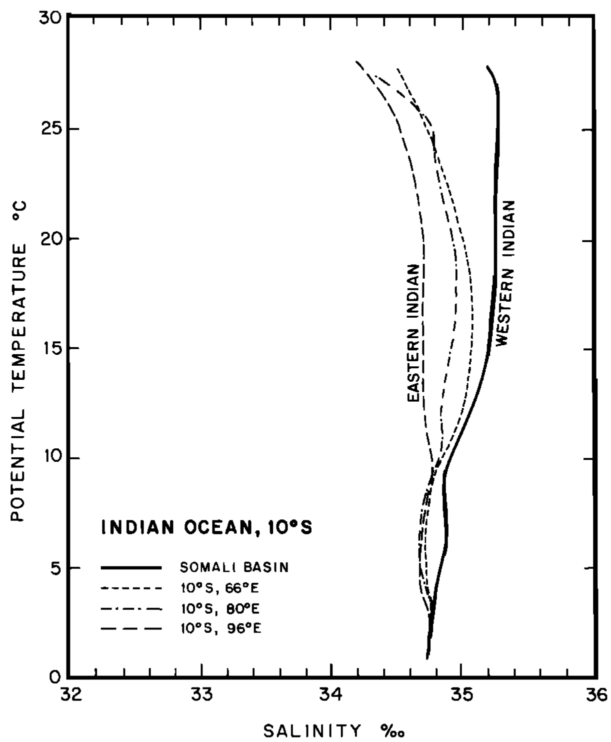

Fig. 6. The potential temperature–salinity relationship for the low-salinity thermocline along the 10° to 15°S latitude belt of the Indian Ocean (see Figure 3), from the Levitus data set. The isohaline character is maintained as the salinity increases by approximately 0.5‰ on proceeding westward with the South Equatorial Current from the eastern Indian Ocean to the western margin, within the Somali Basin.

water within the North Atlantic [*Broecker and Peng*, 1982]. The potential temperature nutrient relation for the southeast Atlantic thermocline is quite similiar to that within the western and central South Atlantic (GEOSECS data of *Bainbridge* [1981]). This may be due to strong exchange between the South Atlantic and Indian Oceans, so "fresh" introduction of Indian water into the South Atlantic may not contrast strongly with the background. Introduction of high silica concentrations from the Indian Ocean water into the South Atlantic on the 27.1-σ_0 surface is inferred by *Kawase and Sarmiento* [1985].

Atlantic

The Indian Ocean water introduced into the South Atlantic as part of the warm water route would be carried to the north by the Benguela Current (the warm surface water is driven offshore by the coastal upwelling process). The South Atlantic subtropical gyre is unique in that it receives heat at the poleward eastern corner. The anomalous oceanic heat loss of 10°S in the eastern South Atlantic (but west of the Benguela upwelling regime) reported by *Bunker* [1980] may be a product of the introduction of warm water from the south.

The path of the northward flowing warm water in the Atlantic is presumably incorporated within the large-scale gyre circulation, passing northward in the western limits of the equatorial region and within the western boundary of the North Atlantic. The path across the equator is unclear, as the upper layer return flow is likely to become involved with the active mixing regime and complicated vertical and zonal circulation pattern characteristic of the equatorial zone. *Kawase and Sarmiento* [1985] show evidence for significant upward flux of nutrients across isopycnal surfaces within the Atlantic equatorial zone induced by mixing processes. Cross-equatorial transfer of mass within the upper layer is supported by inverse solution for sets of zonal hydrographic sections across the Atlantic. *Roemmich* [1983] determines the upper layer northward flux across the equatorial zone accomplished by geostrophic and Ekman transport for the IGY sections at 24°S, 8°S, 8°N, and 24°N as 31.1 Sv, 32.7 Sv, 5.1 Sv, and 18.6 Sv respectively (from his Figure 3).

Molinari et al. [1985] find that the Florida Current average transport from April 1982 to August 1983 is 30.6 Sv. The transport of the Florida Current through the Florida Straits would thus be composed of about 50% thermohaline and 50% wind-driven circulation. There is the question of the similarity of this transport to the wind-driven Sverdrup transport function over the interior North Atlantic [*Leetmaa et al.*, 1977], but as was pointed out by *Roemmich and Wunsch* [1985], the western boundary flow need not match the Sverdrup interior transport, as nonlinear conditions may extend into the interior region.

In summary, it is proposed that the upper layer water flowing northward in the Atlantic Ocean required to feed NADW production is derived primarily from the thermocline and that it is drawn from each ocean, along what is referred to as the warm water route. North Pacific thermocline water enters the Indian Ocean via the Indonesian seas, where strong vertical mixing induces a nearly isohaline condition while carrying heat downward and nutrients upward. The Pacific water, marked by low salinity, is transported across the Indian Ocean within the South Equatorial Current. The excess water introduced to the Indian Ocean by advection through the Indonesian seas is transferred to the Agulhas Current via the Mozambique Channel. The return water becomes saltier during its transit of the Indian Ocean owing to the regional excess evaporation, and in addition its volume flux increases as it incorporates NADW upwelling into the Indian Ocean thermocline. Warm water transfer into the Atlantic is accomplished as a branch of the Agulhas Current enters the South Atlantic rather that curl back to the Indian Ocean as part of the Agulhas retroflection. The introduction of warm water into the poleward eastern corner of the South Atlantic thermocline is responsible for the unique equatorward heat flux of the South Atlantic. Upper layer water is carried to the north in the Atlantic Ocean within the two subtropical gyres. Transfer across the equator is accomplished within the complex vertical and horizontal circulation pattern of the region. The upper layer water is further modified in the Atlantic by excess evaporation, and it incorporates additional NADW.

While additional field work is needed within various sites of the proposed circulation pattern to arrive at better determination of transport values, available information supports the hypothesis that the flow compensating the production and export from the North Atlantic of NADW is accomplished by linkage of the warm water or thermocline layers of the ocean.

The time scale of the circulation pattern is likely to be $O(1000)$ years within the deep water [*Broecker and Peng*, 1982], but the return flow would represent a shorter time scale, as it is concentrated within the upper layer and along a more confined path. The approximate time for thermocline water to be carried from the central tropical Pacific along the 40,000-km-long warm water route to the North Atlantic is only 13 to 130 years, using 0.10-m/s and 0.01-m/s characteristic velocity, respectively.

There is increasing evidence that surface water characteristics in the North Atlantic and the rate of NADW production (including its specific characteristics and changes of the relative contribution from each of the major sites) vary on the decadal time scale [*Lazier*, 1973, 1980; *Clarke*, 1985; *Swift*, 1984; *Roemmich and Wunsch*, 1985]. There is also evidence that deep water geochemical tracers have varied in phase with variations in North Atlantic surface water temperatures on time scales of tens of thousands of years, marking glacial-interglacial oscillations [*Ruddiman and McIntyre*, 1981; *Ruddiman*, 1985; *Mix and Fairbanks*, 1985]. Positive correlation of NADW production rate and North Atlantic surface water temperatures follows from the argument presented by *Warren* [1983]: the buoyancy removal allowing deep convection is induced in part by high evaporation rates sustained by warm surface water temperatures relative to the atmosphere.

There are many causes for climate variability involving the coupled ocean-atmosphere system with numerous positive and negative feedbacks. The thermohaline circulation cell described in the paper may play some role in that the cell may be weakened, strengthened or in other ways altered, by variations in the wind driven circulation. This would change inter-ocean exchange of thermocline water and hence the global heat and fresh water fluxes and perhaps influencing the production rate of characteristics of NADW. The two inter-ocean links may be vulnerable to change.

The Agulhas Link

Variation of the Agulhas Current flow into the Atlantic has been discussed by *de Ruijter and Boudra* [1985] using a wind-driven nonlinear barotropic model. While increasing the Rossby number reduces the connection between the subtropical gyres of the two oceans, changes also are forced by altering the wind field: as the zero wind stress curl (maximum westerlies) moves further south of Africa, exchange between the two subtropical gyres increases. *Ou and de Ruijter* [1985] find that the Agulhas separation from the continental margin becomes less complete (i.e., more water flows into the Atlantic) as the Agulhas transport decreases. Thus the presence of strong seasonal variation of the wind stress over the South Atlantic–Indian ocean basin as reported by *Hellerman and Rosenstein* [1983] (i.e., southward movement of the zero wind stress curl in the summer), may be expected to have an impact on the South Atlantic circulation and climatology.

Van Loon and Rogers [1984] show that much of the seasonal wind variation along 40°S is in the second harmonic, with maximum wind at the time of each solstice and with significant interannual variations: weak in 1958 and 1978 and strong in 1957 and 1979 (the four years included in their study). Interannual variations in the south Indian Ocean may be linked to the Southern Oscillation in that the sea level air pressure along the westerlies over the South Indian Ocean shows negative correlation with air pressure at Darwin, which is representative of changes over much of the central and eastern Indian Ocean [*Rasmusson*, 1985]. As the wind stress curl over the Indian Ocean changes the Agulhas transport and retroflection pattern, its branching into the South Atlantic responds [*de Ruijter and Boudra*, 1985; *Ou and de Ruijter*, 1985], affecting the heat/water flux into the South Atlantic.

On the glacial-interglacial scale, variation of the warm water link around the southern tip of Africa may also have occurred. *Prell et al.* [1980], in their sediment core study of Indian Ocean surface circulation 18,000 years ago (during the height of the last glacial period), found that the position of the subtropical convergence was about 2° further north than the present position and that the Agulhas Current was composed of cooler water. In this case, less warm Indian Ocean water would flow into the South Atlantic during the glacial periods. This would alter the thermal character of the Atlantic thermocline relative to present conditions, weaking the negative esturary thermohaline circulation cell.

The Indonesian Sea Link

Another section of the warm water route that may be susceptible to variability is the Pacific to Indian exchange. The tropical Pacific surface water and that within the Indonesian seas represent a large reservoir of heat and relatively fresh water. Its transfer into the Indian Ocean could represent a significant interocean flux of heat and fresh water. The transport of three primary water mass layers across 30°S for the world ocean as presented by *Stommel* [1980] is very large, unreasonably so when compared with residence time estimates. These transport values are significantly altered towards more "acceptable" levels when the Indonesian sea link is included [*Piola and Gordon*, 1985].

Significant variability of the through flow transports is anticipated on a variety of time scales, including the seasonal cycle forced by the regional monsoon wind system and interannual variations associated with the Southern Oscillation. The presence of strong seasonality is pointed out by *Wyrtki* [1961], who notes: "...the close interrelation between the [monsoonal-driven] circulation at the surface [including upwelling distribution] and in the depth of the water exchange betwen the Pacific and Indian Ocean...." However, interannual changes in sea level between the Pacific and Indian oceans, which would be a factor in driving the interocean exchange, appear to be small (K. Wyrtki, personal communication, 1985). A relation between sea surface temperature in the Indonesian seas and Southern Oscillation–El Niño events, with a few months' lead of the temperature anomalies, has been reported [*Nicholls*, 1984]. This relation may be a manifestation of larger-scale variability, as the heat content of the tropical Pacific is observed to gradually increase prior to an El Niño event [*Wyrtki*, 1985*a*, *b*].

Acknowledgments. The concept presented in this paper was the basis of a number of oral presentations during 1985; helpful comments were received from many people, including K. Wyrtki, T. Takahashi, G. Reverdin, W. Ruddiman, R. Fairbanks, and B. Huber. The work was supported by the Office of Naval Research contract N00014-84-C-0132. Lamont-Doherty Geological Observatory contribution 3962.

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(Received November 11, 1985;
accepted January 10, 1986.)