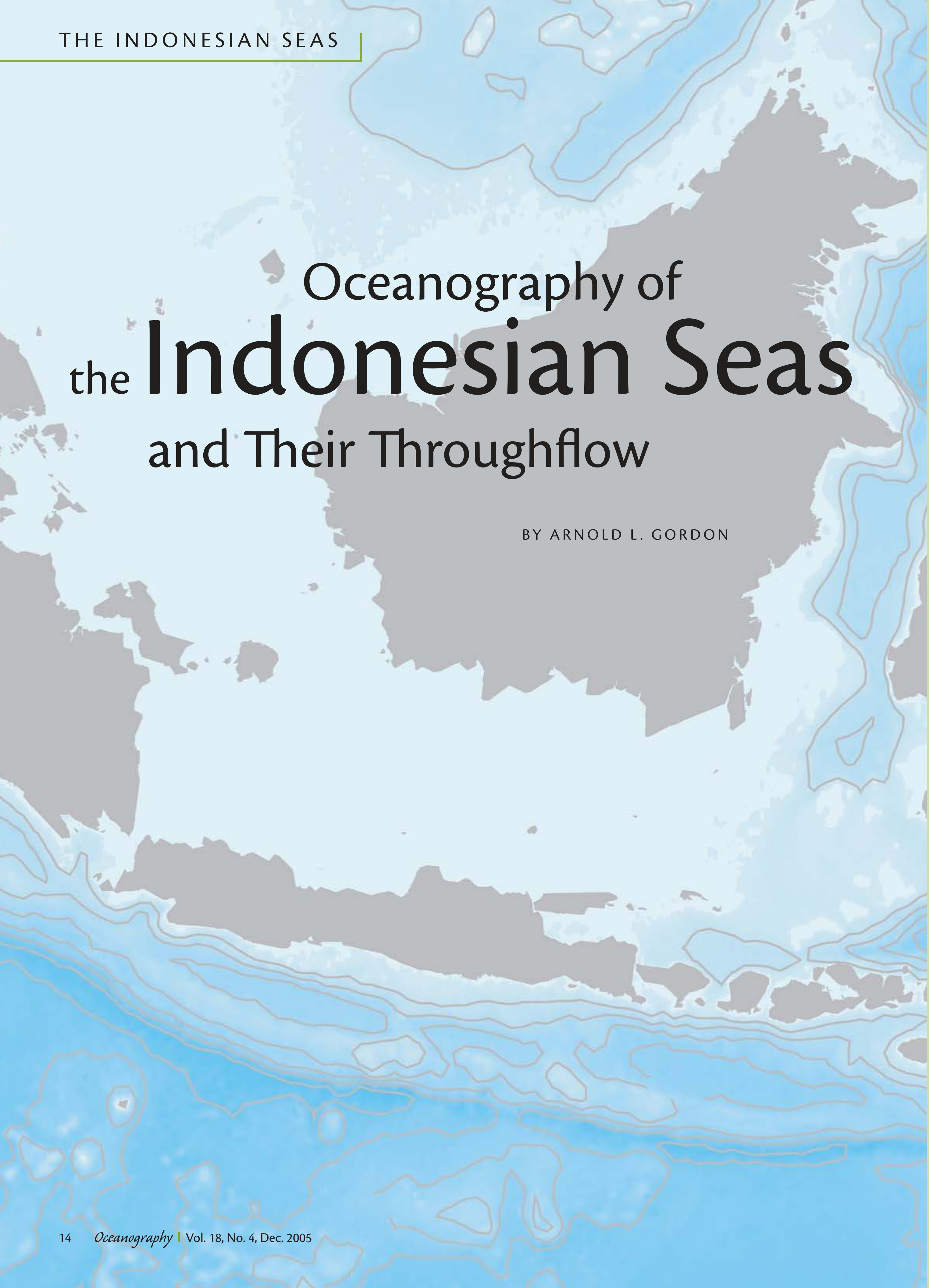

Oceanography of the Indonesian Seas and Their Throughflow

BY ARNOLD L. GORDON

FOR THE LAST 20 YEARS, much of my research has been directed at the ~10 percent of the equatorial circumference represented by the Indonesian seas. To understand my entry into Indonesian oceanography, one needs to begin the story about 10,000 miles away along the southern rim of Africa. There, instead of freely continuing into the Atlantic Ocean, the westward-flowing Agulhas Current abruptly curls back to the Indian Ocean in what is referred to as the Agulhas Retroflection. I was curious about the Agulhas Retroflection, having been aware of Gunter Dietrich's Ph.D. work of 1935 and of the South African oceanographic literature on the subject, and thus I was most pleased to begin fieldwork in this region in November 1983 aboard the R/V *Knorr*. My curiosity was further piqued as we entered into the Benguela Current off Cape Town. There we quickly entered into a pool of relatively buoyant water contained within a strong anticyclonic eddy. The common wisdom at the time was that the Benguela Current was drawn from the cooler water flowing eastward within the poleward limb of the South Atlantic's subtropical gyre. After some thought it became apparent that the encountered pool was composed of Indian Ocean thermocline water that somehow wandered into the southeast corner of the South Atlantic Ocean. The water between the eddy and the African coast contained an abundance of Indian Ocean characteristics. The Agulhas Retroflection is not complete; the Atlantic Ocean and Indian southern subtropical gyres are linked, at least occasionally (Gordon, 2003).

My first reaction to this observation had to do with the role the so-called Agulhas leakage plays in perpetuating the meridional overturning circulation of the Atlantic Ocean (associated with North Atlantic Deep Water) and in driving the counter-intuitive northward ocean heat flux in the South Atlantic Ocean. Then I began to think about the other side of the "equation": if the Indian Ocean was losing water via the Agulhas leakage, what water replaces it? A leading candidate was the flow of Pacific water into the Indian Ocean via the Indonesian seas—the Indonesian throughflow (ITF). Klaus Wyrtki's influential 1961 Indonesian seas monograph also motivated me to look towards these tropical seas, rather than the sub-polar Pacific stream feeding the Agulhas drawn through the Drake Passage (I've been to those wavy seas before). Once I began my investigations of the Indonesian seas I have been increasingly engrossed by its oceanography and its place in the global ocean scheme.

LARGE-SCALE EFFECTS OF THE ITF

Scientists often see reported an ITF heat flux into the Indian Ocean of 0.5 to 1.0 Petawatts (PW, 10^{15} Watts) (Godfrey, 1996; Gordon, 2001; Vranes et al., 2002). These figures are based on relating the ITF temperature and transport to a reference temperature: the temperature of the compensatory transport out of the Indian Ocean, or more often as a temperature flux, relative to 0°C. But, what of simpler questions? Does the ITF warm or cool the Indian Ocean? Does the ITF alter the meridional overturning circulation of the Indian (and Pacific Ocean, too)? And, is the ITF important to the climate system? My short answers are, respectively: cools; yes; I think so.

Temperature and salinity distributions within the Indian Ocean thermocline (Figure 1) depict the ITF waters as a cool, low-salinity streak across the Indian Ocean near 12°S. Indonesian seas waters lost to the ITF stream are replaced by North Pacific thermocline waters, though at the lower thermocline and still deeper levels, the waters are replaced directly from the South Pacific (Gordon and Fine, 1996). These waters enter into what may be viewed as the Indonesian "mix-master." Here, energy derived from dissipation of tidal currents combines the two Pacific waters and mixes downward the buoyancy resulting from the regional air-to-sea heat and freshwater flux. This buoyancy is eventually projected into the Indian Ocean and Agulhas Retroflection, and is perhaps of relevance to the Atlantic Ocean's meridional overturning circulation.

If there were no ITF and thus no cool, low-salinity band across the tropical Indian Ocean, one can safely assume that the warm, salty tropical and northern Indian Ocean thermocline would close in, filling the void. In this way, the ITF cools and freshens the Indian Ocean thermocline. The ITF water injected into the Indian Ocean has no choice but to exit the Indian Ocean within the poleward-flowing western boundary Agulhas Current, but not before mixing with ambient Indian Ocean thermocline water and interacting with the monsoonal atmosphere along a tortuous route on its way to the Agulhas (Schott and McCreary, 2001; Schott et al., 2002; Song et al., 2004). Some ITF water turns southward directly into the thermocline feeding the Agulhas Current, but some ITF water enters into the tropical Indian Ocean where it must first upwell into the surface layer before spreading southward within the surface Ekman layer. The ITF acts to flush the Indian Ocean thermocline waters to the south by boosting transport of the Agulhas Current, increasing southward ocean heat flux across 20-30°S and sea-air heat fluxes within the Agulhas Retroflection, over the no-ITF condition. Using an 8 Sv (one Sv, or Sverdrup, is an ocean transport unit, equal to a current of one million cubic meters per second) ITF, Talley (2003) estimates that the southward heat flux across ~32°S in the Indian Ocean is 0.59 PW, the largest poleward heat flux of the southern hemisphere oceans.

The eastern Indian Ocean is also affected by the ITF. Here, the buoyancy introduced to the eastern tropical Indian Ocean by the ITF sets up a southward pressure gradient that results in a southward flow of warm surface water along the west coast of Australia, called the Leeuwin Current (Smith et al., 1991). This warm layer suppresses the usual coolness of the subtropical eastern boundary regime induced by Ekman upwelling. Were it not for the ITF, the west coast of Australia would be less conducive to swimming, though perhaps fishing would be improved.

What might the Indian Ocean meridional circulation look like if there were no ITF? The Agulhas Current would

With an improved understanding of the ocean processes within the Indonesian seas and of the magnitude and variability of the ITF, we can anticipate enhanced understanding of the importance of the ocean's role in this region in governing ENSO and the Asian monsoon.

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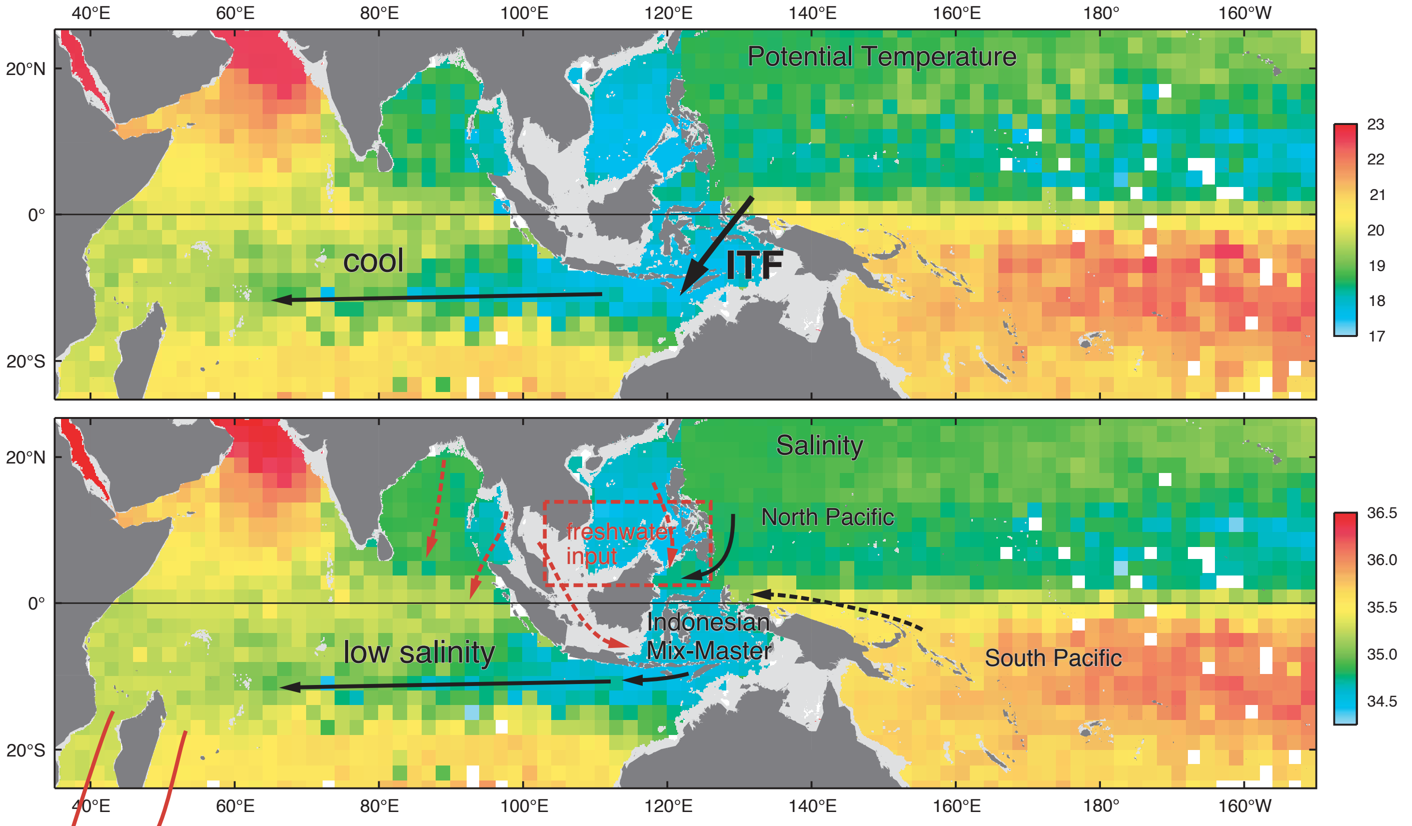


Figure 1. Temperature (upper panel) and salinity (lower panel) on the σ_θ 25.5 surface, which lies within the upper thermocline. The Indonesian throughflow (ITF) can be traced as a relatively cool, fresher, band across the Indian Ocean near 12°S. The attenuation of the ITF characteristics towards the west is due to lateral and vertical mixing of the ITF waters with ambient Indian Ocean thermocline water. The Pacific Ocean supplies the ITF waters. A percentage (perhaps 25%) of the North Pacific thermocline and intermediate water advected southward off the Philippines within the Mindanao Current contributes to the ITF, thus entering the Indian Ocean rather than turning into the tropical Pacific. A stream of South Pacific water feeds directly into the lower thermocline and deeper components of the ITF of the easternmost Indonesian seas. Within the Indonesian seas, a regional excess of freshwater enters into the Pacific waters, which is then altered by strong tidal-induced mixing (dubbed Indonesian mix-master) to produce uniquely Indonesian waters.

be weaker, simply balancing the horizontal and meridional circulation of the southern subtropical Indian Ocean, without coping with the ITF transport. Poleward heat flux would be relaxed, as would be the sea-to-air heat flux within the Agulhas Retroflection (Hirst and Godfrey, 1993). Perhaps without the ITF inflow there would be diminished flushing of tropical Indian Ocean thermocline to the south, resulting in a warmer, saltier, thicker low-latitude Indian Ocean thermocline. This changed thermocline might induce warmer tropical sea surface temperatures, leading to greater evaporation, invigorating the Asian monsoon. Such "fun" conjecture of course must be tested through application of reliable climate models that faithfully replicate the ITF.

There have been many model studies investigating the ITF impact on the Indian and Pacific heat and freshwater budgets and of the ITF role in the climate system (e.g., Hirst and Godfrey, 1993; Murtugudde et al., 1998; Wajsowicz and Schneider, 2001; Wajsowicz, 2002; Schott and McCreary, 2001; Lee et al., 2002). The model-dependent results indicate changes in the surface temperature and meridional circulation between on/off ITF states. But as James Potemra points out (University of Hawaii, personal communication, 2005) on/off ITF constraints should be treated with caution because it is not clear whether such a climate state resulting from a closed ITF is realizable. Oceanic heat and freshwater fluxes into the Indian Ocean—at the expense of the Pacific—affect atmosphere-ocean coupling with potential impacts on the El Niño-Southern Oscillation (ENSO) and monsoon phenomena (Webster et al., 1998). The nature of the link between the ITF and such climate phenomena depends on the depth profiles of the ITF transport and temperature (Song and Gordon, 2004), that is, whether the ITF is surface intensified or thermocline intensified (the latter seems more likely). The vertical profile of the transport within key ITF passages is becoming an active research pursuit, mostly within models (Potemra et al., 2003), as we await proper observational data. The ITF also has an effect on the Pacific Ocean property budgets and sea level as mass, heat, freshwater, and buoyancy are removed (MacDonald, 1993; Maes, 1998; McCreary and Lu, 2001), but perhaps the immenseness of the Pacific isolates it a bit from the measly leak of ~10 Sv ITF into a neighboring ocean.

OCEANOGRAPHY OF THE INDONESIAN SEAS

Like a braided river running through many pathways within the Indonesian seas, the ITF headwaters are in the Pacific and their mouths lie in the multitude of passages within the Sunda archipelago. En route, the inflowing Pacific water is converted by the "mix-master" into a uniquely Indonesian tropical stratification—one of a strong, though relatively

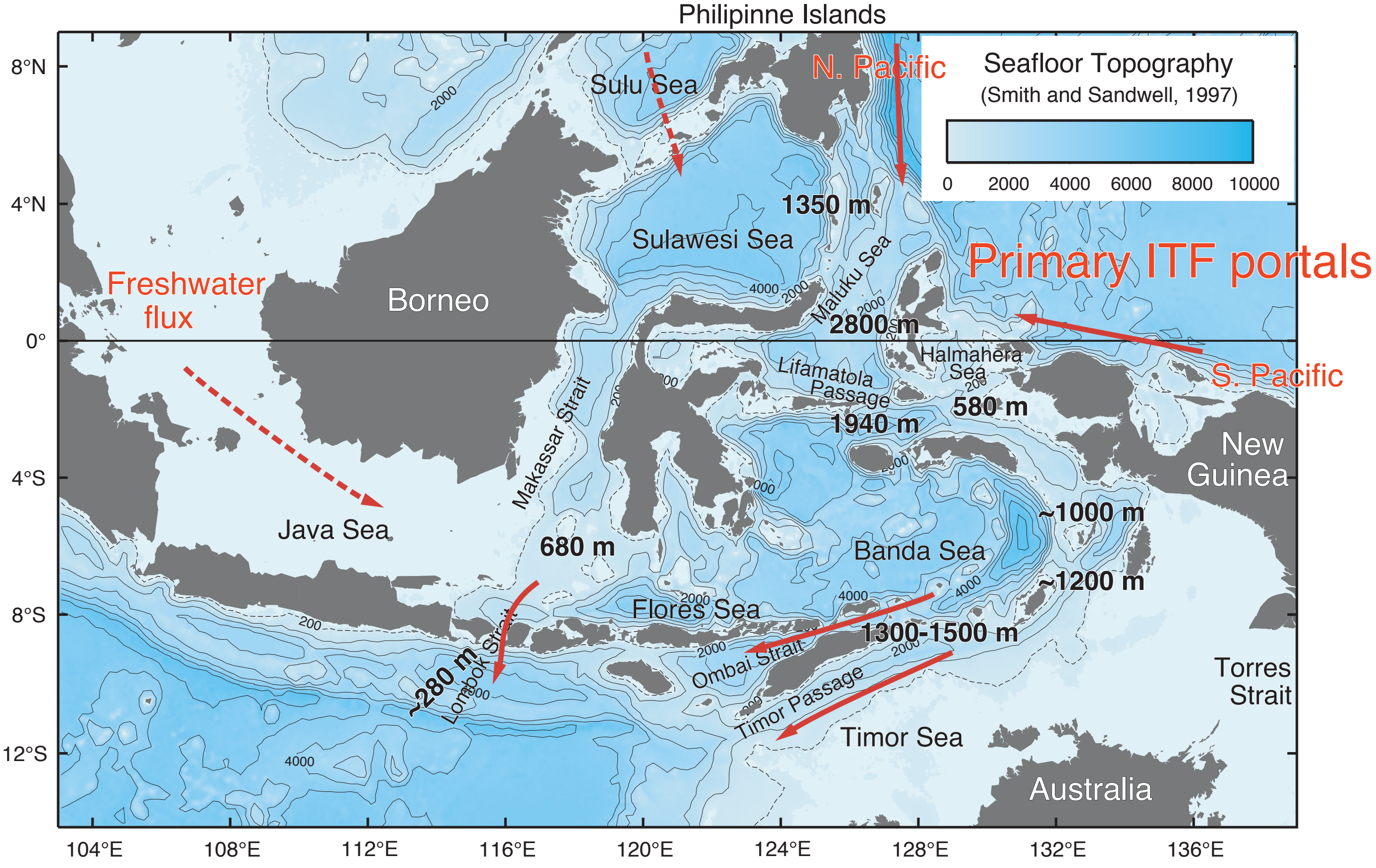


Figure 2. The Indonesian seas, depths are given in meters. The primary inflow and outflow portals of the ITF are shown by red arrow; dashed red arrows indicate secondary inflow portals, which are of importance in terms of freshwater inflow. The bold numbers in black indicate critical deep topographic sill depths (from Gordon et al., 2003a).

isohaline, thermocline.

The primary portals affording inter-ocean routing through the Indonesian seas are the deep-water gaps between the Philippines and New Guinea (Figure 2). The ~10 m deep Torres Strait between Australia and New Guinea does not permit significant throughflow. Although the Philippines and New Guinea portal provides the bulk of the throughflow, the inflow from the Luzon Strait reaching through the Sulu and South China Seas into the Indonesian seas adds slightly (guess: ~1 Sv) to the ITF. More importantly, this Luzon Strait inflow delivers freshwater into the surface layer of the Indonesian seas, which adds to that introduced through regional rainfall and river runoff. The total freshwater input is slowly mixed downward to transform the temperature/salinity characteristics of the Pacific thermocline water into the Indonesian stratification.

The winds over the Indonesian maritime continent and the position of the Inter Tropical Convergence Zone (ITCZ) are strongly monsoonal (Figure 3a) (for a more in-depth discussion of the surface waters of the Indonesian seas, see Qu et al. and Sprintall and Liu, this issue). The wind is directed towards Asia in the boreal summer (July to September) and towards Australia in the boreal winter (January to March); the ITCZ is over the South China Sea from July to September, and is along the Sunda Island archipelago, dipping into northern Australia from January to March. At the sea surface the warmest water also shifts with the sun: further north from July to September, further south from January to March. The seasonal swing of the surface temperature is accentuated by Ekman upwelling in the southeast monsoon of July to September along the Sunda Island archipelago and in the Banda Sea. From January to March, the Ekman transport is convergent, inducing downwelling. The Ekman effects are evident in the surface chlorophyll *a* field (Figure 3b), with upwelling, cooler surface temperatures matching regions of higher primary productivity. The sea-surface salinity (Figure 3c) varies markedly with season. The monsoonal winds shift the lowest surface salinity into the Java Sea and southern Makassar Strait from January to March, and into the South China Sea from July to September, a condition that may impose a significant seasonality on the surface-layer contribution to the throughflow within Makassar Strait (Gordon et al., 2003b).

Regional climate prediction may be improved, enabling informed management decisions regarding agricultural production and freshwater supplies, and preparation for climate-related forest fires.

The salinity within the thermocline is used to identify the ITF sources and pathways (Figure 3d). North Pacific subtropical water dominates the upper thermocline of the Makassar Strait and Banda Sea. The saltier South Pacific subtropical water does not spread into the upper thermocline of the Banda Sea from its entrance portal in the Halmahera Sea. Within the lower thermocline, the North Pacific Intermediate Water dominates the Makassar Strait, but the South Pacific influence is somewhat more pervasive in the eastern seas. There appears to be some seasonality to the distribution, with lesser amounts of North Pacific water, and greater amounts of South Pacific thermocline water during the northwest monsoon of January to March (Gordon and Fine, 1996; Ilahude and Gordon, 1996). The temperature/salinity stratification and thermocline depth clearly responds to ENSO (Bray et al., 1996; Sprintall et al., 2003). In a sense, the stratification seasonality is echoed in ENSO: the January to March northwest monsoon is El Niño-like and the July to September southeast monsoon is La Niña-like.

The evolution of the thermocline stratification from the Pacific source water into Indonesian waters can be traced through the attenuation of the North Pacific subtropical salinity maximum layer (s-max), leading to a nearly isohaline thermocline at the export channels near Timor (Figure 4). With reasonable residence time, the rate of destruction of the s-max implies a thermocline vertical mixing coefficient, K_z, of 1 cgs (Ffield and Gordon, 1992). This K_z value is perhaps ten times that normally associated with thermocline stratification and is likely a consequence of dissipation of

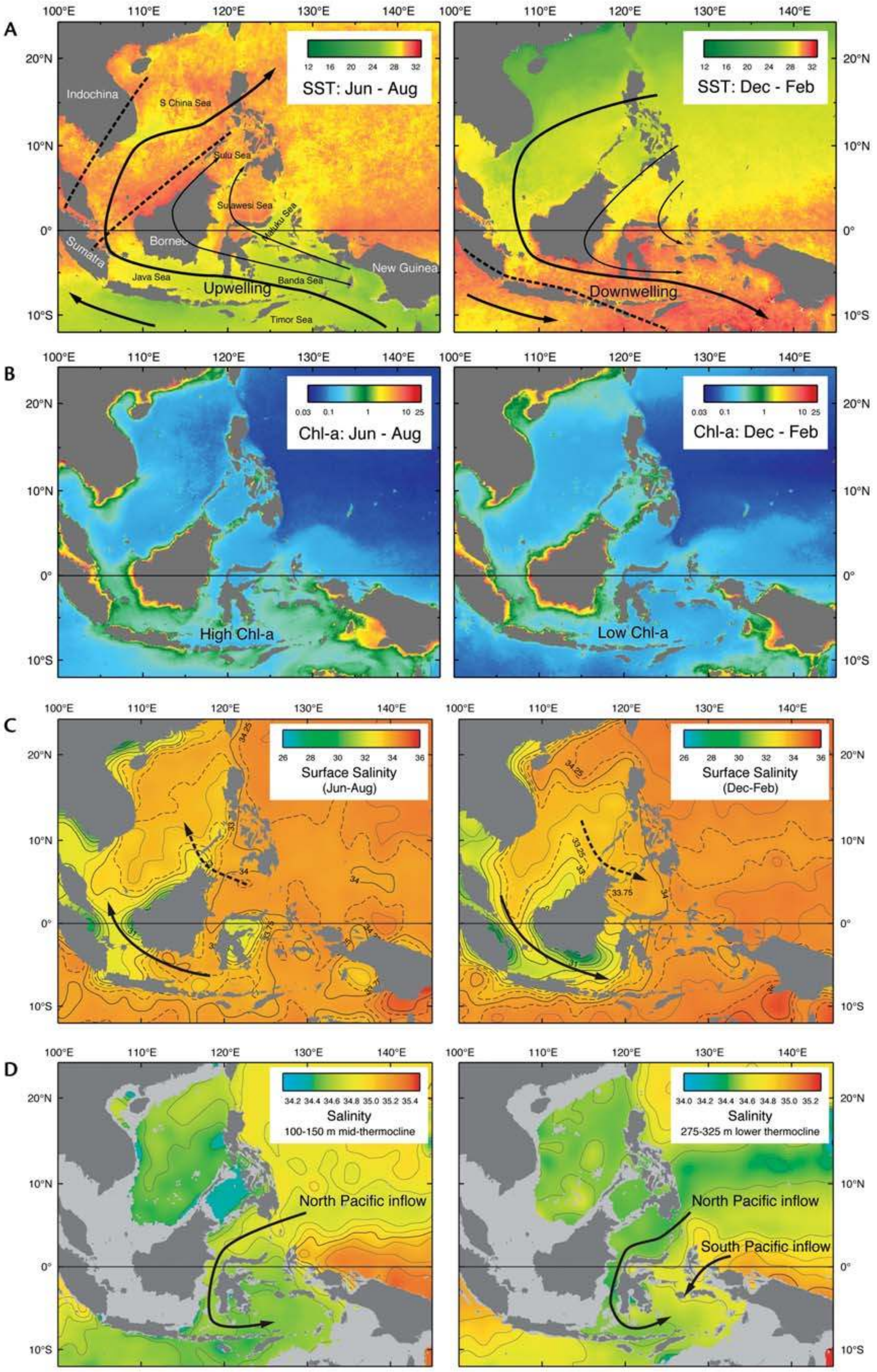


Figure 3. (A) Satellite-derived fields of sea surface temperature from Aqua-MODIS (left: southeast monsoon; right: northwest monsoon). The reversal of the wind direction (black arrows) and the large latitudinal shift of the Inter-Tropical Convergence Zone (dashed black line) are hallmarks of the dominant monsoonal climate. (B) Sea surface chlorophyll *a* from SeaWiFS (left: southeast monsoon; right: northwest monsoon). Areas of wind induced upwelling and downwelling (labeled) are associated with elevated or attenuated (respectively) levels of chlorophyll *a.* (C) Salinity at the sea surface (left: southeast monsoon; right: northwest monsoon) based on archived hydrographic data reveal the shifts of low salinity water in response to the monsoonal winds (black arrows) and precipitation patterns. (D) Salinity within 100-150 m depth interval (lower left) of the upper thermocline and within 275-325 m depth interval (lower right) of the lower thermocline. The traces of North Pacific and South Pacific streams of the ITF (black arrows) denote the primary ITF pathways.

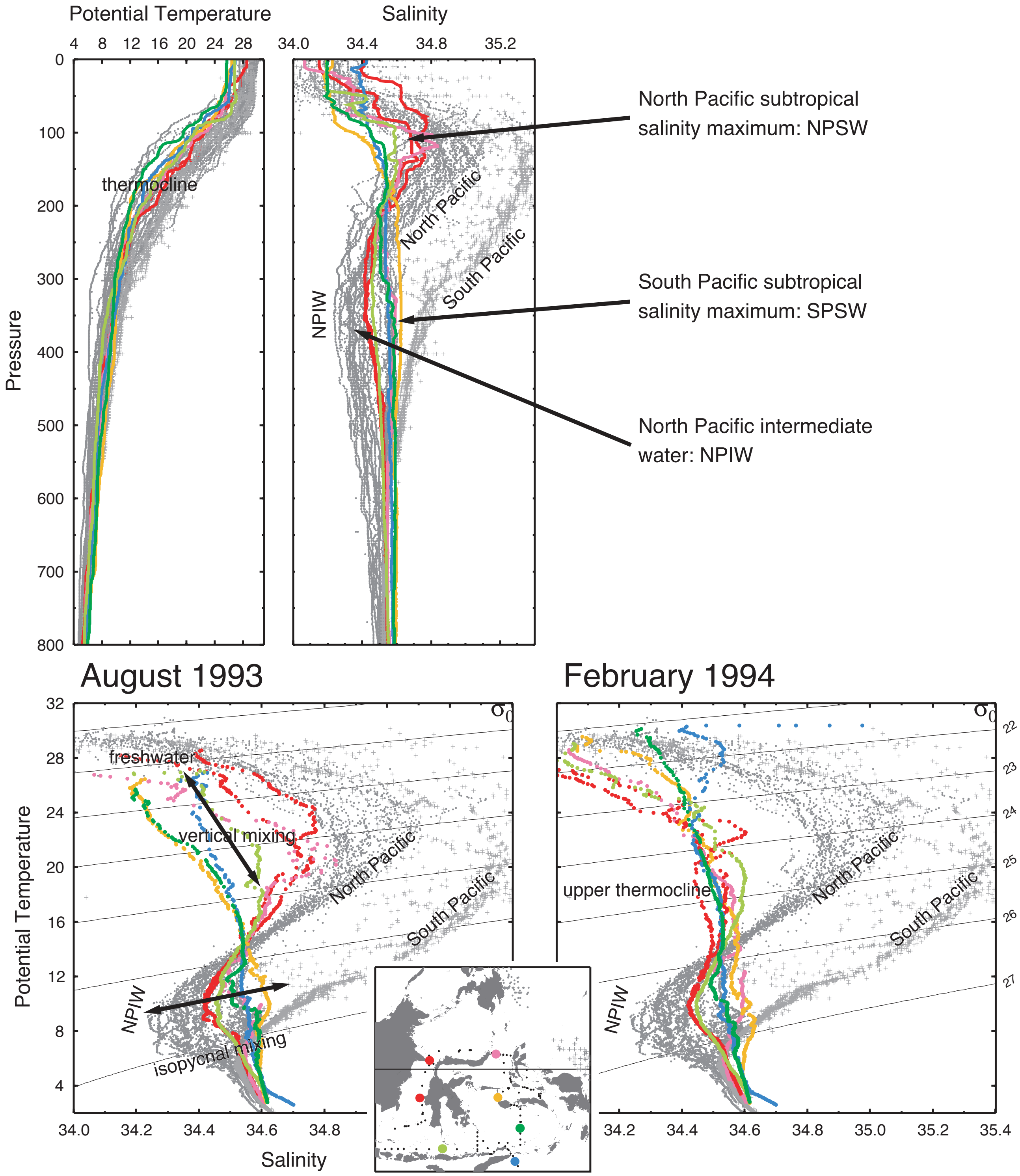


Figure 4. Potential temperature (θ) and salinity stratification during August 1993, and θ/S scatter for August 1993 and February 1994. The color profiles denote specific stations within the Indonesian seas (position shown in map insert), while the grey tones profiles denote the North Pacific (dots) and South Pacific (+ symbol) source waters. The intense thermocline within the Indonesian seas is clearly seen as the temperature drops from near 26°-28°C at 75 m to 10°-12°C at 300 m. The contrasting salinity levels of the North and South Pacific inflow yield a more variable salinity profile within the Indonesian seas. The θ/S scatter is used to investigate the evolution of the water mass stratification as the ITF streams negotiate the complex topography of the Indonesian seas. Vertical mixing is a dominant factor in the upper waters, with isopycnal mixing becoming dominant in the lower thermocline.

tidal energy (Egbert and Ray, 2001) in the vicinity of topographic features (Hatayama, 2004). Hautala et al. (1996) also find that strong vertical mixing accounts for the upper thermocline profile down to an isopycnal of σ_θ = 25.8 (density in kg/m^3), but in the lower thermocline (σ_θ = 26.5), the stratification is more consistent with isopycnal mixing of saline South Pacific water with fresher North Pacific Intermediate Water. Below σ_θ = 27.0, vertical mixing again becomes the dominant process. Fortnightly variability of surface temperature of ~1°C is thought to be a consequence of changes in vertical mixing due to fortnightly tidal variability (Ffield and Gordon, 1996). A fortnightly signal is found in the surface layer temperature records from various passages in the Sunda Islands (Sprintall et al., 2003). Alford et al. (1999) find K_z = 0.1 cgs in the Banda Sea near 100-m depth averaged over a two-week cruise (October 22 to November 7, 1998) a value more typical of the open-ocean thermocline. However, theirs was a spot measurement of microstructure during a period when mixing may have been in a lull: there were very weak winds (usually below 5 m/sec, with a mixed layer depth of less than 10 m). Additionally, their site was in the southern central region of the Banda Sea removed from sidewalls and sills where mixing may be enhanced. Their observational period was close to the semi-annual minimum in fortnightly activity and so tidal effects might have been reduced. The Ffield and Gordon (1996) and Hautala et al. (1996) values are, by inference, based on the net effect along the ITF pathway over many months. A K_z = 1 cgs coupled with an intense thermocline yields vertical heat flux of 40 W/m^2, which along with the downward mixing of freshwater reveals an important attribute of the Indonesian seas: the downward transfer of buoyancy (though the ITF waters are still cooler and fresher than the Indian Ocean thermocline as viewed on isopycnal surfaces [Figure 1]). See the contributions of Ray et al., Robertson and Ffield, and Ffield and Robertson, this issue, for discussion of Indonesian seas' tides and the mixing consequences.

Building a quantitative understanding of the physical marine environment will provide a quantitative basis for modeling the complex ecosystems of the Indonesian seas, leading to improved fisheries and water-quality management and species preservation, as well as further understanding of the impact of marine platforms for mineral recovery.

The ITF, whose pathway is identified from the water-mass distribution (Figure 5), faces a topographic obstacle course within the Indonesian seas, which contain narrow passages and topographic barriers (Figure 2) (Gordon et al., 2003a). The throughflow via the Makassar Strait encounters a sill depth of 680 m. The Makassar stream bifurcates with one branch entering the Indian Ocean through the Lombok Strait with a sill depth of ~300 m, while the bulk of the Makassar transport turns eastward in the Flores Sea, into the Banda Sea, eventually passing into the Indian Ocean on either side of Timor. The primary passages east of Sulawesi are deeper; the Lifamatola Passage sill is 1940 m. The connections of the Banda Sea to the Indian Ocean are many, with sill depths varying from 1000 to 1500 m. Because the main inflow pathway of Pacific water appears to be within the Makassar Strait, measuring the ITF within the Makassar Strait (ideally in the deep-water constriction near 2°51'S—the 45-km wide Labani Channel) provides the most effective way to capture the ITF volume transport. This measurement was done from December 1996 to July 1998, during which there was the "El Niño of the Century" (see Gutman et al. [2000] for a discussion of the devastating effects of this El Niño on Indonesia). Makassar transport for 1997 is determined to be ~8 Sv with an uncertainty of 2 Sv (Susanto and Gordon, 2005); values of ~9 Sv were determined earlier (using more qualitative methods).

The Makassar ITF is thermocline intensified, leading to a transport-weighted temperature of a rather cool ~15°C. This is thought to be a consequence of

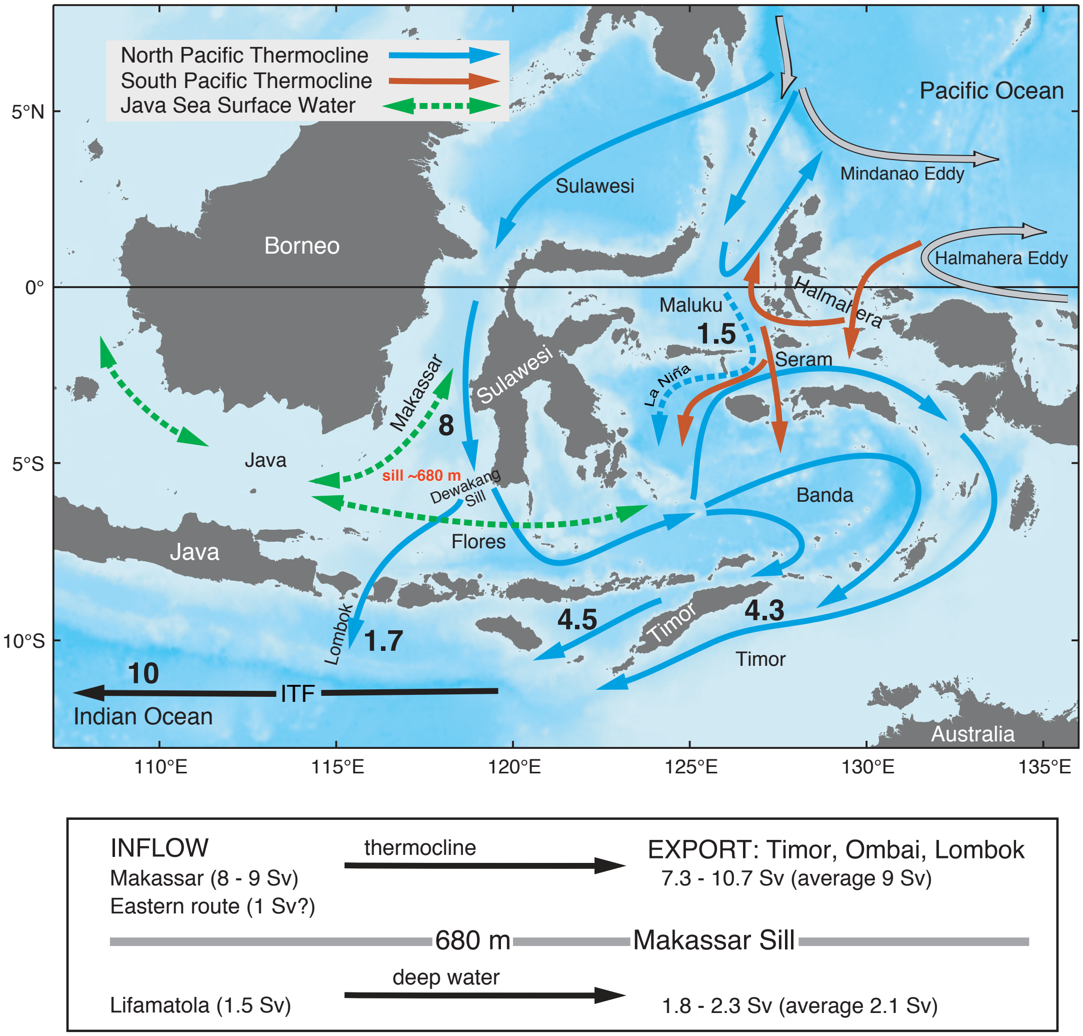


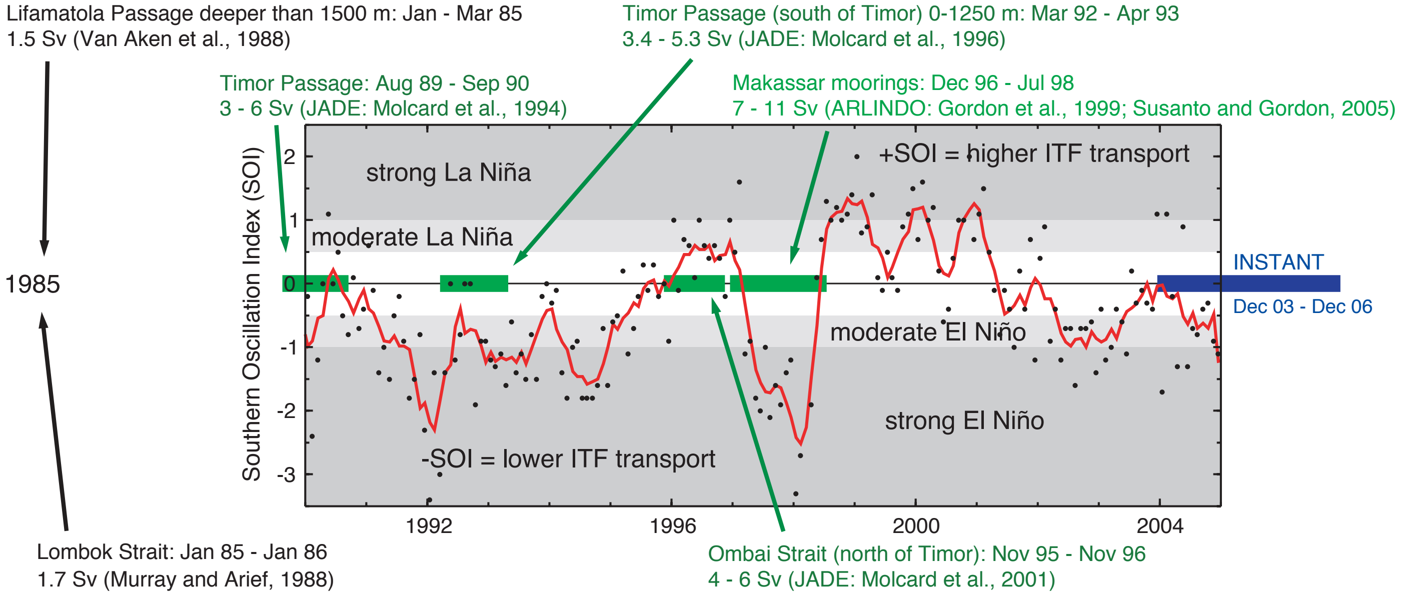
Figure 5. Indonesian throughflow pathways and estimates of total volume transport (in Sv = 10^6 m^3/sec). The lower panel shows the partitioning of transport above and below the Makassar Strait sill depth of ~680 m. See Figure 6 for the sources of the transport numbers given in this figure. Modified from Gordon and Fine (1996).

the regional winds and freshwater fluxes that inhibits the southward flow of surface-layer (less than 50 m) water within Makassar Strait (Gordon et al., 2003b). During the northwest monsoon, buoyant, low-salinity surface water (Figure 3c) from the Java Sea is "blown" into the southern Makassar Strait. This surface-water movement induces a northward pressure gradient within the surface layer of the Makassar Strait, counteracting the seasonal southward winds. During the July to September southeast monsoon, reversal of Java Sea winds force more saline surface water from the Banda Sea into the southern Makassar Strait, eliminating the northward pressure gradient, though the July to September winds over Makassar act to constrain the surface throughflow.

Overflow of deep Pacific water into the isolated topographic bowl of the deep Seram and Banda Seas occurs within the 1940-m deep Lifamatola Passage (van Aken et al., 1988, 1991). The density-driven overflow forces upwelling of resident waters. Postma and Mook (1988), using carbon-14, find a flushing rate of 10 years in the western and northern Banda Sea and Seram Sea, with a basin-wide average of 25 years. Within the confines of the basin (to maintain steady state, the overflow is balanced by diapycnal mixing), a nearly perfect exponential deep-water temperature and salinity profile ensues (Gordon et al., 2003a). A scale depth ($Z^*=K_z/w$) of 420-530 m is characteristic of the 300 m to 1500 m depth range. The upwelled water within the confines of the Banda Sea, once over the confining sill of the Sunda Arc, may contribute 1.8 to 2.3 Sv the interocean throughflow, with a deep water K_z of ~13 cgs. Most of the mixing is expected to be accomplished along the sidewalls. Based on near-bottom radon profiles in the Banda Sea, the K_z is found to vary from 46 to 64 x 10^{-4} m^2/s, reaching 83 to 2000 x 10^{-4} m^2/sec over rough topography and sills (Berger et al., 1988).

The transformation of Pacific water into Indonesian water through the actions of sea-air flux of heat and freshwater, mixing (mostly tidal), and Ekman upwelling occurs for the most part within the expanse of the Banda Sea. An Ekman-driven seasonal upwelling/downwelling cycle within the Banda Sea induces a 40-m seasonal oscillation of the thermocline depth (0.33 m in sea level), instilling a seasonal divergence/convergence pattern of surface water volume and affecting the phase relationship between the Makassar ITF and the Sunda passage export (Gordon and Susanto, 2001). Maximum convergence of 1.7 Sv is attained during October and November, with matching loss (divergence) during April and May. Surface-layer divergence during the 1997 El Niño was as high as 4 Sv. The Banda Sea seasonal storage has a significant effect in projecting an ITF monsoonal pulse, with an ENSO modulation into the Indian Ocean. Vranes and Gordon (2005) find that the surface-to-600 m Makassar Strait transport, as measured by current meter moorings from December 1996 to July 1998, correlates at r = 0.77 ± 0.14 with the geostrophic transport constructed from repeat XBT (expendable bathythermograph) sections from western Java to Australia for that time interval, if the XBT time series is lagged by 98 days, a reasonable advective time scale for flow from Makassar to the XBT section south of Java.

The export passages into the Indian Ocean have been measured at various times (Figures 5 and 6). The transport of Timor Passage and Ombai Strait (Mol-



Lifamatola Passage deeper than 1500 m: Jan - Mar 85
1.5 Sv (Van Aken et al., 1988)

Timor Passage (south of Timor) 0-1250 m: Mar 92 - Apr 93
3.4 - 5.3 Sv (JADE: Molcard et al., 1996)

Timor Passage: Aug 89 - Sep 90
3 - 6 Sv (JADE: Molcard et al., 1994)

Makassar moorings: Dec 96 - Jul 98
7 - 11 Sv (ARLINDO: Gordon et al., 1999; Susanto and Gordon, 2005)

Lombok Strait: Jan 85 - Jan 86
1.7 Sv (Murray and Arief, 1988)

Ombai Strait (north of Timor): Nov 95 - Nov 96
4 - 6 Sv (JADE: Molcard et al., 2001)

Figure 6. The timing and Southern Oscillation Index (SOI) value of transport measurement through the key passages of the Indonesian throughflow pathways. In 1985, at the time of the Lombok and Lifamatola measurements, the SOI was very close to neutral. Only the Ombai measurements were made during a La Niña, albeit weak, condition.

card et al., 1996; Molcard et al., 2001) from the sea surface and 680 m is between 5.6 to 9.0 Sv; within the ~280-m-deep Lombok Strait, transport is ~1.7 Sv (Murray and Arief, 1988). The total 0 to 680 m transport is 7.3 to 10.7 Sv, which is not significantly different than the Makassar Strait transport of ~8 Sv (leaving room for ~1 or 2 Sv from eastern route). The total ITF export below 680 m into the Indian Ocean is 1.8 to 2.3 Sv. The Lifamatola Passage overflow (van Aken et al., 1988) of 1.5 Sv can explain roughly all but 0.3 to 0.8 Sv of the greater than 680-m export to the Indian Ocean based on direct current-meter measurements, or half of the value inferred from deep Banda Sea budget calculations. Noting the short time span of the Lifamatola mooring data (a three-month current meter record, from January to March 1985), an additional 0.5 or even 1.5 Sv of Lifamatola Passage overflow, as required to close the deep throughflow budget, is reasonable. Talley and Sprintall (in press), using heat, freshwater, oxygen, and silica budgets within the Indonesian seas, suggest at least 3 Sv of inflow is through the Lifamatola Strait. An ITF of ~10 Sv (somewhere between 8 to 14 Sv, with interannual modulation by ENSO) is probably a pretty good "ball-park" figure. It appears that the Makassar pathway provides maybe 70 to 80 percent of the total ITF.

Although the near balance of the inflow and outflow transports of the ITF stream is instructive, caution is urged. The ITF measurements in specific passages were made at different times and phases of ENSO (Figure 6), and as the ITF is surmised to vary with the ENSO phase (Bray et al., 1996; Meyers, 1996; Hautala et al., 2001; England and Huang, 2005), the assumption of a steady-state system does not necessarily apply.

Satellite-derived altimeter data provide a synoptic view of sea surface topography, but there are difficulties in relating sea-level slope to ITF values owing to the numerous islands along the altimeter track, the weak geostrophic relationship of low latitudes, the frictional effects within passages, and of course, the very energetic tidal environment (see Ray et al., this issue). *In situ* measurement of sea-level slope across key ITF passages with shallow pressure gauges provides another view of the ITF (Hautala et al., 2001), but as with the satellite altimeter, there is uncertainty as to how to relate sea surface slope to subsurface transport.

INSTANT

International Nusantara Stratification and Transport (INSTANT) is a multinational program to "do it right": to measure profiles of velocity, temperature, and salinity of the ITF with simultaneous mooring deployments in both the inflow and outflow passages over a three-year period. With such data, cost-effective monitoring schemes for the ITF can be formulated. INSTANT is a coordinated effort by the Republic of Indonesia, Australia, France, the Netherlands, and the United States, involving 11 instrumented moorings, one of which is in Timor Leste waters (Sprintall et al. 2004) (Figure 7). The first 1.5 years of mooring data were recovered in June and July 2005; all of the INSTANT moorings were redeployed for an additional 1.5 years. An ocean modeler said that "the INSTANT data set will be a benchmark that every global ocean modeler will need to match reasonably well to be taken seriously."

With an improved understanding of the ocean processes within the Indonesian seas and of the magnitude and variability of the ITF, we can anticipate enhanced understanding of the importance of the ocean's role in this region in governing ENSO and the Asian monsoon. Regional climate prediction may be improved, enabling informed management decisions regarding agricultural production and freshwater supplies, and preparation for climate-related forest fires. Building a quantitative understanding of the physical marine environment will provide a quantitative basis for modeling the complex ecosystems of the Indonesian seas, leading to improved fisheries and water-quality management and species preservation, as well as fur-

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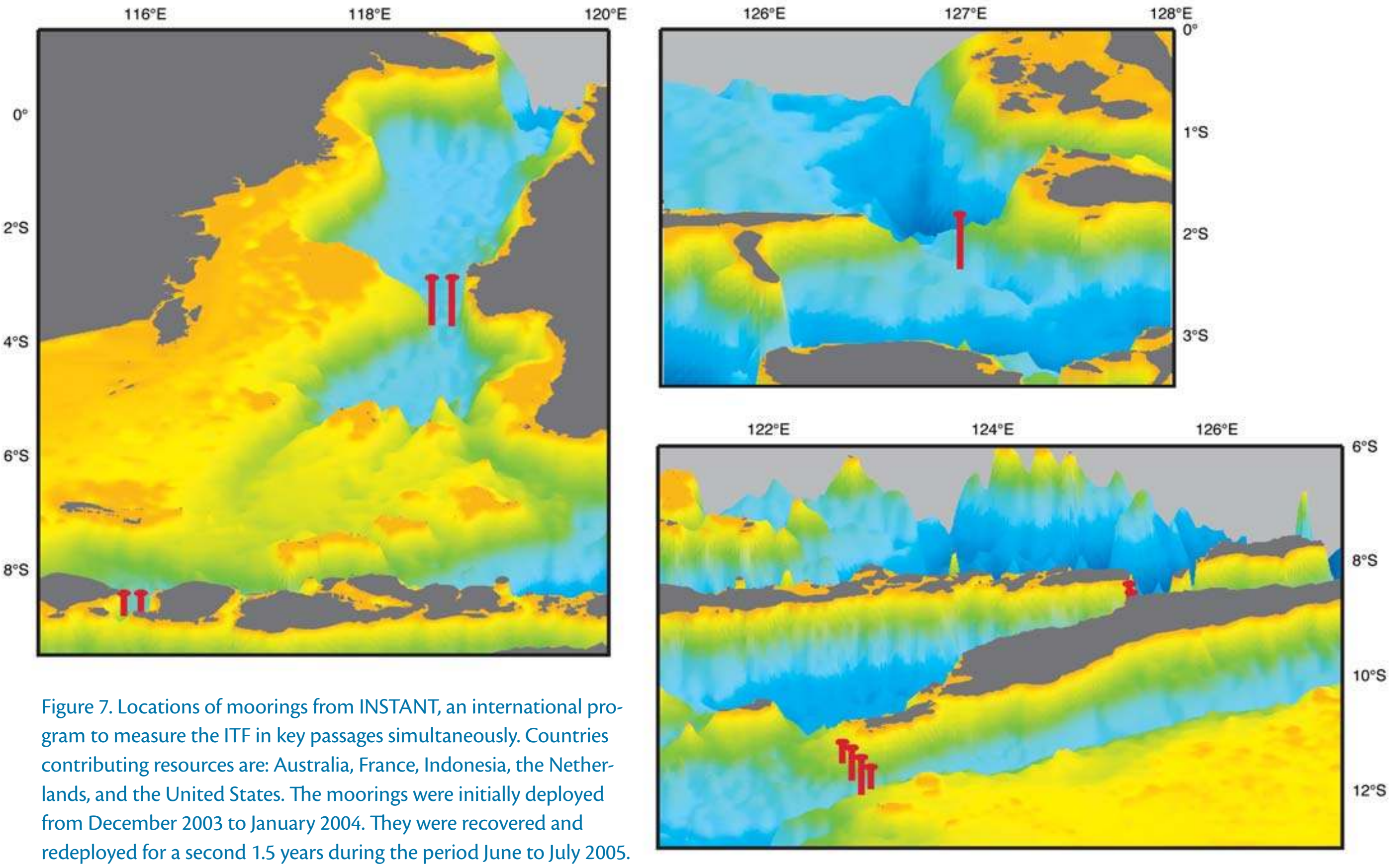

Figure 7. Locations of moorings from INSTANT, an international program to measure the ITF in key passages simultaneously. Countries contributing resources are: Australia, France, Indonesia, the Netherlands, and the United States. The moorings were initially deployed from December 2003 to January 2004. They were recovered and redeployed for a second 1.5 years during the period June to July 2005. Left Panel: There are two moorings in the Labani channel, near 3°S, of the Makassar Strait; there are two moorings within the Lombok Strait, near 8°S. Upper right panel: The Lifamatola passage mooring near 2°S is sited within the deepest channel of the passage. Lower right panel: Ombai passage, north of the eastern tip of Timor has two moorings; Timor passage southwest of Timor has four moorings.

ther understanding of the impact of marine platforms for mineral recovery. And, of course, one should not underestimate the importance of ITF (ocean) research solely for the pursuit of intellectual curiosity of our watery world. Great discoveries have an element of serendipity.

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