When is Appearance Reality? A Comment on Why Does the Indonesian Throughflow Appear to Originate from the North Pacific*

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ABSTRACT

The transfer of water from the Pacific to the Indian Oceans within the Indonesian Seas is comprised primarily of North Pacific water masses. To state that this water is in reality South Pacific water and that it only "appears" to be North Pacific water is misleading and does not properly reflect the large-scale climate role of the North Pacific Ocean.

1. Introduction

Using water mass characteristics Fine (1985), Gordon (1986), and Ffield and Gordon (1992) show that the main source of the Pacific to Indian transfer within the Indonesian Seas is derived from the North Pacific. The Mindanao Current returns the bulk of its transport to the North Equatorial Countercurrent via the Mindanao Eddy (Toole et al. 1988), but an inshore branch provides for the primary throughflow (Ffield and Gordon 1992). These conclusions are consistent with and expanded by the CTD stations obtained within the Indonesian Seas during the 1993 southeast monsoon and the 1994 northwest monsoon US—Indonesian Arlindo Project (Fig. 1).

Godfrey et al. (1993, hereafter GHW) using numerical model results (Semtner and Chervin 1992; Hirst and Godfrey 1993) show that while the Indonesian Throughflow is derived from the Mindanao Current, a North Pacific current; it is drawn from a South Pacific source. The South Pacific water flows westward along the north coast of New Guinea as does the South Equatorial Current, but rather than continuing through the Indonesian Seas, as linear models would suggest, it is retroflected, or folded back toward the east within the Halmahera Eddy. The South Pacific water is then advected eastward with the North Equatorial Countercurrent, eventually turning northward to again flow to the west within the North Equatorial Current. This current feeds the southward flowing Mindanao Current, which in turn contributes to the throughflow. GHW argue that the freshening of the South Pacific water in the ". . . rainy region of the northwest equatorial Pacific . . ." makes the throughflow appear to be derived from the North Pacific.

Nof (1995) using a nonlinear analytical model finds that the bulk of the throughflow is North Pacific (6 $\times 10^6$ m^3 s^{-1} out of a total of 7 $\times 10^6$ m^3 s^{-1}). The GHW and Nof (1995) studies clearly show that higher-order dynamics play a crucial role in determining the source of the throughflow. Strong tidal-induced mixing, characteristic of the Indonesian Seas (Gordon et al. 1994; Ffield 1994), may be the primary contributing factor for the significant nonlinear forces and thus for the selection of the North Pacific as the primary provider of throughflow water.

GHW do a fine job of interpreting the model results, and I consider the model-derived circulation scheme for the equatorial Pacific including the northward progression of South Pacific thermocline water as basically correct (consistent with observations). However, I do take umbrage with their use of the word "appear" in the title of their work. Clearly, South Pacific water is the source for all North Pacific water (except for the small accumulation of freshwater), but to say that the export of all water from the North Pacific Ocean is composed of South Pacific water masses is misleading from a climate point of view.

GHW imply that there is an impervious east–west oriented barrier within the North Equatorial Current that divides a southern component of diluted South Pacific upper-layer water from a northern component that forms the North Pacific subtropical gyre's equatorial limb. I believe that this is the reason GHW uses the word "appears"—with the "real" North Pacific water residing along the northern edge of the North

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Equatorial Current that does not contribute to the Indonesian Throughflow, while the South Pacific component along the equatorial side of the North Equatorial Current, so diluted with locally derived freshwater is cleverly masquerading as North Pacific water. I consider this view to be in error on three points. 1) I believe that the South Pacific derived water within the North Equatorial Current is altered sufficiently to correctly be referred to as a North Pacific water mass; 2) the North Equatorial Current is not insulated by impervious barriers, lateral mixing blends subtropical and tropical water masses across the current; and 3) the western boundary Mindanao Current transports to the south water masses that are clearly formed within the subtropical and subpolar North Pacific Ocean, as it exports the oceanic products of Northern Hemisphere climatic forcing.

2. Discussion

Climatic forcing in the North Pacific (excess precipitation) converts the saltier South Pacific inflow into lower-salinity North Pacific characteristics. The export of water in the Bering Straits (0.8×10^6 m^3 s^{-1}, Coachman and Aagaard 1988) and Indonesian Seas (a wide range of estimates exist; the recent work of Fieux et al. 1994 suggests a value of $18.6 \pm 7 \times 10^6$ m^3 s^{-1} for the upper 1900 dbar) clearly consist of low-salinity North Pacific water masses. In addition to these upper-layer exports, there is a deep water export of

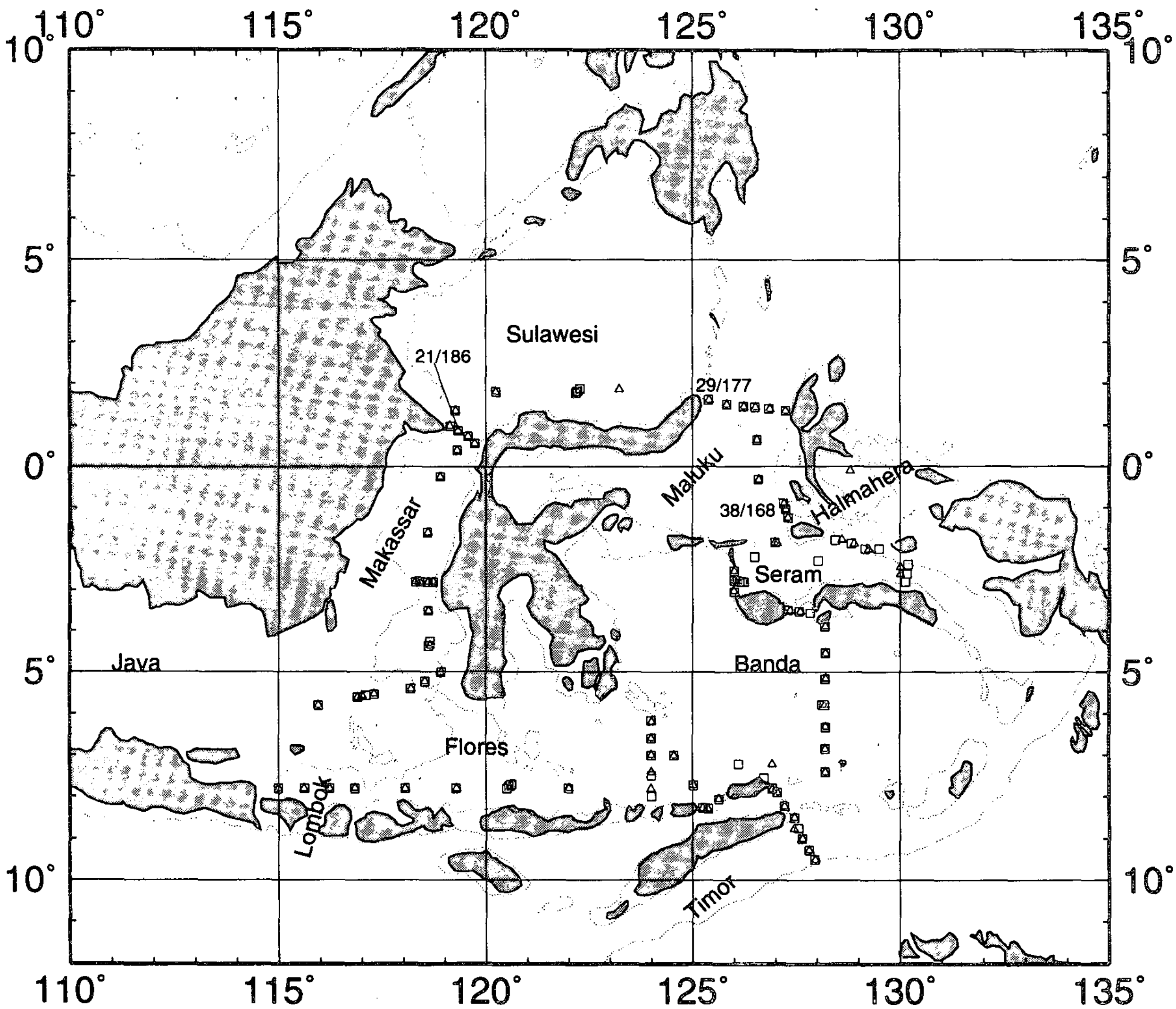

FIG. 1. Distribution of CTD stations obtained during the U.S. Indonesian Arlindo Project. The stations were obtained from the Indonesian Research Ship *Baruna Jaya I*. Stations 1–103 (open box symbols) represent the 1993 southeast monsoon conditions; stations 104–202 (open triangle symbols) represent the 1994 northwest monsoon conditions. The names of the various Indonesian Seas are shown along with the 500-m isobath (shown as a fine dotted line). Station pairs used in Fig. 3: 21 and 186, 29 and 177, and 38 and 168 (labeled).

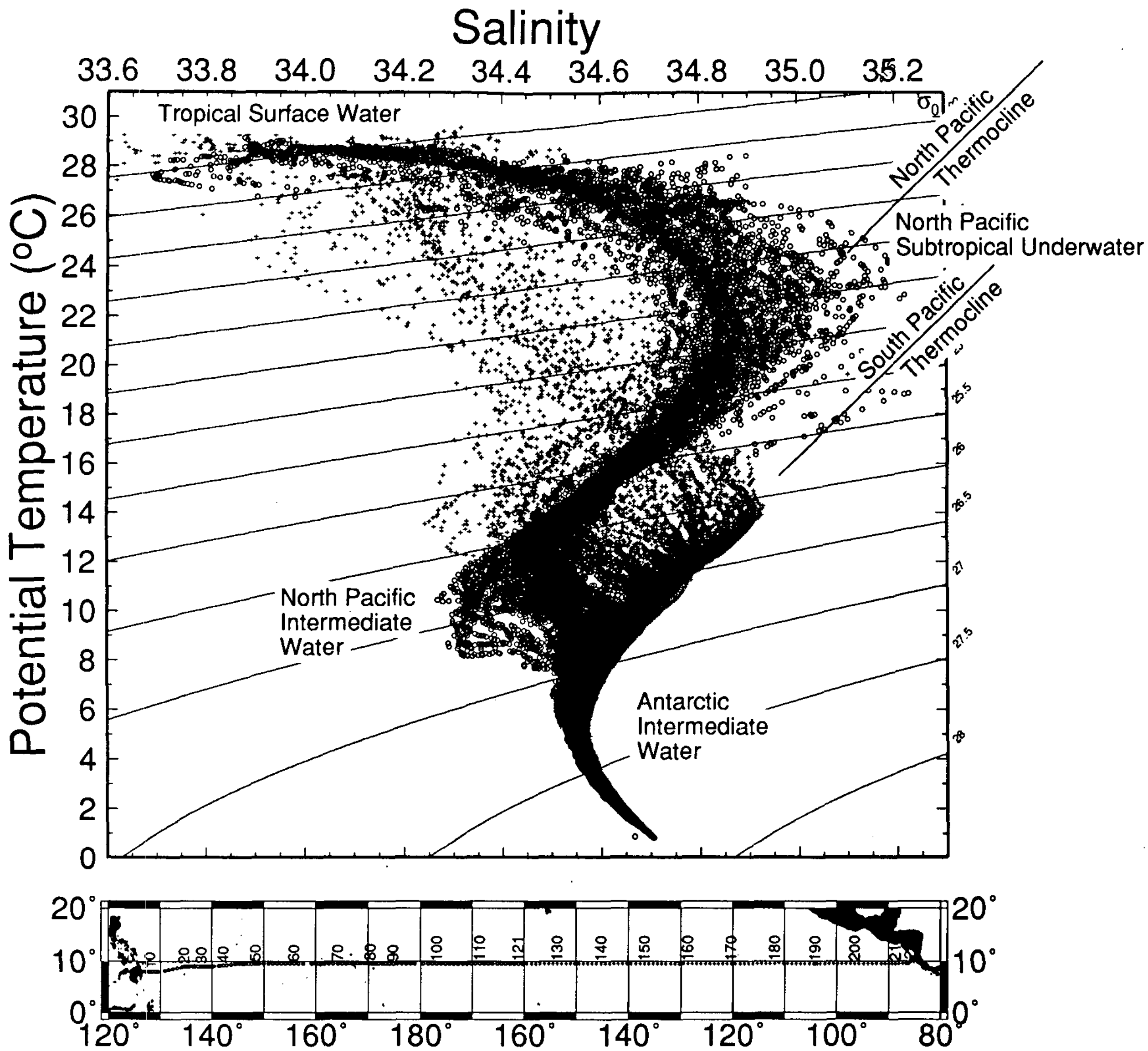

FIG. 2a. Potential temperature and salinity along 10°N in the Pacific Ocean. The CTD stations were obtained from the R. V. *Moana Wave* in January–May 1989. Stations west of 160°W are shown as open circle symbols; stations east of 160°W are shown as + symbols.

relatively low salinity North Pacific Deep Water mass that spreads into the South Pacific and Antarctic Circumpolar Current (Reid 1989; Johnson and Toole 1993). Presumably the North Pacific Deep Water is derived from the approximately 10×10^6 m^3 s^{-1} of saltier bottom water flowing northward within the Samoa Passage (Taft et al. 1991). The source of the upper-layer Bering Straits and Indonesian Seas export is more likely to reside in the upper-layer "horizontal" plane circulation of the Pacific Ocean, though some deep water upwelling to the upper layer may take place (Gordon 1986; Semtner and Chervin 1992; Johnson and Toole 1993).

While all of the ocean's waters are linked, we usually use water mass characteristics to define the source region of a particular water volume. Water mass characteristics are usually defined first by temperature and salinity, and secondarily by oxygen, nutrients, and exotic chemical tracers. Oceanographers debate the dilution point for which the water mass is no longer named after a remote source region, but yet we speak of Antarctic Bottom Water in the North Atlantic though it contains less than 10% of the initial characteristics (Wüst 1933). I look at this as more of a convenience, allowing a distinction to be made of water flowing directly from the North Atlantic Deep Water

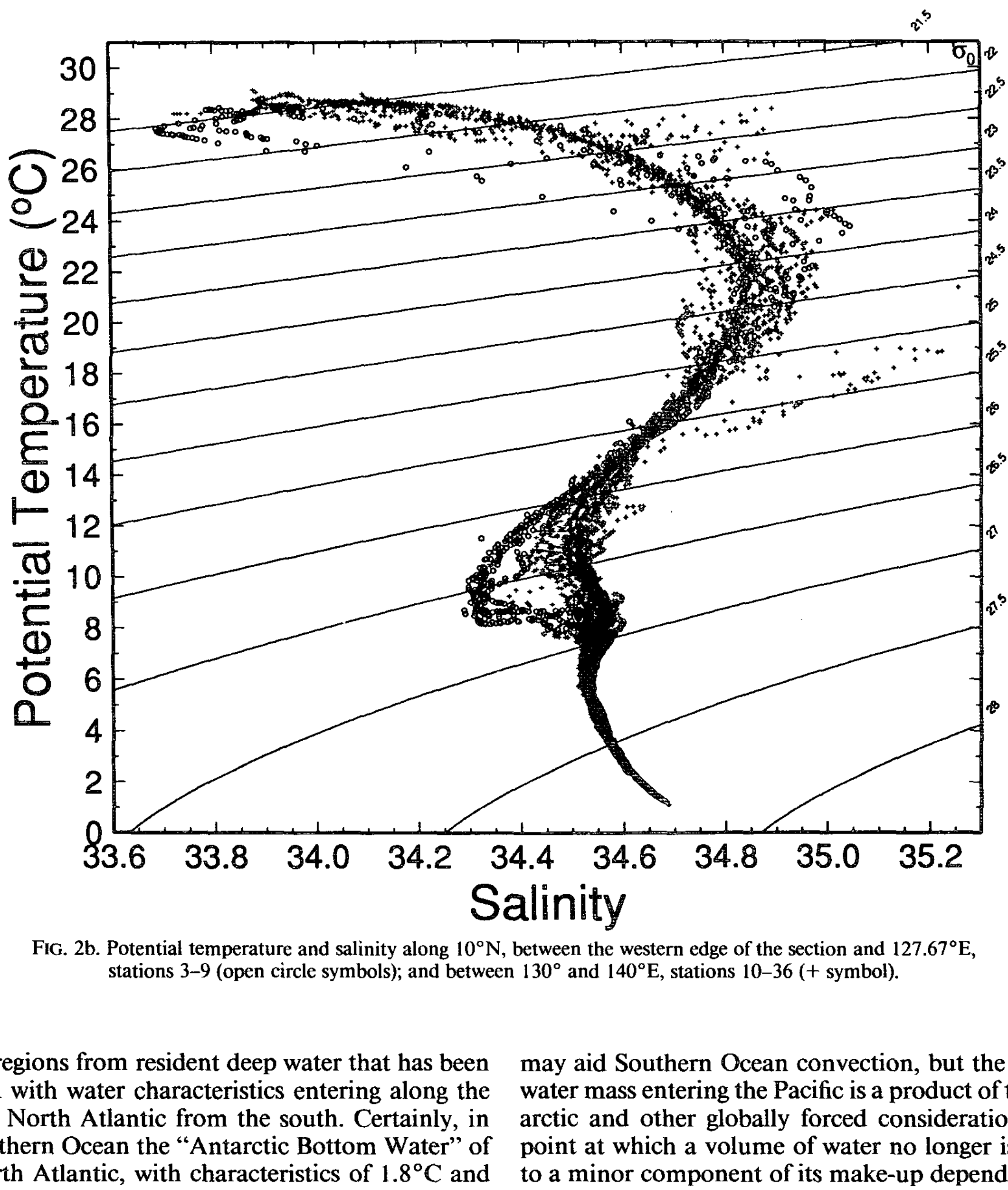

FIG. 2b. Potential temperature and salinity along 10°N, between the western edge of the section and 127.67°E, stations 3–9 (open circle symbols); and between 130° and 140°E, stations 10–36 (+ symbol).

source regions from resident deep water that has been blended with water characteristics entering along the floor of North Atlantic from the south. Certainly, in the Southern Ocean the "Antarctic Bottom Water" of the North Atlantic, with characteristics of 1.8°C and 34.89 (this is defined as the 10% concentration level in the western trough of the Atlantic Ocean by Wüst 1933), would be referred to as North Atlantic Deep Water. (After all it is composed of 90% North Atlantic Deep Water.) The bottom water characteristics flowing through the Samoa Passage into the North Pacific are 0.8°C and 34.72 (Taft et al. 1991). Global circulation schemes often mistakenly refer to this water as North Atlantic Deep Water, but it is very close to the characteristics of the deep water found within the Weddell Gyre that may be considered as Lower Circumpolar Deep Water (Johnson and Toole 1993). Yes, many of the molecules might have "seen" the North Atlantic in the distance past and traces of North Atlantic salt may aid Southern Ocean convection, but the bottom water mass entering the Pacific is a product of the Antarctic and other globally forced considerations. The point at which a volume of water no longer is tagged to a minor component of its make-up depends on the point of view of the author; there are no absolutes, which is why the water mass approach of observationalists often causes confusion with the modelers and theoreticians.

The northward migration of South Pacific water into the North Pacific is evident in an oceanographic section across the North Pacific at 10°N, which falls within the North Equatorial Current (Johnson and Toole 1993; Fig. 2a). The presence within each water column (each oceanographic station) of both North Pacific and South Pacific thermocline indicates that the saltier South Pacific water slides below less dense, fresher North Pacific water, with the South Pacific water surviving at temperatures below 15°C; the former occur-

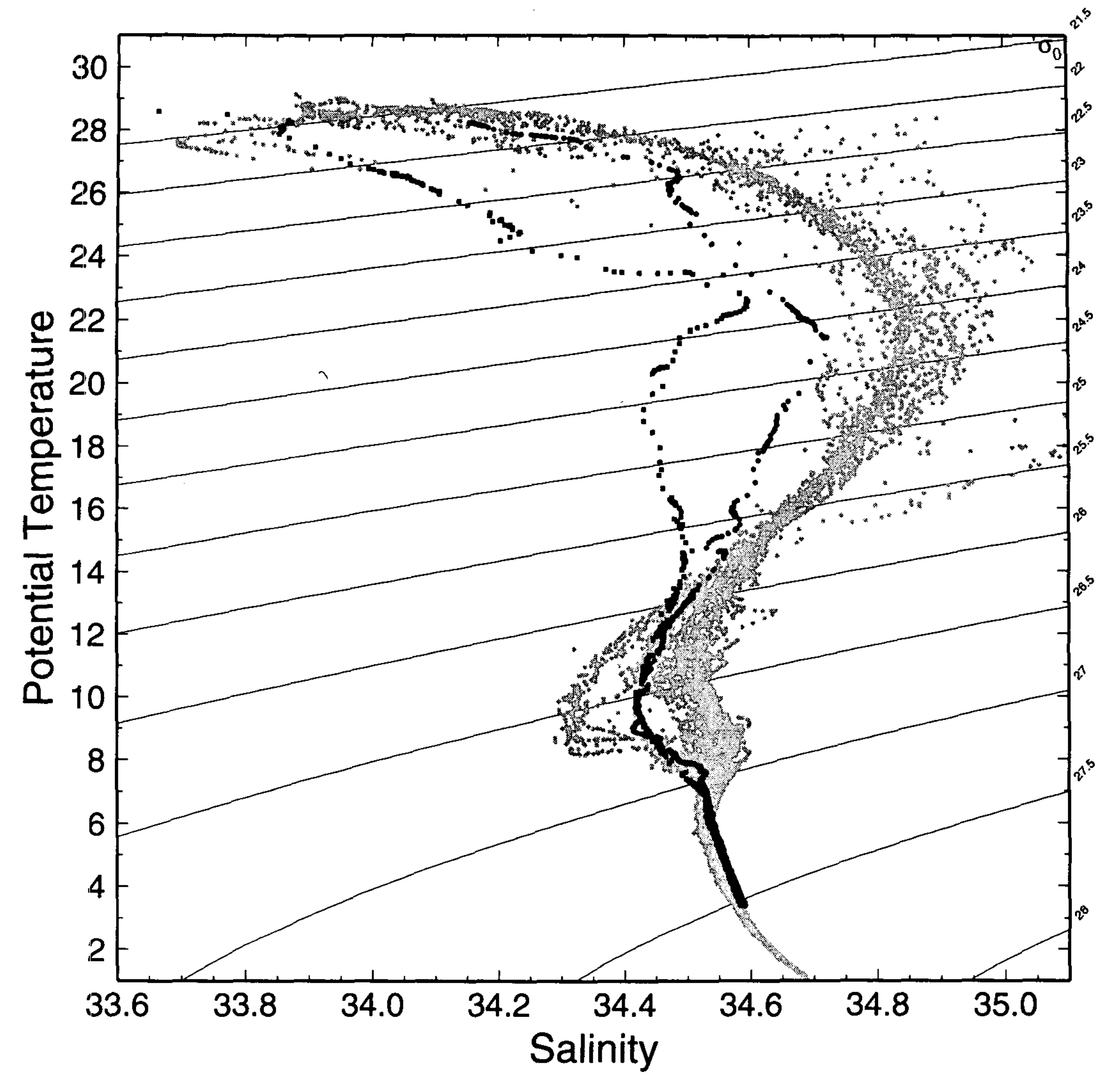

FIG. 3a. Potential temperature and salinity at the northern entrance to the Makassar Strait, station 21 (southeast monsoon, August 1993) and station 186 (northwest monsoon, February 1994). *Moana Wave* stations 3–36 (Fig. 2b) are shown in gray.

ring at temperature above 9°C. The overlap interval from 9° to 15°C may best be described as mixtures of the two thermoclines, forming a salinity minimum layer at the base of the North Pacific thermocline and a deeper salinity maximum layer at the top of the surviving South Pacific thermocline. The salinity minimum at the base of the North Pacific thermocline may best be identified as remnant North Pacific Intermediate Water. This water mass spreads southward as a narrow filament along the western margin of the North Pacific (Talley 1993; details of this flow and its continuation into the Sulawesi Sea have recently been presented by Bingham and Lukas 1994). The crossover from North to South Pacific thermocline water occurs at progressively warmer/saltier levels proceeding toward the east. The salty water near 24°C is the North Pacific subtropical underwater. This shallow salinity maximum is quite strong (above 34.7) for the longitudes west of 160°W. At the western extreme of this section the North Equatorial Current bifurcates (closer to 12°N, Toole et al. 1988), with part of the current flowing south with the Mindanao Current and part flowing north, forming the root of the Kuroshio Current. Stations 3–9 and 10–36 along the western edge of the section (Fig. 2b) within the Mindanao Current show a rapid transition from North to South Pacific lower thermocline water with distance from the western boundary: more concentrated North Pacific Intermediate Water follows along the western border (stations 3–9; see also Bingham and Lukas 1994). The shallow

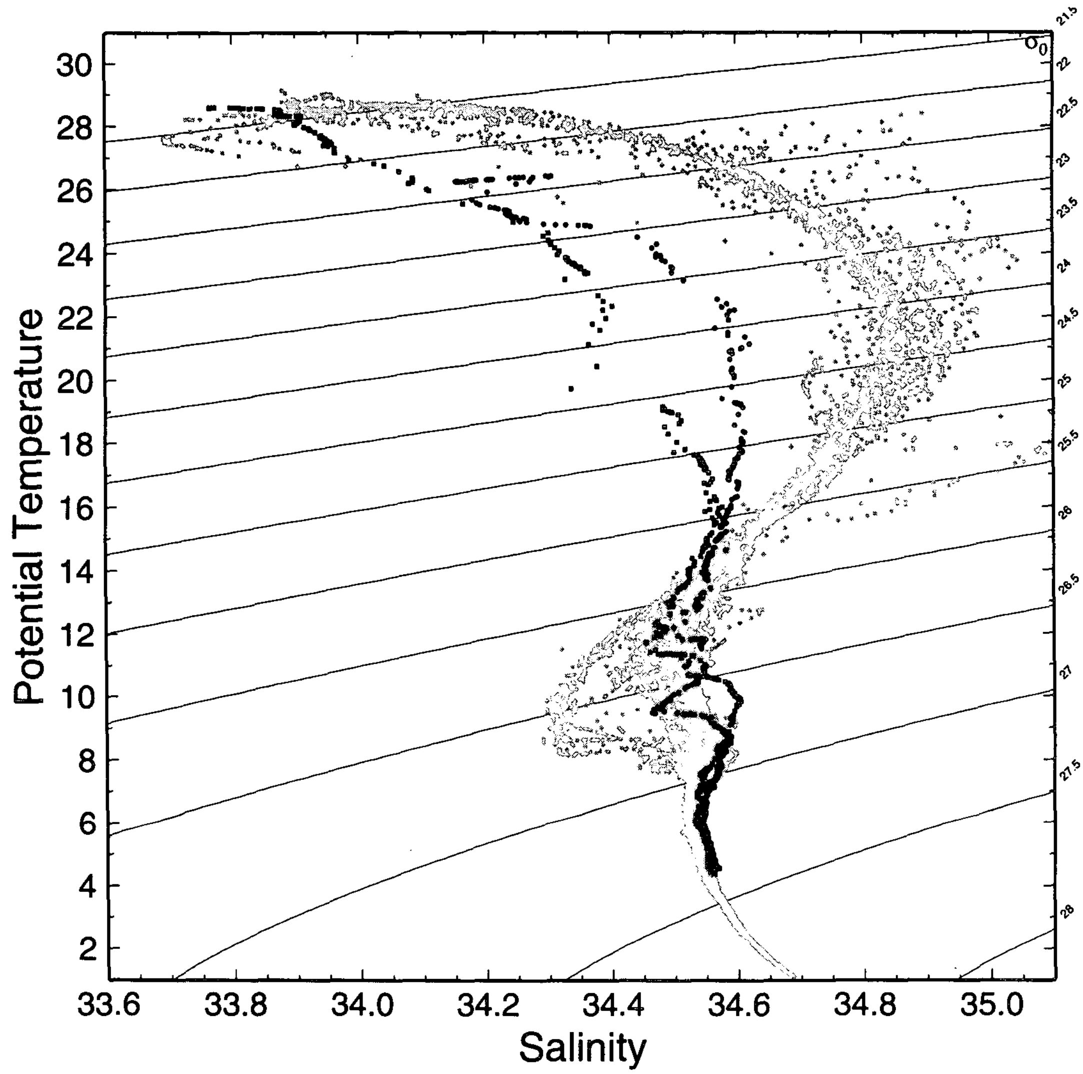

FIG. 3b. Potential temperature and salinity at the northern entrance to the Maluku Sea, station 29 (southeast monsoon, August 1993) and station 177 (northwest monsoon, February 1994). *Moana Wave* stations 3–36 (Fig. 2b) are shown in gray.

salinity maximum of the North Pacific is evident in approximately equal strength for stations 3–36. The origin of the salty, approximately 40-m-thick finestructure intrusion near 19°C, 200-m depth, along the 25.5σ_0 isopycnal (stations 12 and 13, with a remnant in station 14) is not clear. It probably represents a concentrated lens of South Pacific thermocline water that may have followed the Mindanao Eddy to "short circuit" the trans-Pacific transfer to the North Pacific water column.

The water mass pattern revealed by the Arlindo (1993, 1994) CTD datasets within the northern entrances to the Indonesian Seas (Fig. 1; Figs. 3a–c) reflects the west to east structure observed in the Mindanao Current (Fig. 2b). Within the northern entrance to the Makassar Strait (Fig. 3a), the salinity maximum near 22°C and the minimum near 10°C is similar (though some attenuation of these core layers by vertical mixing is evident) to the stratification along the westernmost edge of the 10°N section (stations 3–9, Fig. 2b), indicating a direct feed from that boundary to the Makassar Strait via the Sulawesi Sea. The Arlindo water mass data clearly shows that the Makassar Strait is the primary, perhaps sole, throughflow route for the North Pacific water masses. In the Maluku Sea (Fig. 3b) the stratification is similar to the eastern-most edge of the Mindanao Current, suggesting a flow from the outer boundary of the Mindanao Current. It is unlikely that much of this water continues flowing southward into the Banda Sea. In

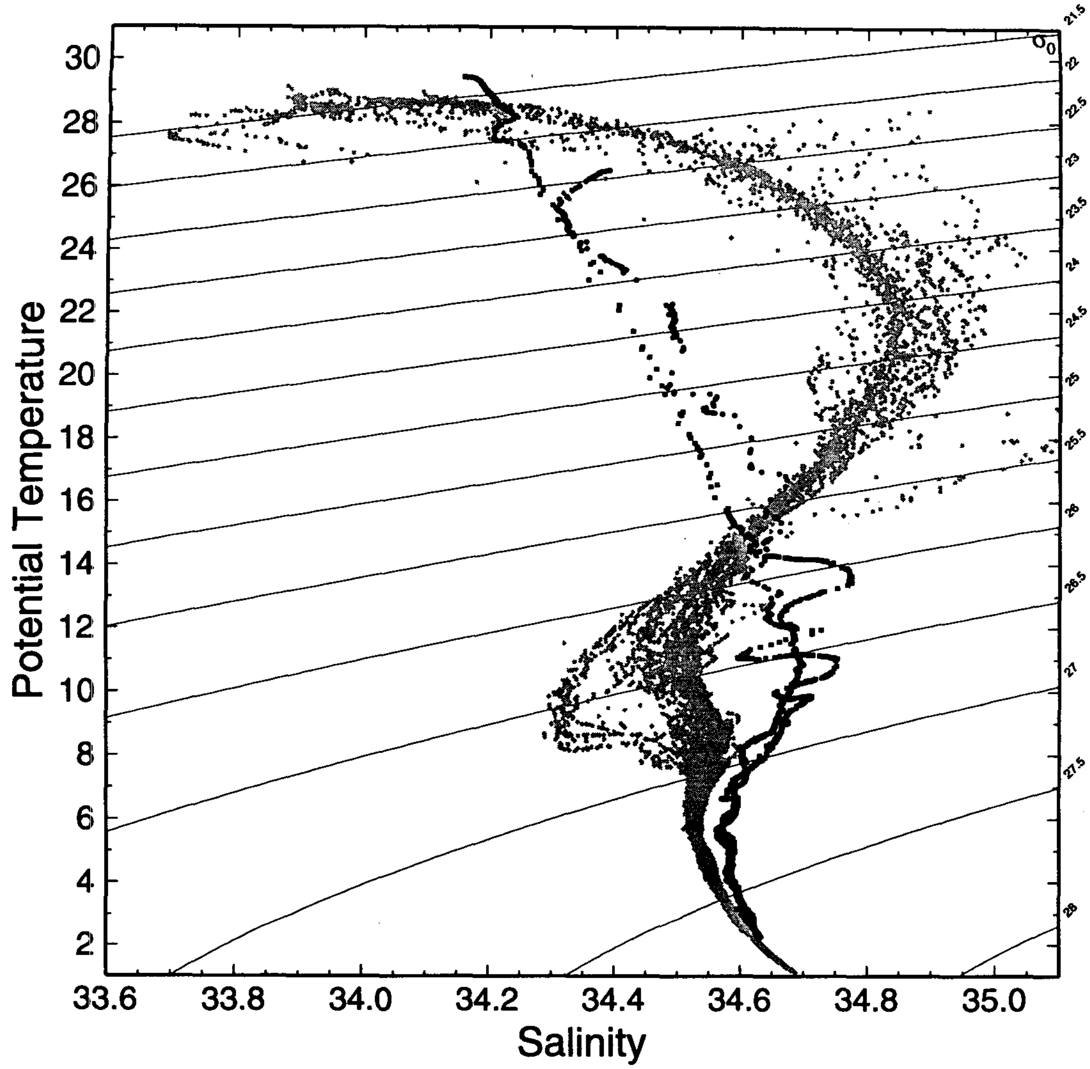

FIG. 3c. Potential temperature and salinity at the Obi Strait entrance to the southern Maluku Sea (Obi Strait is located at the "H" in "Halmahera" shown in Fig. 1), station 38 (southeast monsoon, August 1993) and station 168 (northwest monsoon, February 1994). *Moana Wave* stations 3–36 (Fig. 2b) are shown in gray.

the outflow from the Halmahera Sea into the southern Maluku Sea via the Obi Strait (Fig. 1; Fig. 3c) there is a rather salty water layer in the 8°–16°C interval (150–300-meter interval). This water is South Pacific water derived directly from the South Equatorial Current flowing along the northern coast of New Guinea. Intrusion of South Pacific water was more wide spread during the northwest monsoon (February 1994), than during the southeast monsoon (August 1993). It is suggested that South Pacific water enters the Indonesian Seas at depths below the stronger opposing North Pacific pressure head, whose weakening in the northwest monsoon (Wyrtki 1987) allows for increased South Pacific influx.

3. Summary

The export of water from the North Pacific to the Arctic Basin and to the Indian and South Pacific Oceans carries with it the products of climatic forcing of the North Pacific basin. As such, this water must be considered as North Pacific water masses, not just in appearance but in fact.

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