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Thermocline stratification within the Indonesian Seas

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Abstract. An extensive suite of conductivity-temperature-depth stations was obtained from the *Baruna Jaya I* during the southeast monsoon of 1993 and northwest monsoon of 1994, as part of the Indonesian/U.S. Arlindo project. The main objective of these cruises was to determine sources, pathways, and mixing histories of the throughflow water masses for the monsoon extremes. Water mass analysis indicates that the most penetrating route followed by Pacific water occurs within the Makassar Strait. This supports the notion that this strait carries the bulk of the Pacific to Indian throughflow, consisting of North Pacific Subtropical Water (upper thermocline S_{max}) and North Pacific Intermediate Water (lower thermocline S_{min}). The more attenuated S_{max} core during the northwest monsoon relative to the southeast monsoon suggests that the throughflow may slacken in that season. There is only minor contribution within the possible throughflow pathway east of Sulawesi. However, relative salty water of South Pacific origin is observed in the lower thermocline within the Seram and southern Maluku Seas, particularly in the northwest monsoon. Density-driven, sill depth overflow into the deep Banda Sea basin via the Lifamatola Passage also contributes to the total throughflow, though this contribution is likely to be minor. While some of the throughflow has been shown to pass through the Lombok Strait, water mass analysis clearly shows the Makassar throughflow turning into the Flores Sea and Banda Sea before curling southward into the Timor Sea and Indian Ocean.

1. Introduction

The transfer of water between the tropical Pacific and the Indian Oceans has been the focus of much interest to those involved in climate research. The interocean transport is for the most part believed to be confined to the upper 300 m, composed of warm surface water and North Pacific Subtropical and Intermediate Water [*Wyrtki*, 1987; *Fine*, 1985; *Ffield and Gordon*, 1992; *Fine et al.*, 1994]. Transport estimates based on observations, models, and conjecture range from 1 to nearly 30 Sv (Sv = 10^6 m^3/s) [*Wyrtki*, 1961; *Godfrey and Golding*, 1981; *Fine*, 1985; *Gordon*, 1986; *Kindle et al.*, 1989; *Murray and Arief*, 1988; *MacDonald*, 1993; *Cresswell et al.*, 1993; *Hirst and Godfrey*, 1993; *Meyers et al.*, 1995]; the transport estimate for August 1989 (representing the season of maximum transport which may have been enhanced by the cold phase of El Niño–Southern Oscillation (ENSO) active in 1989) is 18.6 Sv [*Fieux et al.*, 1994]. About 1.7 Sv exits the Indonesian Seas within the Lombok Strait [*Murray and Arief*, 1988; *Murray et al.*, 1989], with most flowing eastward into the Flores Sea and Banda Sea, where a clockwise turn carries it into the passages on either side of Timor, into the Indian Ocean [*Ffield and Gordon*, 1992; *Gordon et al.*, 1994]. Density-driven overflow into the deep Banda Sea [*Broecker et al.*, 1986; *Van Aken et al.*, 1988; *Van Bennekom*, 1988] contributes a minor amount to the total throughflow, about 1 Sv.

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2. Arlindo Project

The Arlindo project ("Arlindo" is an acronym for Arus Lintas Indonesia, meaning "throughflow" in Bahasa Indonesian) is a joint oceanographic research endeavor of Indonesia and the United States. Arlindo has as its primary goal to study the circulation and water mass stratification within the Indonesian Seas. Arlindo mixing, the first phase of the Arlindo project, consisted of an extensive suite of conductivity-temperature-depth (CTD) extending to the seafloor or to 3000 decibars (dbar), tracer chemistry, and biological productivity stations (Figure 1) obtained from the Indonesian research vessel *Baruna Jaya I* during the southeast monsoon of 1993 (August 6 to September 12) and northwest monsoon of 1994 (January 25 to March 3). During this period the southern oscillation index remained negative, representing a rather prolonged warm episode.

What follows is a preliminary assessment of the thermohaline stratification primarily of the thermocline as measured during the two Arlindo CTD cruises (also see *Gordon* [1995] and *Ilahude and Gordon* [1995]). Further analysis of the thermocline and deeper waters and internal wave activity will be reported in continued research analysis of the Arlindo mixing data set.

3. Water Masses

Following the trends of core layer attenuation and evolution of the shape of the potential temperature (θ) to salinity (S, in practical salinity units (psu)) relationship, water mass spreading patterns achieved by advective and mixing processes can be established from the θ/S spatial structure.

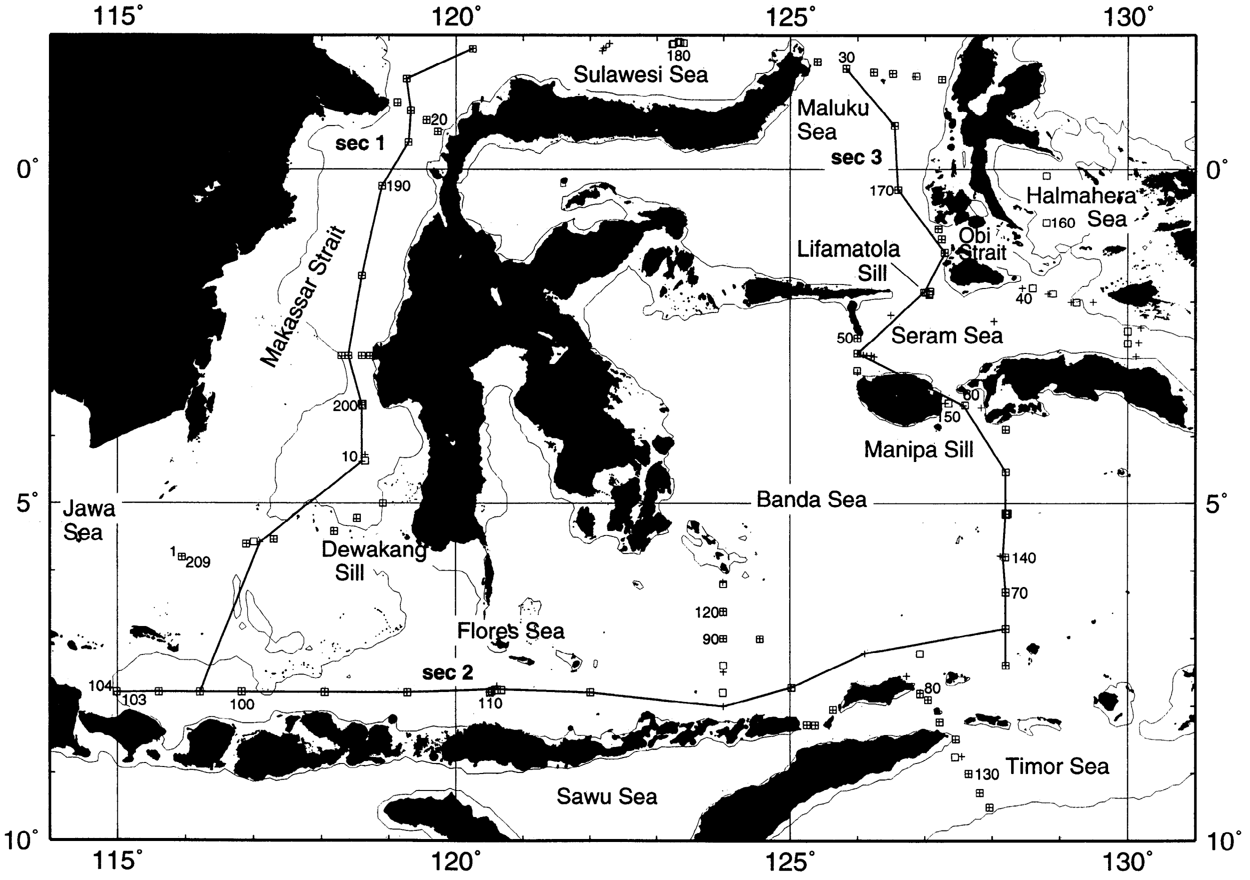

Figure 1. Arlindo station map. Stations 1 to 103 were obtained during the southeast monsoon (1993) and are shown as crosses. Stations 104 to 209 are from the northwest monsoon (1994) and are shown by open symbols. The southeast monsoon stations follow a clockwise course around Sulawesi; the opposing course was followed in the northwest monsoon. The names of geographic features mentioned in the text are shown, as are the three sections shown in Figures 3–7. The fine dotted line marks the 500-m isobath.

Southeast Monsoon, August–September 1993

During the southeast monsoon (SEM) (Figure 2a) the deep cold end-member of the θ/S pattern falls near 34.63 and 2°C, while the warm surface water fans out in θ/S space along a 0.4 salinity range within a temperature range of just below 26°C (Seram and northern Banda) to just over 29°C (Makassar). A departure from a rather restrictive deep water θ/S pattern is found only in the Timor Sea where saltier and more oxygenated water is encountered for water colder than 4°C (below 1400 m). This water is drawn from the southern Indian Ocean as mentioned by *Postma* [1958], *Wyrtki* [1961], and *Fieux et al.* [1994]. The Maluku Sea displays a weak $S_{\min}$ near 6°C which represents Antarctic Intermediate Water, below which are North Pacific Deep Water and a trace of Antarctic Bottom Water (bottom potential temperature near 1.8°C).

Between the surface and deep water extremes the general shape of the θ/S scatter is that of a "figure eight," with a wide range of salinity at 10° and 20°C and a somewhat narrower range near 14°C (particularly if only the Makassar, Flores, and Banda Seas are considered). The wide range of salinity near 20°C reflects the contrast between the high-salinity North Pacific Subtropical Water (NPSW) and the upper layer of the Banda Sea which has been subjected to strong vertical mixing, with freshwater dilution. The limited salinity range of the "neck" near 14°C and 34.55 is formed by the intersection of the Makassar and Banda θ/S curves, the latter mixed to near isohaline conditions, while the former is influenced by salinity extremes above and below 14°C. Stations within the Seram Sea and southern regions of the Maluku Sea display higher salinity around 14°C isotherm, up to 34.75. This water falls along the South Pacific thermocline θ/S curve, making it reasonable to conclude that it is South Pacific in origin [*Gordon*, 1995]. The relative salty midthermocline condition within the Seram Sea extends to cooler, deeper water, causing a particularly broad salinity range at the 10°C isotherm, as the low-salinity North Pacific Intermediate Water (NPIW) with salinity about 34.4 most prevalent in the Makassar and Flores Seas competes with the more saline water derived from the thermocline of the South Pacific. Water mass analysis indicates that the NPIW flows through the Makassar Strait, into the Flores and Banda Sea, where it mixes with the saltier water spreading into the Banda from the north. As the northern Maluku Sea does not show these high midthermocline salinity values, it is concluded that the saltier South Pacific water enters the Indonesian Seas via the Halmahera Sea, drawn into the Halmahera by the South Equatorial Current. We refer to this water as South Pacific Subtropical Water (SPSW), though it is clear that the warmer upper thermocline of the South Pacific subtropics does not spread into the Indonesian Seas.

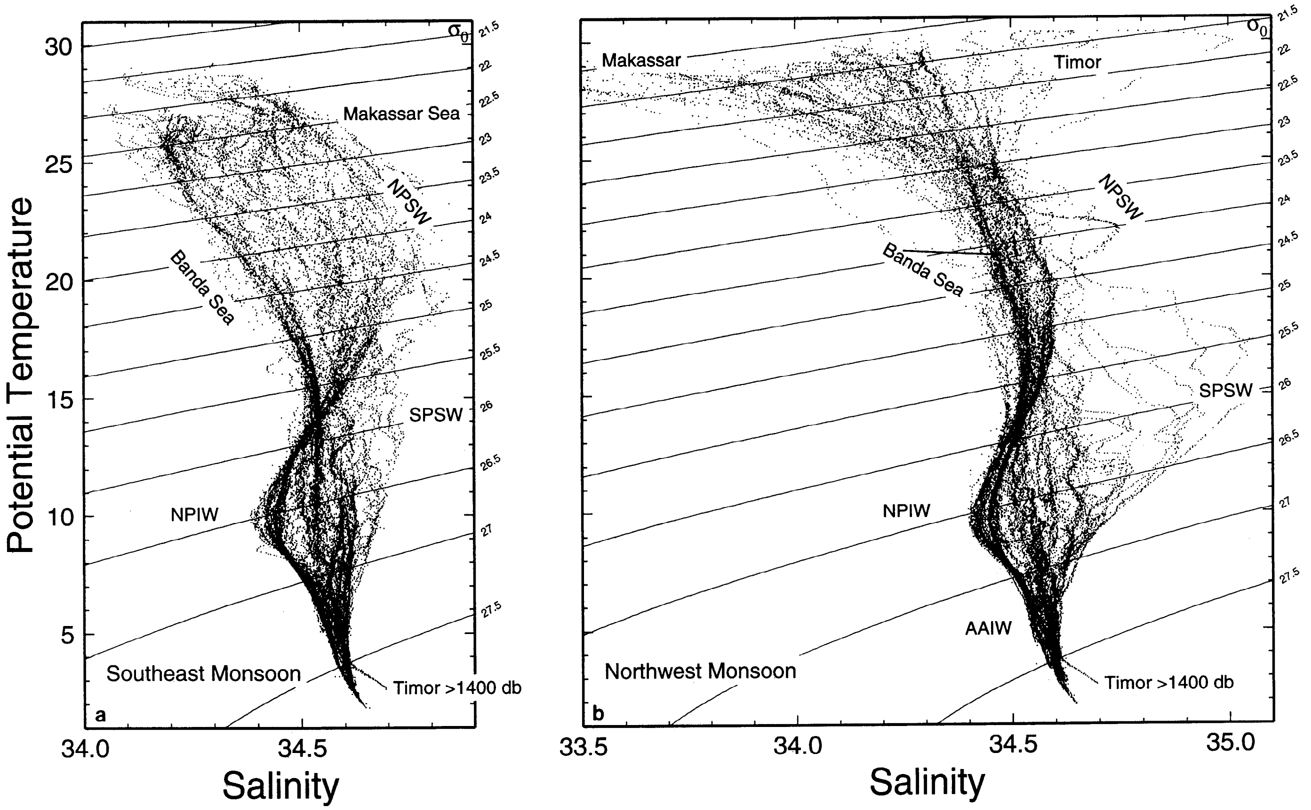

Figure 2. Potential temperature versus salinity for the (a) southeast monsoon and (b) northwest monsoon. NPSW is shallow salinity maximum of the North Pacific Subtropical Water, SPSW is the deeper salinity maximum derived from the South Pacific Subtropical Water, AAIW is the Antarctic Intermediate Water, and NPIW is the lower thermocline salinity minimum marking North Pacific Intermediate Water.

Northwest Monsoon, January–March 1994

The θ/S distribution for the northwest monsoon (NWM; Figure 2b) reveals some significant changes in water mass distribution between the two monsoon seasons. The sea surface temperature of the NWM is on average 3°C warmer than that of the SEM, with the greatest difference in the Banda Sea. Surface salinity shows a much greater range, from a low of 31.1 in the southern Makassar to 35.1 in the Timor Sea, in contrast to only a 34.1–34.5 range in the SEM. North Pacific subtropical S_{max} core water is more attenuated in the northwest monsoon, about 0.2 below the SEM S_{max}. Reduced S_{max} presence may result from reduced throughflow, with the continued presence of strong vertical mixing; more vigorous vertical mixing during the NWM; and downward mixing of the very low salinity surface water characteristic of the NWM. These concepts will be fully tested, but at this point we believe that the reduced throughflow idea is most likely.

There is a greater presence of SPSW in the Seram Sea, with S_{max} values above 34.9, but this effect does not seem to spread as a well-formed core layer into the Banda Sea. The Maluku Sea has less concentrated cores of North Pacific and South Pacific water masses; it is somewhat more homogeneous than observed in the SEM, with slightly more SPSW influence in its southern region. The Halmahera Sea was not sampled during the SEM, so the northwest monsoon observations represent the only representation in the Arlindo mixing data set. The Halmahera S_{max} is over 35.0 at 16°C, water that can only be derived directly from the South Pacific via the South Equatorial Current (not the indirect route via Mindanao Current). Below 500 m the Halmahera water column is homogeneous, controlled by sill depth separating the Halmahera from the open Pacific.

4. Vertical Distribution

The stratification as revealed within vertical sections aligned along the various throughflow routes (Figure 1) is now presented for each monsoon. They provide a sense of the spatial scales lacking in the θ/S patterns. First, we present sections with depth as the vertical coordinate; then, in order to expand the upper layers and remove internal wave effects, we present sections using σ_0 as the vertical coordinate.

Sections 1 and 2: The Makassar Strait, Flores Sea, and the western Banda Sea

Surface temperature and salinity. During SEM the sea surface temperature (SST) of the Makassar Strait (Figure 3) is mostly between 28.2° and 28.7°C, marking it as part of the >28°C warm pool of the tropical Pacific Ocean. The NWM SST is about 0.8°C higher, attaining values around 29.4°C. In both monsoons the SST in the southern end of Makassar Strait is less than that to the north. This trend of cooler SST continues into the Flores Sea and western Banda Sea. During SEM the Flores Sea SST falls below 28°C, in the range 26.8°–27.5°C. The SST of the western Banda Sea is still lower, a value being around 26.1°–27.4°C, 2°C below that of Makassar. The en route SEM cooling is likely a product of water flow toward regions of reduced solar radiation, vertical mixing, and ocean heat loss forced by the somewhat less humid air flow from Australia.

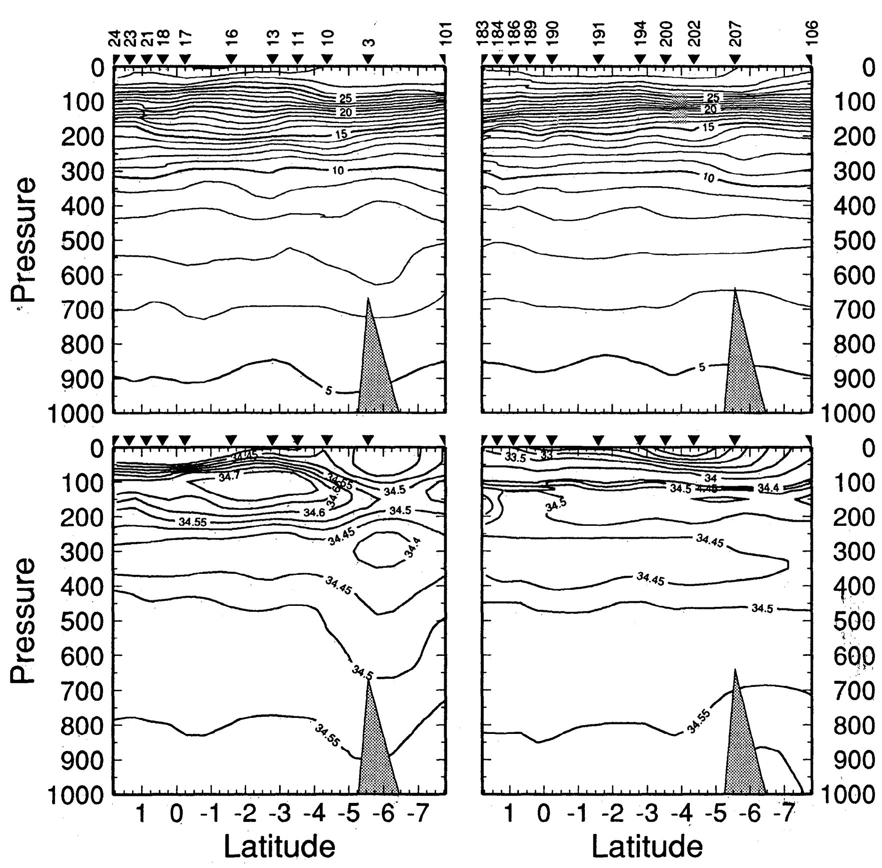

Figure 3. Makassar Strait sections of the upper 1000 dbar for (top) potential temperature and (bottom) salinity during the 1993 southeast monsoon (SEM) and 1994 northwest monsoon (NWM).

During NWM the SST trend is reversed. The Flores Sea (Figure 4) SST warms during the NWM to between 28.2° and 29.0°C; the western Banda Sea SST warms to between 28.4° and 30.3°C. In the Flores Sea the seasonal swing of the SST is about 1.5°C; in the western Banda Sea the monsoon SST difference is much larger, attaining 4.0°C. The seasonal swings of the Banda Sea are linked to thermocline changes, the thermocline being 40 m shallower in the SEM. This leads *Wyrtki* [1961] to suggest Banda Sea upwelling in the SEM, a period when the regional wind field removes surface water from the Banda Sea to be compensated by thermocline uplift. The opposite effect occurs during the NWM season.

During SEM the Makassar Strait surface salinity (SSS) values are above 34.1, mostly between 34.20 and 34.45. The SSS is very much reduced during NWM, especially in the central part of the Makassar Strait, where the NWM SSS is 2.6 lower than that of the SEM. The Flores Sea SSS in the SEM is between 34.1 and 34.4. During NWM the SSS values drop to 33.4–34.0 as the outwash from the Jawa Sea introduced fresher water to the area [*Wyrtki*, 1961]. In the western Banda Sea the SSS is between 34.2 and 34.6 for both monsoon seasons.

Thermocline. The main Makassar Strait thermocline layer is found between 60 and 300 dbar with the temperature falling from 27.0° to 10.0°C (Figure 3), a gradient of 0.7°C/m. In the Flores Sea (Figure 4) during the SEM the main thermocline is found between 80 and 300 dbar, but the large temperature drop begins at 26°C, slightly cooler than Makassar. In the western Banda Sea (Figure 4) the thermocline begins with the 25°C isotherm, a degree below the Flores Sea. Below the 10°C isotherm near 300 dbar the thermocline relaxes with the drop of only 2°C in the next 100 dbar. The cold, subthermocline water begins from the depth of 400 dbar, where temperature values decrease with depth but slowly, reaching 4.2°–4.6°C at 1000 dbar in the Flores Sea and between 4.4° and 4.8°C in the Banda Sea at 1000 dbar. The warmer SST values of the NWM with essentially invariant deeper temperatures produce a stronger thermocline during that season. This is especially evident in the Banda Sea, which experiences the greatest SST range.

Within the thermocline a layer of salinity maximum (S_{max}) is found between 80 and 200 dbar. This S_{max} is the core layer of the North Pacific Subtropical Water [*Wyrtki*, 1961; *Ffield and Gordon*, 1992; *Fine et al.*, 1994]. The core layer S_{max} is above 34.6 in Makassar during the SEM, reaching values above 34.7, but is reduced to 34.5 in the southern end of the strait and in the Flores Sea. The S_{max} core values do not follow a smooth transition from high values in the Sulawesi Sea to lower values of the Flores Sea, along the Makassar Strait axis. Perhaps there is a thin axis of flow along the strait, which weaves in and out of the Arlindo station array, but this is not likely as the cross section of the strait was well resolved at 1°N and 3°S. We suspect variability in the introduction of the NPSW into the Makassar Strait from the Sulawesi Sea possibly associated with variability of the Mindanao Eddy.

The low SSS of the NWM in Makassar Strait forces a sharp halocline in the upper 100 dbar. Below 100 dbar the salinity maximum layer of NPSW is still present from 100 to 200 dbar. However, the salinity in its core layer is reduced by about 0.1

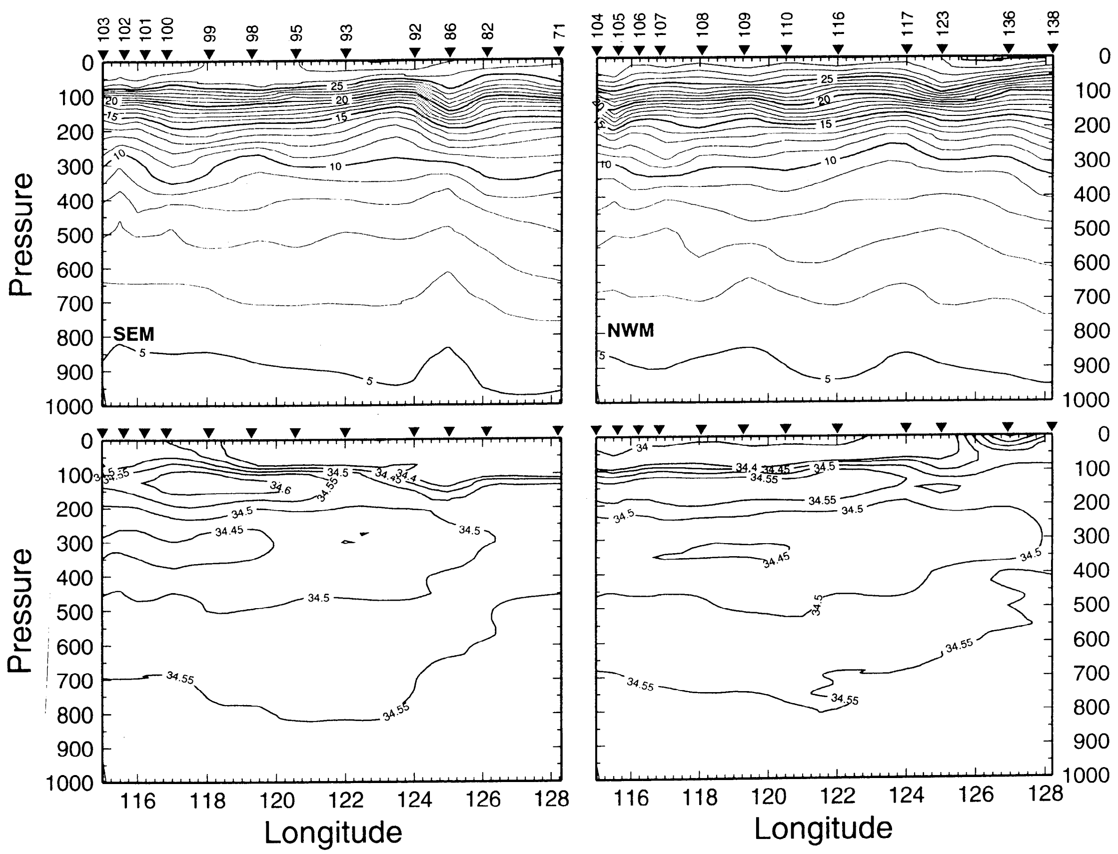

Figure 4. Flores and western Banda sections of the upper 1000 dbar for (top) potential temperature and (bottom) salinity during the 1993 southeast monsoon (SEM) and 1994 northwest monsoon (NWM).

to values no higher than 34.66 in the most northern part of the Makassar Strait and only slightly above 34.5 in the southern end.

In the Flores Sea (Figure 4) the subsurface S_{max} is still present but with much reduced intensity. In the western part of the Flores Sea the S_{max} core values range from 34.60 to 34.66 at interval between 80 and 150 dbar. The Flores S_{max} value is about 0.1 below the S_{max} of the Makassar Strait. *Ffield and Gordon* [1992] attribute this to the downstream, accumulative effects of vertical mixing with surface low salinity and with the deeper salinity minimum layer of North Pacific Intermediate Water. During the NWM the Flores Sea S_{max} values are about 0.2–0.4 lower than observed during SEM. In the Banda Sea the NPSW S_{max} layer is still discernible with salinity of about 34.55. However, its core layer as indicated by the 34.6 isohaline has almost entirely vanished.

Below the NPSW S_{max} is a salinity minimum (S_{min}) layer within the depth range 250–400 dbar with salinity less than 34.45 and less than 34.40 in isolated pockets during the SEM. This layer marks the presence of North Pacific Intermediate Water. Similar to the seasonal behavior of NPSW, the NPIW core in the Makassar Strait during NWM is much attenuated. The salinity in its core layer has increased to values closer to 34.45 and above this value in the southern Makassar Strait. This is taken as a further sign of relaxed throughflow during the NWM, allowing additional resident time for the accumulative core layer modification by vertical mixing. The layer of salinity minimum in the Flores Sea is also reduced in its intensity and extension in the NWM relative to the SEM. The core layer of NPIW (290–380 dbar), having the salinity of less than 34.45, is limited to the SEM season and is found only in the western part of the Flores Sea.

In the western Banda Sea the salinity is nearly homogeneous below 120 dbar. Its value increases very slightly from 34.5 at this depth to 34.59 at 1000 dbar with some sign of the remnant of NPSW, salinity 34.54 at 210 dbar, and NPIW, salinity 34.51 at 380 dbar.

Section 3: The Maluku Sea–Banda Sea

Surface temperature and salinity. In the Maluku Sea (Figure 5) during SEM the SST is between 26.1° and 27°C; it is somewhat lower, 25.7°–26.1°C, in the central Banda Sea. During NWM the SST in the Maluku Sea is between 28.6° and 29.6°C, about 2.6°C higher than during SEM. In the central Banda Sea the surface temperature is between 29.6° and 30.3°C, which as noted above is about 4°C higher than observed during SEM. During SEM the surface salinity in the Maluku and central Banda Seas is between 34.1 and 34.4. During NWM the surface salinity in the central part of the Maluku Sea decreases to less than 34.0. In the Banda Sea the surface salinity is the same as during SEM except in its most southern area where values exceed 34.5, sharing its more saline state with the Timor Sea.

Thermocline. Below a mixed layer of about 50 m the intense segment of the thermocline in the Maluku Sea (Figure 5) is found at the depth range of 50–260 dbar with temperature decreasing from 28° to 12°C, a somewhat shallower, warmer thermocline than observed in the Makassar Strait and Flores Sea (Figures 3 and 4). This condition may be due to the weaker presence (in the northern Maluku during the SEM) or even

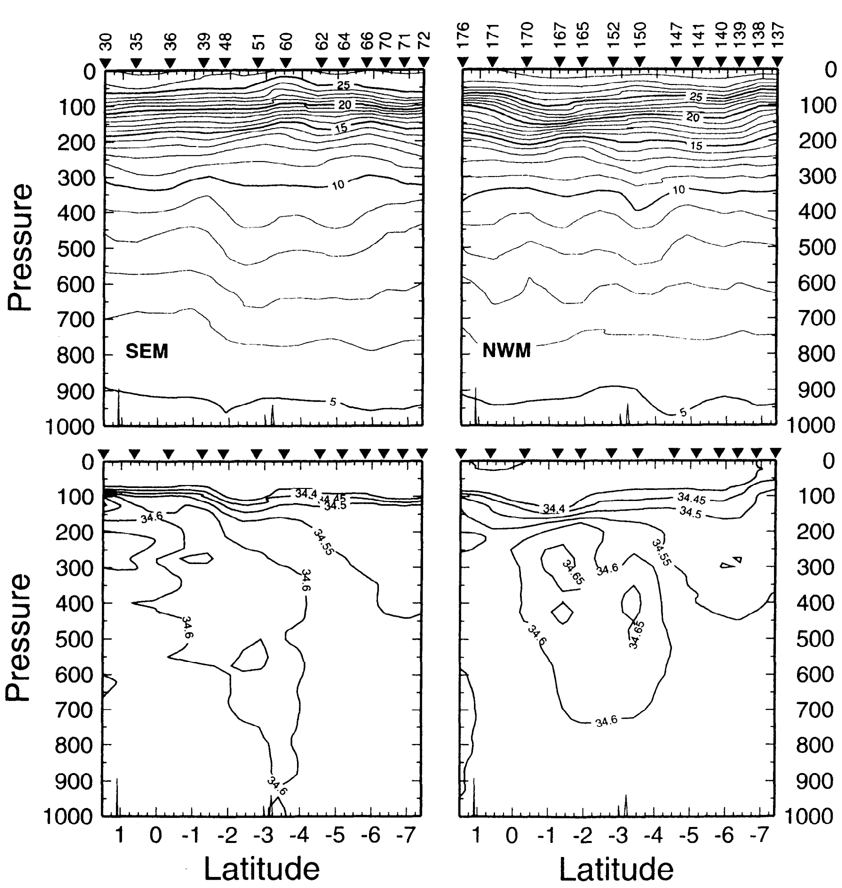

Figure 5. Maluku, Seram, and Banda sections of the upper 1000 dbar for (top) potential temperature and (bottom) salinity during the 1993 southeast monsoon (SEM) and 1994 northwest monsoon (NWM).

absence (southern Maluku Sea during the SEM and entire Maluku Sea during the NWM) of NPSW and NPIW in the Maluku Sea. In the southern Banda Sea the main thermocline structure is similar to the Makassar and Flores Sea, another indicator that the main throughflow pathway is via these western seas into the Banda Sea. Energetic internal waves and associated mixing at the Lifamatola Strait [*Van Aken et al.*, 1988] essentially destroy both extreme salinity values of SPSW and South Pacific Intermediate Water (SPIW) as they spread southward into the Seram Sea. The vertical salinity distribution is fairly homogeneous around 34.61 from 200 to 1000 dbar at the Manipa Sill, the entrance to the northern Banda Sea.

Adjacent to the Obi Strait (Figure 1), another salinity maximum has replaced NPSW at 150- to 550-dbar depth range. The potential temperature–salinity relationship indicates that this water mass, with salinity of 34.67 in SEM and in excess of 34.7 in NWM and with midthermocline temperatures of less than 15°C, is drawn from the SPSW; the Arlindo data show its entrance can only be from the Halmahera Sea. From there it spreads to southern Maluku Sea and is observed throughout the Seram Sea. The presence of this water mass up the northern Maluku Sea is clearly discernible at 380 dbar, deeper than the S_{min} of NPIW, even though its salinity is much reduced to slightly less than 34.60.

A 600- to 700-dbar salinity minimum layer is found in the northern Maluku Sea; its effect in lowering the salinity values to less than 34.58 at around 750 dbar is still discernible up to the Lifamatola Strait in the southern Maluku Sea. The potential temperature–salinity relationship indicates that this is South Pacific Intermediate Water or Antarctic Intermediate Water [*Wyrtki*, 1961] that enters the northern Maluku Sea directly from the Pacific Ocean.

The Timor Sea (Not Shown in Section 3)

During SEM the SST varies between 26.2° and 27.0°C, similar to that of the Banda Sea. During NWM the SST is much warmer, between 29.9° and 30.4°C. Another notable NWM development is that the surface salinity increases to values up to 34.92. We suggest that this warm, salty NWM surface water is advected from the northwest coast of Australia. The spreading of this water in the Timor Sea causes the formation of a very thin (60 m), salinity minimum layer of less than 34.50 between 50 and 110 dbar. Below the salinity minimum the presence of NPSW is no longer present, and a much attenuated NPIW is confined to the northern Timor Sea, with a core layer salinity near 34.50 at 300 dbar.

5. Isopycnal Distributions

The thermocline of the Indonesian Seas is highly stratified and prone to strong internal oscillation. Comparison of the CTD up and down traces reveals very active internal waves, displacing isopycnals by 20–50 dbar, and up to 90 m displacement is measured within the Lifamatola Strait and passages near Wetar. Sections using density as the vertical coordinate have an advantage over pressure coordinate sections as the oscillatory effect of internal wave is removed, showing more clearly the primary spreading surfaces.

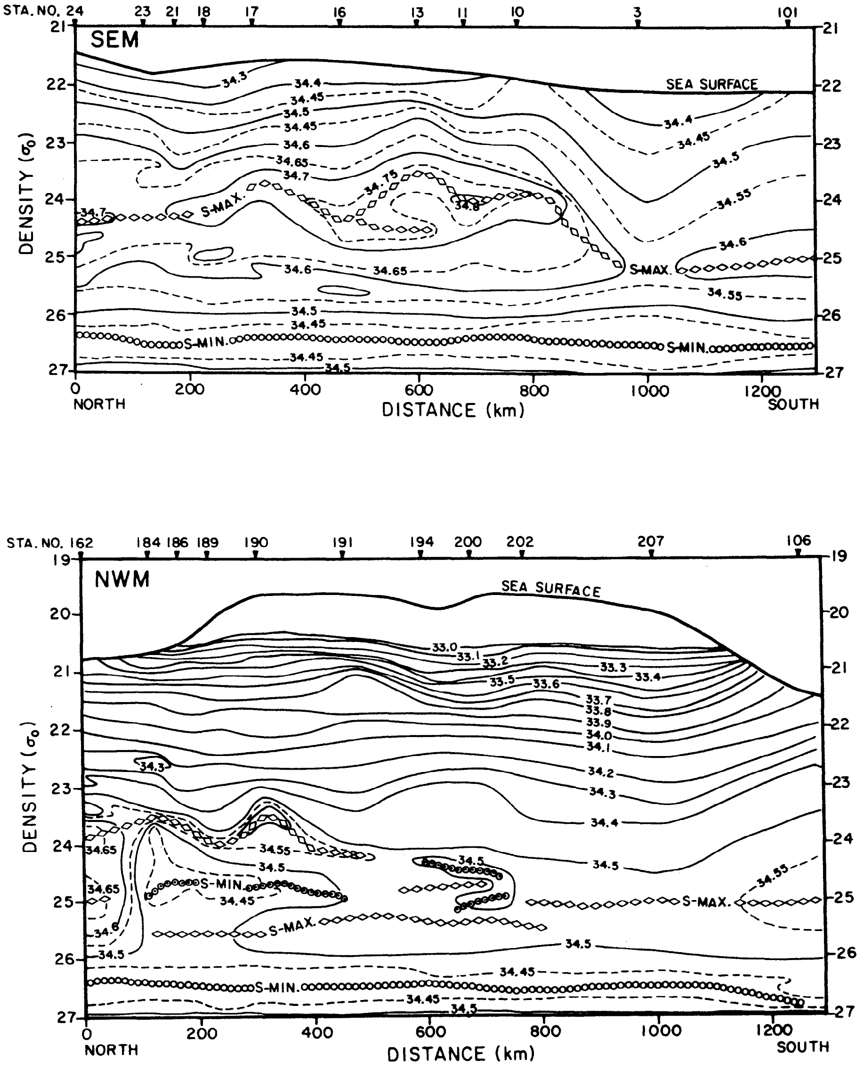

Figure 6. Makassar Strait section for salinity with σ_0 as the vertical coordinate during the 1993 southeast monsoon (SEM) and 1994 northwest monsoon (NWM).

The Arlindo data for meridional sections 1 and 3 (see Figure 1) are plotted with density, σ_0, as the vertical coordinate (Figures 6 and 7). The σ_0 range is 21–27. Indonesian Seas' surface water is mostly denser than 21°, the exception is found within the Makassar Strait during the NWM, when low-salinity water floods the surface layer, reducing surface density to 19.4 σ_0. The 27 σ_0 falls near the 500-dbar level, so the density coordinate sections include the NPSW and NPIW core layers.

Makassar Strait (Figure 6)

During SEM the NPSW follows relatively continuously along the 24 σ_0 surface, dropping to the 25 σ_0 surface in the western Flores Sea. As the S_{max} in the western Flores is close to the salinity at that same density surface in the Makassar, it is suggested that the deepening of the NPSW core layer is due to stronger vertical mixing in the near-surface layer. The saltiest (above 34.75) NPSW occurs from stations 10 to 16 within the central and southern Makassar Strait. This feature is isolated from the Sulawesi Sea, as the transverse section at the northern entrance to the Makassar Strait (stations 19 to 22) does not show a S_{max} above 34.713 (at station 22). The isolation of more concentrated NPSW indicates a sporadic nature in the supply from the Mindanao Current and Sulawesi Sea or perhaps a localized, though time-dependent, upstream mixing process. The NPIW S_{min} core layer is essentially flat in the density coordinate, near 26.5 σ_0.

During the NWM the surface water is much fresher than in the SEM, reduced to about 32 as river water from the two large neighboring islands spreads into the narrow Makassar Strait. The NPSW S_{max} core layer water is now more fragmented and, overall, lower in salinity (below 34.6). It is also distributed over a wider density range than observed in the SEM. S_{max} cores are observed slightly less than 24 σ_0 at the northern end and near 25.0–25.5 σ_0 along the central and southern end of Makassar Strait and within the western Flores Sea. Between these S_{max} cores is a localized S_{min} core, in the 24–25 σ_0 range near 19°–20°C, about 150-dbar depth. The origin of this water is not yet identified, though a source in the Sulu Sea is possible. During the NWM the Sulu Sea near surface water is cooler than that of the more tropical Indonesia waters, and it is also fresher than the NPSW. The general southward drift of Sulu Sea water across the western end of the sill spanning Kalimantan to Mindanao [*Wyrtki*, 1961] would inject Sulu Sea water

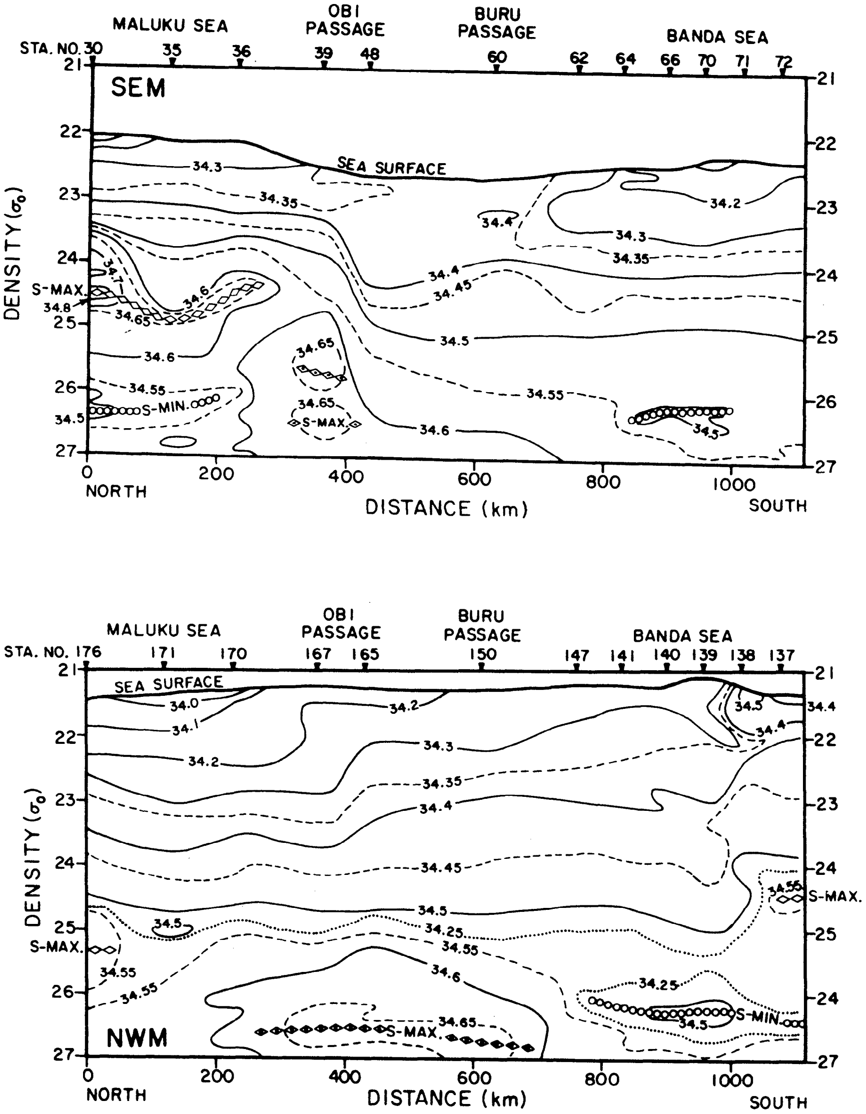

Figure 7. Maluku, Seram, and Banda section for salinity with σ_0 as the vertical coordinate during the 1993 southeast monsoon (SEM) and 1994 northwest monsoon (NWM).

into throughflow. Might the Sulu Sea transport be of sufficient magnitude to serve as a significant factor in the attenuation of the NWM S_{max} core?

Maluku-Banda Seas (Figure 7)

During the SEM the lowest surface salinity values are observed in the Maluku Sea and southern Banda Sea. In the Maluku Sea the NPSW S_{max} and the NPIW S_{min} core layers terminate abruptly between stations 36 and 39 and hence do not spread across the Lifamatola Passage into the Seram Sea. In the southern extrema of the Maluku Sea, adjacent to the Obi Passage, a S_{max} is detected near 25.5–26.5 σ_0. This water can be traced to the Halmahera Sea and is derived from the South Pacific water column. Within the Seram Sea the water column does not display extrema core layers. In the Banda Sea the NPIW S_{min} core layer is reestablished by inflow of Makassar Strait throughflow water, via the Flores Sea.

The surface density during the NWM is lowered mainly by increased SST, about 3°–4°C above the SEM value. The presence of NPSW and NPIW cores is much reduced in extent in the Maluku Sea, as is the case in the Makassar, and may be indicative of reduced contribution to the throughflow from the North Pacific. North Pacific water is reenforced in the southern Banda Sea by injection of water from the Flores Sea. The deeper S_{max} of South Pacific water is somewhat more widespread in the NWM, extending throughout the Seram Sea.

6. Geostrophic Transport

Geostrophic determinations without current meter time series data for reference are often just guess work, but in the Indonesian Seas the very sharp shear of the upper 200–300 m makes the resultant velocity field nearly invariant to reference levels below 300 m. That's the good news. The bad news is that there are significant pitfalls in the geostrophic approach in the Indonesian region: (1) There is probably significant nongeostrophic flow within narrow straits, (2) low latitude allows small slopes (relative to instrumental and "geophysical" noise) of the isopycnals to produce large geostrophic currents, amounting to large uncertainty, and (3) vigorous internal waves distort the isobaric and isopycnals surfaces.

Comparison of the Arlindo CTD up and down traces reveals internal oscillations of the thermocline of 50 m. Such displacement of pressure surfaces introduces a change in the sea surface dynamic height relative to 1000 dbar of 20 dynamic centimeters (dyn. cm). As the range of values of the 0/1000 dynamic height for the entire Arlindo surveyed area is 23 dyn. cm in the SEM and 33 dyn. cm in the NWM, the error introduced by internal waves for typical station pair separation is unacceptably large, making even detection of the geostrophic flow direction questionable. For this reason we do not present geostrophic transports. We are exploring various averaging techniques to calculate meaningful geostrophic transport estimates.

7. Conclusions

Water mass preliminary analysis of the Arlindo mixing CTD data set indicates that the Makassar Strait has a strong presence of North Pacific thermocline water, confirming its role in carrying the bulk of the interocean throughflow. The lack of a continuous trace of Pacific water masses within the interocean pathways east of Sulawesi suggests that these are not conduits for significant throughflow. The Makassar throughflow consists of North Pacific Subtropical Water (S_{max} core near 20°C and 100 m) and North Pacific Intermediate Water (S_{min} core near the 10°C isotherm at 300 m). The S_{max} core layer is fragmented, suggesting an uneven injection from the Mindanao Current or transient advective/mixing events within the Indonesian Seas. During the NWM the Makassar throughflow may slacken, as a higher degree of attenuation of the S_{max} core is observed, presumably due to diminished advective replacement. Relatively salty water of South Pacific origin is observed in the 10°–14°C interval of the Maluku and Seram Seas. This water enters with the Mindanao Current inflow to the Maluku Sea and directly from the South Pacific via the New Guinea Coastal Current into the Halmahera Sea. Invasion of South Pacific lower thermocline water is stronger during the NWM.

Water mass indicators show that while some of the throughflow passes through the Lombok Strait [*Murray and Arief*, 1988], the bulk of the throughflow after transversing Makassar Strait flows into the Flores and Banda Seas before turning southward into the Timor Sea and Indian Ocean. The salinity and form of the S_{max} at the northern end of Makassar Strait during the SEM are similar to that of the eastern Flores Sea region during the NWM, suggesting an advective time lag of about 5 months.

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