

Project Description

PACSWIN: Indonesian Throughflow: Pacific Source Water Investigation

1. The project and aims

The Indonesian seas provide a low latitude passage for various Pacific source water masses to pass through to the Indian Ocean. The Indonesian Throughflow (ITF) represented by an admixture of these sources produces a band of relatively low temperature, salinity and oxygen with high silicate, phosphate and nitrate across the Indian Ocean near 10°S. The ITF plays a crucial role in Indo-Pacific heat and freshwater budgets and perhaps to the global thermocline circulation. Gordon and Fine 1996 and Ilahude and Gordon 1996 identified the water mass sources of the waters observed within the Indonesian seas [extending the seminal study of Wyrki, 1961], but they did not trace the paths back to the Pacific Ocean source regions. To understand the role of ITF in global ocean circulation and climate change, it is essential to discuss its water mass structure in a much broader spatial view than the Indonesian seas themselves. PACSWIN proposes a thorough investigation of water-mass inventory in the Indonesian seas and trace the paths by which the Pacific waters reach the Indonesian seas.

Previous studies of water-mass structure in the Indonesian seas were largely based on temperature and salinity data. However, because of the many water masses contributing to the ITF composition, and of the complicated mixing history of these waters within and en route to the Indonesian seas, it is important that more parameters are explicitly employed, such as the nutrients. This is particularly true in the eastern route of the ITF and deep water where a T-S diagram cannot resolve well the South Pacific sources. The eastern path has a deeper sill limit of about 1400 m than the western path of about 600 m, and permits a deep water inflow from the Pacific. Nutrients data have not been properly used in the Indonesian seas, partly because of their non-conservativeness properties, but by removing the effect of biological consumption nutrients can be converted to useful conservative variables.

In the last decade or so, several national and international projects were carried out in the ITF and neighboring regions, such as Western Equatorial Pacific Ocean Circulation Study (WEPOCS; Lindstrom et al., 1987), Tropical Ocean Global Atmosphere (TOGA), World Ocean Circulation Experiment (WOCE), Java Australia Dynamic Experiment (JADE; Fieux et al., 1994), and by the ARLINDO program from 1993 to 1998 within the Indonesian seas (Gordon, 1995; Ilahude and Gordon, 1995, 1996; Gordon and Fine, 1996). With gathering of these new data we have an unique opportunity to address the poorly understood pathways and associated mixing experienced by North and South Pacific water masses en route to the Indonesian seas.

The PACSWIN project aims at using the updated hydrography in order to address several currently elusive questions:

- *How many water types of Pacific origin can be identified within the Indonesian seas and what are their spreading characteristics as accomplished by advection and mixing within the Indonesian seas?*
- *Where do the ITF waters come from: Where are their formation regions and what are the pathways that eventually carry them into the Indonesian seas?*
- *How are Pacific source waters transformed en route to and within the Indonesian seas?*

- *What is the relative importance of the various ITF source waters to interocean heat and freshwater transport?*

Addressing these objectives will be accomplished by detailed water-mass analysis using updated hydrography, especially new data gathered within the last decade, and a set of novel Indo-Pacific source water mixing and water-mass transformation models.

2. Background

2.1 A local view of water mass structure and transport

The Indonesian seas connect the Pacific with the Indian Ocean. As shown in Fig. 1, the primary source of ITF is from the North Pacific thermocline and intermediate water carried by the Mindanao Current into the Sulawesi Sea, through the Makassar Strait into the Flores Sea and Banda Sea and finally to the eastern Indian Ocean via either side of Timor with a small amount out from Lombok Strait (Wyrтки, 1961; Gordon, 1986; Gordon and Fine, 1996). Additional ITF source in the lower thermocline, intermediate and deep water, of the direct South Pacific origin, is derived through the eastern route, via the Maluku and Halmahera Seas into the Banda Sea. With careful examination of deep topographic barriers, Gordon (2001) and Gordon et al. (2003) concluded three possible paths of Pacific water into the northern Indonesian Seas as shown in Fig. 1.

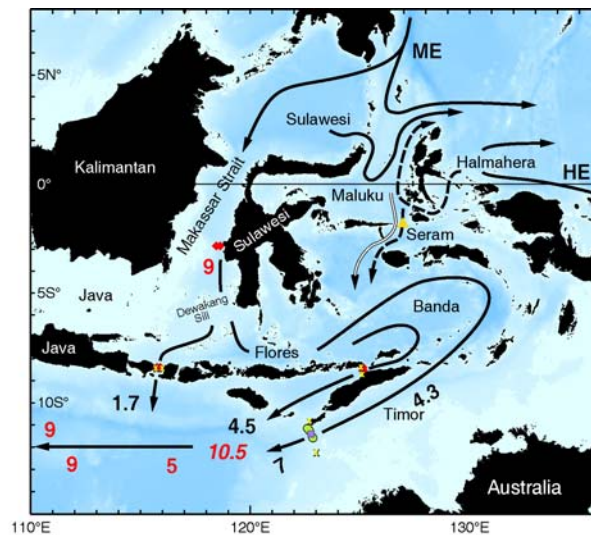


Figure 1. Schematic of Indonesian Throughflow pathways (modified from Gordon, 2001).

In water-mass property, North and South Pacific sources are most distinguishable in salinity field, indicating a low salinity in North Pacific source and a high salinity in South Pacific source (Ilahude and Gordon, 1996). Chlorofluorocarbon (CFC-11 and CFC-12) decreases monotonically with depth showing a major stratification within the Indonesian seas but does not delineate vertical water-mass structure

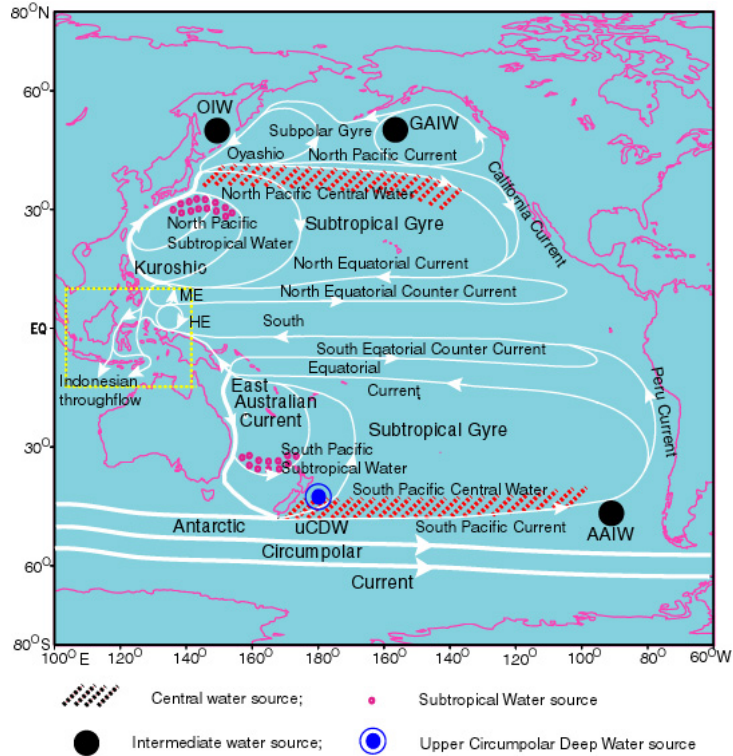
(Gordon and Fine, 1996). Oxygen shows generally a high value in South Pacific source and a low value in North Pacific source below the upper thermocline on isopycnal surfaces mapped to follow the major water mass cores by Hautala et al. (1996). Situation is reversed in the upper thermocline; North Pacific source shows a relatively higher oxygen. Within the Indonesian seas, Ffield and Gordon (1992) discovered that oxygen curves could not be used to distinguish between sources, suggesting that an oxygen consumption must be considered. Likewise, nutrients have not been favorably used for tracing Pacific source waters because of their non-conservativeness, although ITF itself is often referred to be a high nutrients water in the Indian Ocean water mass category (You and Tomczak, 1993; You, 1997; You et al., 2003).

The thermohaline [T/S] stratification, the water mass structure of the Indonesian seas can be summarized as upper thermocline water (S_{\max} , $24.5\sigma_\theta$, at 130 m), main thermocline water (high S and O_2 , at 220 m), North Pacific Intermediate Water (NPIW; S_{\min} , $26.5\sigma_\theta$, at 300 m), Antarctic Intermediate Water (AAIW; low S, high O_2 , $27.25\sigma_\theta$, at 800 m) and deep water (high S, $27.4\sigma_\theta$, about 1000 m; Ilahude and Gordon, 1996; Ffield and Gordon, 1992; Hautala et al., 1996). However, remote sources of Pacific origin such as the main thermocline, AAIW and deep waters are not well resolved since they do not show property extrema due to long distance transformation and dilution. Spatially, the water-mass structure in the western route is better resolved than the eastern route, because the western route is predominated by North Pacific sources and is shallower with sill control of about 600 m (implying less water types involved). The eastern route is mixed by both North and South Pacific sources whose marking relies on spatial salinity contrast and therefore, cannot resolve so many water types. Given its high salinity appearance, South Pacific source is implicated in the Halmahera and Maluku Seas (Ffield and Gordon, 1992; Gordon et al., 2003). However, its ultimate join with ITF is still very much controlled by the Lifamatola Passage, a gate leading to the Seram and then Banda Sea. Overall, the remote Pacific source waters, the water masses in the eastern ITF route and deep water as a whole need to be better resolved in extended property fields. For example, it is still unclear whether or not there is a shortcut by North Pacific source from the Mindanao Current (MC) southward along east of Sangihe Ridge to the Maluku Sea, and a circulate path by south pacific source to the MC through the equatorial current system (Godfrey, 1996), and how much South Pacific sources successfully cross the Lifamatola Passage although evidence is building up that South Pacific origin does get into the Halmahera and Maluku Seas (Cresswell and Luick, 2001; Luick and Cresswell, 2001). The PACSWIN will examine the water-mass structure with extended variables including converted conservative variables.

The ITF transport given in Fig. 1 is based on updated estimates (Gordon, 2001). The main throughflow path is accomplished by passing through the Makassar Strait within the thermocline layer with a transport of 9 Sv ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$). The continuation of the southward transport is limited by a shallow Dewakang Sill of 680 m. About 1.7 Sv of throughflow water escapes to the Indian Ocean through the 300 m deep Lombok Strait. Most flow continues eastward to the Banda Sea and enters the Indian Ocean over the deep gaps of the Lesser Sunda Arc on either side of Timor with almost the same amount of transport, 4.5 Sv through Ombai Strait into the Sawu Sea and 4.3 Sv into the Timor Sea. The east route contributes to a small portion of 1.5 Sv through Lifamatola Passage via the Halmahera and Maluku Seas, consisting of mainly South Pacific sources. This gives a total mean ITF transport of 10.5 Sv, though close to the mean of previous estimates of 2-22 Sv (Godfrey, 1996; Fieux et al., 1994), but is less divergent. Improvement is made by recent mooring programs such as ARLINDO (Gordon et al., 1998; Gordon and Susanto, 1999; Ffield et al., 2000; Susanto et al., 2000). In spite of a number of measurements undertaken in the Indonesian seas region, a serious shortcoming appears, i.e., their lack of temporal coherence. The data cover different time periods and depths in different passages leading to ambiguity of ITF estimates. Even the transformation of thermohaline can be misinterpreted. This is the initiative of the INSTANT program to resolve the shortcomings. The PACSWIN will attempt to quantify ITF transport contributed by individual source water types.

2.2 A large-scale view of ITF in the Pacific Ocean water-mass structure and circulation

Figure 2. A schematic of the Pacific Ocean upper circulation, source water masses and linkage with the ITF.



The Indonesian seas provide Pacific warm water a way out to the Indian Ocean. In a two-layer conveyor belt scheme (Broecker, 1991; Gordon, 1986; Schmitz, 1996), the cold water route of Circumpolar Deep Water (CDW) and Antarctic Bottom Water (AABW) flows as deep western boundary currents to the northern Pacific and upwells in subpolar region to link with the warm water route. The return route is in main thermocline and intermediate waters, that is, the North Pacific Central Water (NPCW) and NPIW in general (Fig. 2). Since the Indonesian seas have a deepest sill of about 1400 m in the western Timor Strait (although the Ombai Strait has a sill depth of 3250 m, embarking of ITF to the Savu Sea is affected by a shallower sill of 1200 m farther west; Gordon et al., 2003), the ITF provides primary a connection of warm water route. However, one should keep in mind that the sill depth of the east route is deep enough for upper CDW (uCDW) to pass through as its source shoals from about 1800 m east of New Zealand to slightly below 1000 m in the northern Indonesian seas. Some of the Indonesian basins are as deep as a few thousands meters. Sources to fill these deep basins need to be addressed. The PACSWIN will investigate the pathway of uCDW to the Indonesian seas.

Possible connection of the Indonesian seas water masses with Pacific's sources and large-scale circulation is schematically presented in Fig. 2. As seen, at least 6 sources from the North and South Pacific may contribute to the ITF, which are described, respectively, as follows.

The tropical salinity maximum water: This water, with a typical salinity maximum of 34.5-34.8 in the Indonesian seas, a core depth of about 130 m or density of $24.5\sigma_{\theta}$, and contributing to perhaps about one third of the total thermocline transport, can be traced to both North and South Pacific western subtropical gyre region where a salinity maximum is found. The North Pacific source is formed in the North Pacific

subtropical front and carried first by recirculation of the Kuroshio Extension and then by the North Equatorial and MC currents (Fig. 2). The core density $24.5\sigma_\theta$ outcrops at about 30°N , which is the center of the subtropical front of $28^\circ\text{-}35^\circ\text{N}$ (at 140°E) defined by Roden (1975). The original winter surface salinity maximum in the western subtropical gyre of the North Pacific is about 0.8 less than that in the South Pacific. Therefore, although the observed relative low salinity of North Pacific Subtropical Water (NPSW) in the Indonesian seas may ascribe to dilution by local high rainfall, its origin is actually already at a lower level than the South Pacific source. In the South Pacific, the Tasman front is observed in a similar latitudinal position of $30^\circ\text{-}36^\circ\text{S}$ with a mean of 33°S but is much weak with strong variability (Mulhearn, 1987). The winter outcrop of $24.5\sigma_\theta$ can be found at about $33^\circ\text{-}35^\circ\text{S}$. The path of South Pacific Subtropical Water (SPSW) in the western subtropical gyre and then in the South Equatorial Current (SEC) through the Vitiaz Strait is rather clear (Lindstrom et al., 1987) (Figure 2). The salinity in the South Pacific subtropical gyre is generally high.

The main thermocline water: The main thermocline or Central Water is formed by late winter subduction at the surface along the Subtropical Convergence Zone of the South Pacific at about 40°S and south of the Subarctic-tropical frontal zone (SATFZ) of the North Pacific at 40°N (Iselin, 1939; Stommel, 1979). Central Water has a typical maximum in salinity and oxygen at the formation region, showing an equatorward tongue. The South and North Pacific Central Waters are carried by subtropical gyre circulation to the equatorial current system and then to the Indonesian seas in the North and South Equatorial Currents (Fig. 2). Central Water has a core density of about $26.0\sigma_\theta$ at a depth of 300-400 m with a salinity maximum of about 35.0 in the South Pacific and 34.2 in the North Pacific and an oxygen maximum of about 5.5 ml l^{-1} in both North and South Pacific at the Ekman subduction zone of the subtropical convergence. It shoals to about 220 m in the Indonesian seas with a moderate salinity of 34.5 and oxygen of 3 ml l^{-1} . Salinity in the South Pacific decreases but increases in the North Pacific, while oxygen of both oceans decreases towards the Indonesian seas. The water-mass property becomes undistinguishable in the Indonesian seas with a moderate salinity value lying in between the NPTW and SPTW salinity maximum and intermediate water salinity minimum. Oxygen profile shows stratification in main thermocline like CFC11 and CFC12 (Field and Gordon, 1992). To delineate Central Water thus relies upon nutrients, which increase from a minimum at formation region to a maximum in the Indonesian seas, implying an age increase.

The intermediate water: Intermediate water formation in the North and South Pacific differs greatly. NPIW is confined only to the subtropical gyre of the North Pacific with core density of $26.8\sigma_\theta$ at about 600 m which is much shallower than AAIW in the South Pacific whose core density is at $27.25\sigma_\theta$ and a depth of 900 m. AAIW enters the South Pacific from the southeast Pacific and crosses the equator in the western equatorial Pacific through New Guinea Coastal Undercurrent (NGCUC) (Tsuchiya, 1991; Lindstrom et al., 1987; Fine et al., 1994; Hautala et al., 1996). While AAIW is formed by winter convection as its core density outcrops in the Southern Ocean, NPIW is not formed by open ocean convection since its core density is not found in winter surface density of the whole North Pacific (Sverdrup et al., 1942; Reid, 1965; Talley, 1993). Rather, it is formed by diffusive convection in the subpolar region and then transformed by cabbeling across the SATFZ into the subtropical gyre (You, et al., 2000; You, 2003a, 2003b). Two NPIW sources are defined in the subpolar region, the Okhotsk Sea Intermediate Water (OIW) and Gulf of Alaska Intermediate Water (GAIW) (You, et al., 2000), while in the South Pacific AAIW is the only source (Fig. 2). The salinity minimum water of the Indonesian seas at 300 m with a density of $26.5\sigma_\theta$ is derived from the transformed NPIW, exported from the subtropical gyre of the North Pacific through the MC (Bingham and Lukas, 1994; You, 2003). The decrease of its core density from 26.8 to $26.5\sigma_\theta$ is caused by strong equatorward attenuation resulting in a buoyancy increase owing to heat gain. The same depth for South Pacific water is, however, still in the lower thermocline, which can be identified as high temperature and salinity in the eastern Indonesian seas. AAIW is observed in the Maluku Sea at about 800 m as a low salinity and oxygen (Gordon et al., 2003). The oxygen minimum is observed, instead, because the AAIW core density of $27.25\sigma_\theta$, which though follows an oxygen maximum tongue in the South Pacific, crosses into an oxygen minimum layer immediately below NPIW in the North Pacific.

The uCDW water: The uCDW can be identified as a temperature minimum water in the South Atlantic at a potential density of $27.40\sigma_0$ (You, 2002). In the Pacific, the temperature minimum is not observed but uCDW is marked by distinct oxygen minimum and nutrients maxima. The path of uCDW into the Pacific is via east of New Zealand and through deep western boundary current (Fig. 2). Its crossing of the equator is likely by east of New Britain rather than the Vitiaz Strait because the sill depth of 1000 m in the Vitiaz Strait is too shallow for uCDW. The uCDW is likely to fill up the deep basins of the Indonesian seas below 1000 m as well. Very little is known about uCDW's pathway, water mass characteristic and transport to the Indonesian seas.

3. Design of the PACSWIN project

3.1 Hydrographic data: The PACSWIN is a data analysis project, making effective use of existing data. Its success relies heavily on a good coverage of hydrographic data. Following the successful operation of World Ocean Circulation Experiment (WOCE), data coverage for the entire Pacific Ocean has been largely improved, particularly in the South Pacific. You et al. (2000) have shown a well covered hydrographic station map with over 100,000 data points including most of the North Pacific WOCE stations in the NPIW layer. In the thermocline layer hydrography stations increase to over 300,000. In the South Pacific, with selected cruise sections Gouretski and Jancke (1999) showed over 25,000 historical hydrographic stations. These historical archive along with updated hydrography and the whole Pacific WOCE stations (Fig. 3) provide a unprecedented hydrographic data set, which satisfies PACSWIN's data requirement for the large-scale analysis of the Pacific Ocean.

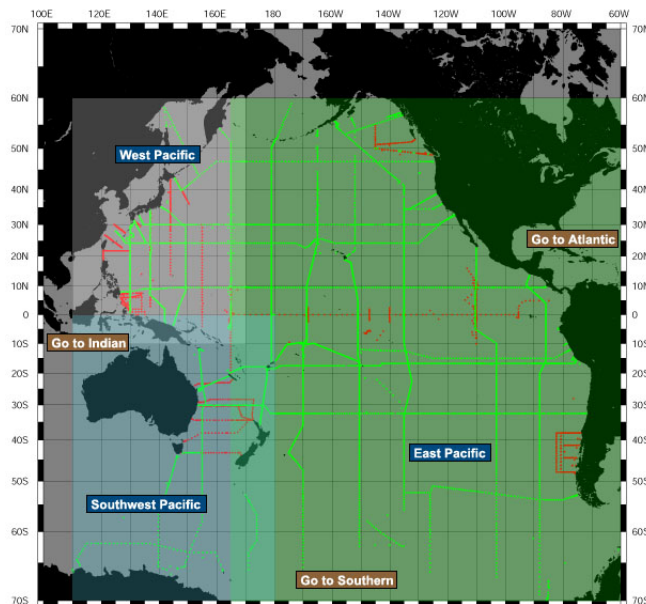


Figure 3. The Pacific WOCE hydrographic stations (adapted from WHO).

However, for the Indonesian seas region, $15^{\circ}\text{S}-10^{\circ}\text{N}$, $114^{\circ}-136^{\circ}\text{E}$, one is concerned whether or not sufficient hydrographic data are available for the PACSWIN, in particular the nutrients data. Updated hydrography stations for the deep water Indonesian seas (region within the square, Fig. 4) and adjacent regions are shown in Fig. 4. As seen, the ITF region has good data coverage with stations of over 7,000.

Although most stations are CTD stations containing pressure, temperature and salinity, oxygen and nutrients data are also reasonably well covered. In order to view the detailed data coverage of individual variable especially for oxygen

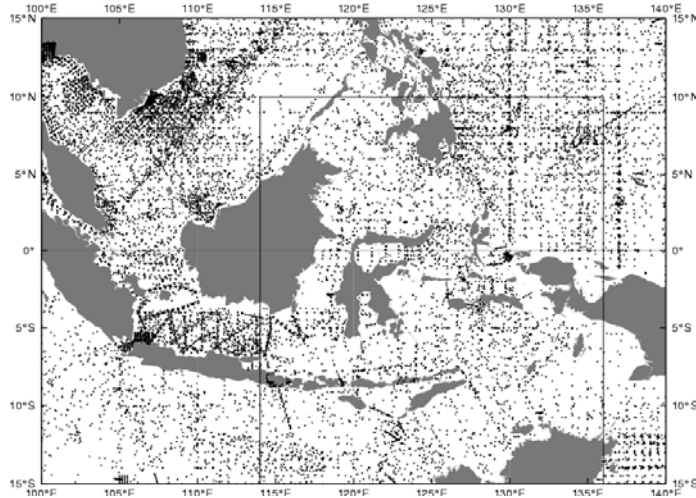


Figure 4. Updated hydrographic stations in the ITF and adjacent region.

and nutrients, stations are mapped as light gray dots on the neutral density surface $\sigma_N=24.5$ contour maps (Fig. 5). Figures 5a-5c show a rather good data coverage for pressure, temperature and salinity. For oxygen, at least 4000 data points are found in Fig. 5d, followed by phosphate of about 3000 points in Fig. 5e, silicate of about 2000 points in Fig. 5f and nitrate of about 1000 points in Fig. 5g. Although the number of data stations decrease with depth, acceptable data coverage is found until the uCDW depth of about 1100 m. Thus, overall data requirement for the PACSWIN in the Indonesian seas region can be satisfied.

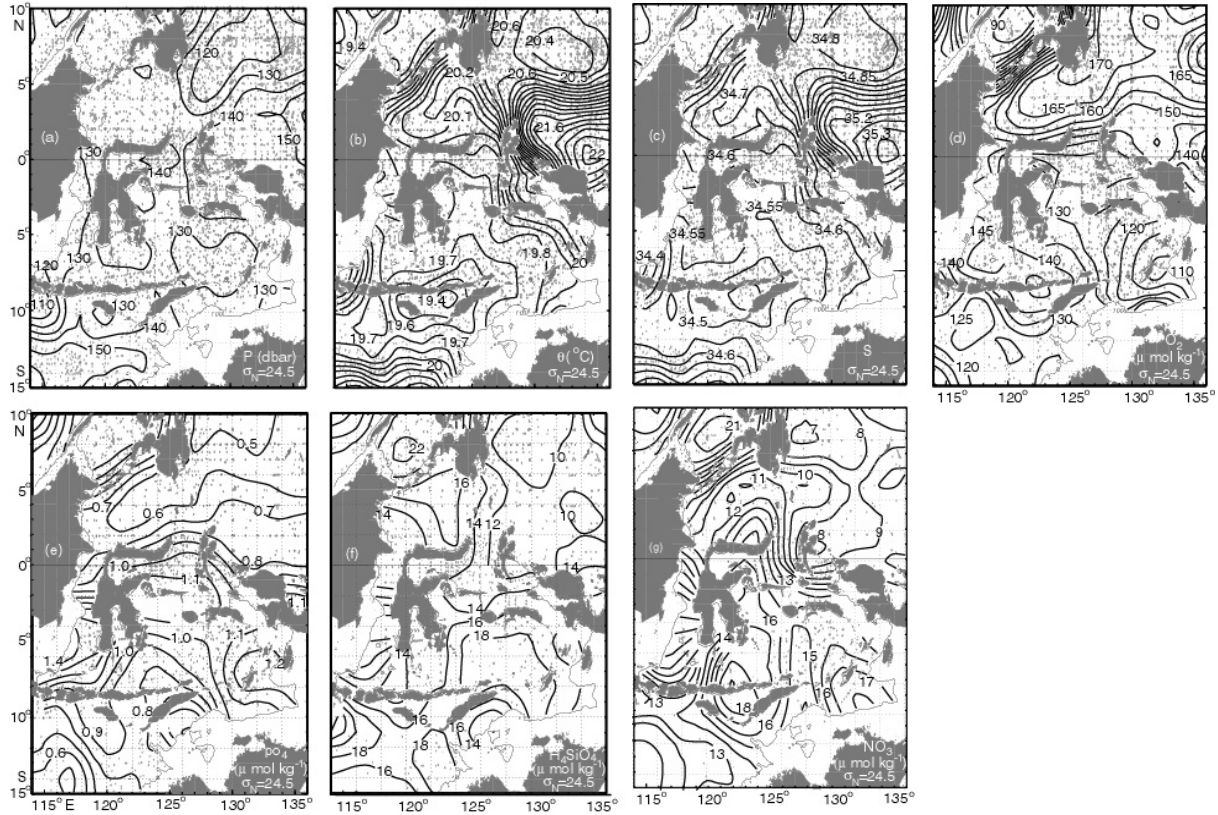


Figure 5. Contour plotting of property distribution on neutral density surface $\sigma_N=24.5$: (a) pressure (P, dbar), (b) potential temperature (θ , °C), (c) salinity (S), (d) dissolved oxygen (O_2 , $\mu\text{ mol kg}^{-1}$), (e) phosphate (PO_4 , $\mu\text{ mol kg}^{-1}$), (f) silicate (H_4SiO_4 , $\mu\text{ mol kg}^{-1}$) and (g) nitrate (NO_3 , $\mu\text{ mol kg}^{-1}$). Corresponding data points are marked with light gray.

3.2 Methodology

(a) Choice of neutral density surfaces. Water-mass mixing in the ocean is believed to occur along neutral density surfaces since water parcels move along such surfaces have no work required to be done to overcome buoyancy restoring force (McDougall, 1987; You and McDougall, 1990). This is important for PACSWIN to trace Pacific source waters. Neutral density surfaces have already been mapped to follow NPIW core and boundary (You et al., 2000; You, 2003a). You et al. (2000) argue that neutral density surface is more accurate than potential density surface in describing NPIW formation, transformation and transport. With the hydrographic data in Fig. 4, five neutral density surfaces will be selected, $\sigma_N=24.5$ (about $24.5 \sigma_\theta$) to follow the upper thermocline salinity maximum of the Indonesian seas to its source region in the western subtropical gyre of the Pacific, $\sigma_N=26.0$ (about $26.0 \sigma_\theta$) to follow the main thermocline or Central Water of the Pacific, $\sigma_N=26.5$ (about $26.5 \sigma_\theta$) to trace the salinity minimum of the Indonesian seas to the upper NPIW in the northern North Pacific, $\sigma_N=27.4$ (about $27.25 \sigma_\theta$) to following AAIW core from the South Pacific, and $\sigma_N=27.6$ (about $27.40 \sigma_\theta$) to follow the oxygen minimum of uCDW east of New Zealand, a northward branch of Antarctic Circumpolar Current (ACC). How these neutral density surface span the water mass core in the

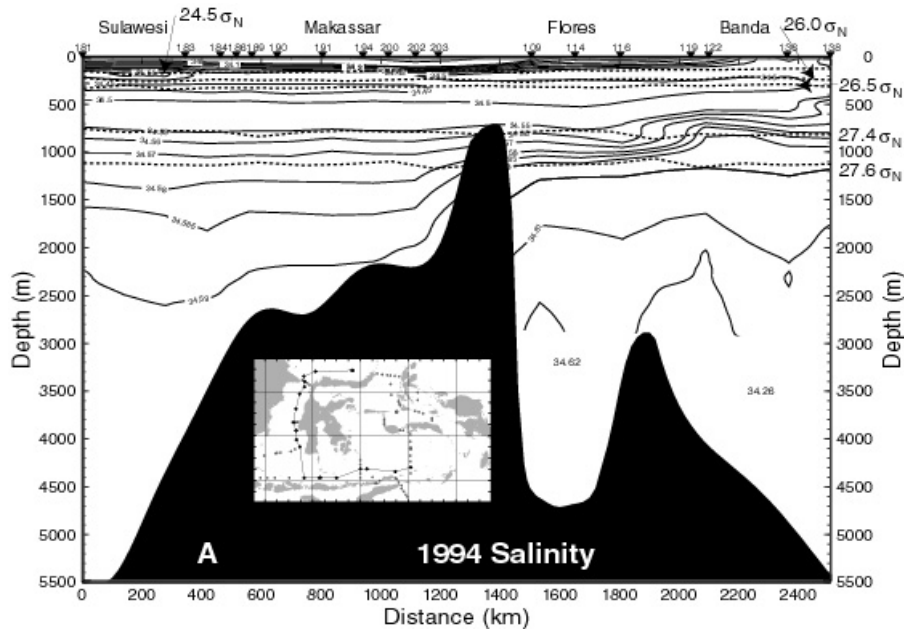


Figure 6. A salinity section in the western route of the ITF with chosen neutral density surfaces (marked in short dashed line).

western route of ITF is shown in a salinity section in Fig. 6 (short dashed line). The $\sigma_N=24.5$ and $\sigma_N=26.5$ surfaces well follow the NPSW and NPIW salinity extrema. NPIW seems to be the lowest possible water mass to pass the west route as the neutral density surface $\sigma_N=27.4$ for AAIW lies below the Dewakang Sill. Spanning the source water mass cores by these same surfaces in the Pacific is shown in the corresponding P15 salinity section (Fig. 7). The shallowest salinity maximum is well followed by the $\sigma_N=24.5$ surface which outcrops in midlatitude. The main thermocline salinity maximum is represented by the $\sigma_N=26.0$ surface outcropping in the subtropical convergence at latitude of 40° . Although $\sigma_N=26.5$ surface follows well the salinity minimum in the Indonesian Seas, it does not follow the NPIW salinity minimum tongue which is represented by a deeper surface $\sigma_N=26.9$ (You et al., 2000). The reason is that NPIW is confined only to north of 15°N (NEC) and ITF contains the exported NPIW through a bifurcation branch of NEC to the MC. To deal with NPIW, boundary surfaces will be carefully chosen in the PACSWIN by including an additional $\sigma_N=26.9$ surface. In contrast, the chosen $\sigma_N=27.4$ surface follows AAIW rather well in the South Pacific north of 40°S though it lies deeper in the South Ocean. It is also seen that $\sigma_N=26.5$ surface crosses into the lower thermocline of the South Pacific and $\sigma_N=27.4$ surface extends to an oxygen minimum below NPIW. The deepest surface $\sigma_N=27.6$ is mapped to follow uCDW characterized by an oxygen minimum which therefore has to be examined in an oxygen section of P15 (not shown).

As an example in Fig. 5, properties mapped on neutral density surface $\sigma_N=24.5$ show a clear path of Pacific source waters into the Indonesian seas from western subtropical gyre with a good contrast between North and South Pacific sources. Nutrients give additional useful water-mass characteristics to source waters, especially the phosphate (Fig. 5e). The North Pacific source shows a remarkable tongue of low values in pressure, temperature, salinity, phosphate, silicate and nitrate but high oxygen extending to the Makassar Strait. The South Pacific source has opposite water-mass properties. Since the surface is shallow at 130 m, effect of biological consumption will be removed. You et al. (2003) demonstrated that

conversion of nutrients to conservative variables could make nutrients to be useful tracers. We have briefly examined nutrients distribution in deeper surfaces and found that nutrients do differentiate and trace source water masses better than a T-S diagram.

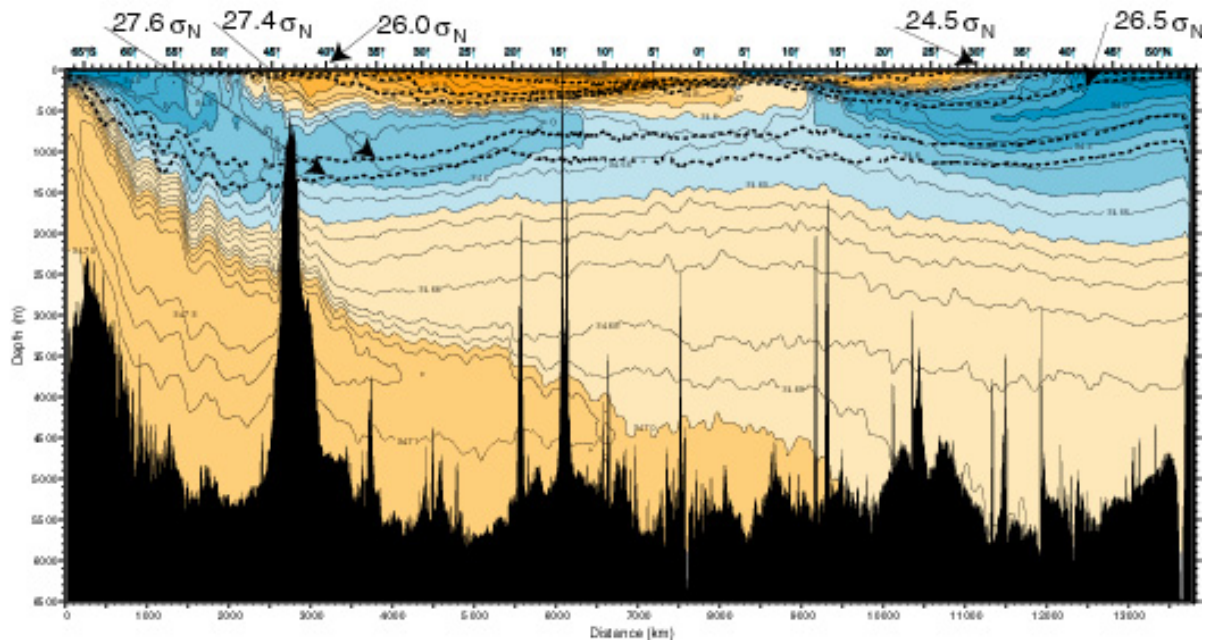


Figure 7. WOCE P15 salinity section marked with the same neutral density surfaces mapped in Fig. 6 (marked by short dashed line).

In Table 1, water-mass layers are defined to span the Indonesian seas' water column into 5 layers spanned by neutral density surfaces following the source water cores and boundaries. These layers are chosen so that spreading paths of Pacific source waters would most probably take.

Table 1. Definition of water mass layers associated with Pacific sources, spanned by neutral density surfaces in the Indonesian seas

Water masses	Defining neutral density surfaces
Upper thermocline layer (NPSW and SPSW)	Upper boundary: bottom of mixed layer; Core: $\sigma_N=24.5$; Lower boundary: $\sigma_N=25.5$
Main thermocline (North and South Pacific Central Waters (NPCW and SPCW))	Upper boundary $\sigma_N=25.5$; Core at $\sigma_N=26.0$; Lower boundary: $\sigma_N=26.2$
NPIW and lower thermocline of the South Pacific	Upper boundary: $\sigma_N=26.2$; Core: at $\sigma_N=26.5$; additional surface at $\sigma_N=26.9$ to follow the NPIW core in the North Pacific;

	Lower thermocline: $\sigma_N=27.2$
	Upper boundary: $\sigma_N=27.2$;
AAIW and oxygen minimum layer below NPIW	Core: at $\sigma_N=27.4$;
	Lower boundary: $\sigma_N=27.55$
	Upper boundary: $\sigma_N=27.55$;
uCDW and bottom water	Core : at $\sigma_N=27.6$;
	Lower boundary: bottom of the Indonesian seas

(b) Establishment of source water mass mixing models. Source water mass mixing model for the PACSWIN is similar to those used by PI You's previous studies such as You et al. (2003) for quantifying the interocean exchange of intermediate water around southern Africa and You (2003a) for quantifying the NPIW source water contribution by OIW and GAIW (see Fig. 2). The methods include source water types defined and tested in ocean basin water-mass structure and circulation, a set of hydrographic data as chemical and dynamical tracers and linear water-mass mixing equations underdetermined by input source water types and parameters. Output result or solution of the model is a quantitative description of individual source water contribution in percentage fractions. When the fractions are mapped on neutral density surfaces, source water spreading path can be inferred. Water mass, heat and fresh water transports can thus be quantified as individual source water contribution. The method was first applied to the Indian Ocean thermocline circulation and ventilation by You and Tomczak (1993). The linear system for any water sample is written as

$$G\mathbf{x}_g - \mathbf{x}_v = \mathbf{R}, \quad (1)$$

where G is a matrix containing the parameter values that define source water types, \mathbf{x}_v is a vector containing parameter values for observational sample, \mathbf{x}_g is a vector containing the relative contributions or mixing ratios of the source water types to the sample, and \mathbf{R} is a vector containing the residual of water-mass conservation. The water-mass conservation equation is

$$\sum_{k=1}^m (\mathbf{x}_g)_k = 1, \quad (2)$$

where $(\mathbf{x}_g)_k$ represents individual contribution of source water type and m is the total number of source water types. We also have \mathbf{x}_g , where

$$0 \leq \mathbf{x}_g \leq 1. \quad (3)$$

With the available number of variables in Fig. 5, we will derive at least 6 parameters (some will be replaced by converted conservative tracers) including calculated dynamical tracer with pressure, potential temperature and salinity to resolve mixing system of about 7 source water types or 3 to 4 source water masses. Given the total number of source water types in Table 1 which are beyond the number of which system equation (1) can resolve. Here we have not included the Indian Ocean sources yet, which will be combined to the Indo-Pacific mixing model. A solution to the problem is to solve the source water

mixing layer by layer, “a layered mixing model”. Thus, for each model run the number of source water types is reduced to about 3-4 which can be solved by equation (1). For example, the main thermocline source waters include North and South Pacific Central Waters, Indian Central Water and Red Sea Water (RSW) (including Persian Gulf Water) which give 7 source water types if RSW is treated as a single water type like You and Tomczak (1993). Thus, with 6 parameters and equation (2) the mixing model (1) can be solved. The corresponding Indian Ocean source water types to Table 1 have already been defined in PI You’s previous studies (You and Tomczak, 1993; You, 1997, 1998, 2000).

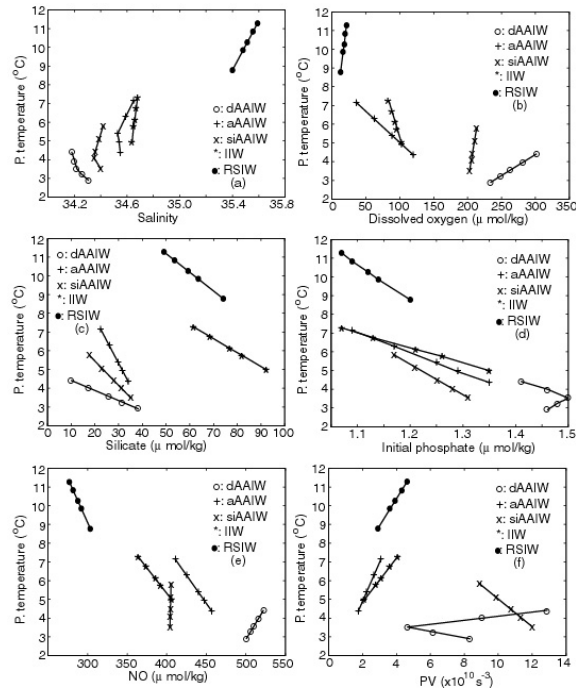


Figure 8. Defined model source water types in property-property plots (each marker corresponds to one neutral density surface), denoted by symbol “o” for dAAIW, “+” for aAAIW, “x” for siAAIW, “*” for IIW and “•” for RSIW, (a) θ vs S, (b) θ vs O_2 , (c) θ vs H_4SiO_4 , (d) θ vs PO_4^0 , (e) θ vs NO and (f) θ vs PV (adapted from You et al., 2003).

The feasibility of applying mixing model (1) to quantify the Indo-Pacific interocean exchange is supported by You’s previous study for quantifying the interocean exchange of intermediate water around southern Africa (You et al., 2003, and Fig. 8). As shown in Fig. 8, You et al. used 7 parameters, potential temperature, salinity, dissolved oxygen, silicate, initial phosphate, NO and potential vorticity (PV), to resolve 5 source water masses mixing including the Drake Passage AAIW source (dAAIW), South Indian AAIW (siAAIW), Indonesian seas intermediate water source (IIW), intermediate RSW (RSIW) and aged/transformed AAIW (aAAIW). To PACSWIN, IIW is not a source but a solution.

(c) Quantifying the dianeutral mixing and water-mass transformation. The above source water mixing model does not resolve processes how a source water is transformed to the Indonesian seas but documents the results of mixing since it is based on past record of hydrographic observations. Water-mass transformation of Pacific sources to the ITF will be described by a set of equations of water-mass transformation and dianeutral velocity

$$\begin{aligned} \theta \Big|_n + [V - h^{-1} \nabla_n(hK)] \cdot \nabla_n \theta = K \nabla_n^2 \theta + DgN^{-2} \theta_z^3 \beta \frac{d^2 S}{d\theta^2} \\ + F_z^\theta \frac{[R_\rho - r]}{[R_\rho - 1]} + KgN^{-2} \theta_z \{C_b \nabla_n \theta \cdot \nabla_n \theta + T_b \nabla_n \theta \cdot \nabla_n P\} \end{aligned} \quad (4)$$

$$\begin{aligned} S \Big|_n + [V - h^{-1} \nabla_n(hK)] \cdot \nabla_n S = K \nabla_n^2 S + DgN^{-2} \theta_z^3 \alpha \frac{d^2 S}{d\theta^2} \\ - F_z^S \frac{[R_\rho - r]}{[R_\rho - 1]} + KgN^{-2} S_z \{C_b \nabla_n \theta \cdot \nabla_n \theta + T_b \nabla_n \theta \cdot \nabla_n P\} \end{aligned} \quad (5)$$

and

$$\begin{aligned} [e - D_z] g^{-1} N^2 = D[\alpha \theta_{zz} - \beta S_{zz}] + [\beta F_z^S - \alpha F_z^\theta] \\ - K \{C_b \nabla_n \theta \cdot \nabla_n \theta + T_b \nabla_n \theta \cdot \nabla_n P\} \end{aligned} \quad (6)$$

where h is a distance between two closely-spaced neutral surfaces, K is the lateral diffusivity of scalars, D is the vertical turbulent diffusivity, V is the horizontal velocity vector, $R_\rho = \alpha \theta_z / \beta S_z$ is the density ratio, $r = \alpha F_z^\theta / \beta F_z^S$ is the ratio of the double-diffusion flux divergences of heat and salt, e is the dianeutral velocity, C_b is the cabbeling parameter $[\partial \alpha / \partial \theta + 2(\alpha / \beta) \partial \alpha / \partial S - (\alpha / \beta)^2 \partial \beta / \partial S]$, T_b is the thermobaric parameter $[\partial \alpha / \partial P - (\alpha / \beta) \partial \beta / \partial P]$, g is the gravitational acceleration and $N^2 \equiv g[\alpha \theta_z - \beta S_z]$ is the square of the buoyancy frequency. These equations have been applied recently to NPIW by You (2003b). The dianeutral velocity equation (6) will be used along with vertical velocity W derived from thermal wind relation to estimate the total cross neutral surface transport in the Indonesian seas.

3.3 Work plan and expected outcomes

Work plan. The PACSWIN is an intensive two year data analysis project through 2005 to 2006. Its work plan is outlined in Table 2:

Table 2. Work plan for the PACSWIN project

Project year	Work taken
2005	Large data processing and analysis to derive a water mass inventory of the Indonesian seas, identify Pacific source waters and define source water types
2006	Applying water-mass mixing model to get results of source water mixing fractions and pathways. Applying water-mass transformation model to quantifying source water transformation to the Indonesian seas.

Outcomes. The PACSWIN will address the proposal's objective through the following results:

- An inventory of end water types of Pacific origin in the Indonesian seas;
- Source water mixing fractions in the Indonesian sea region;
- Identification of Pacific source waters, their formation regions and pathways;
- A quantitative description of volume, heat and fresh water transports contributed by individual sources;
- Quantification of Pacific source water transformation;
- Total dianeutral mixing and transport in the Indonesian seas including the component by dianeutral velocity e and the component contributed by vertical velocity W from thermal wind relation.

The results will be presented in about five papers corresponding to the five defining water-mass layers in Table 1, two in 2005 and three in 2006.

4. Significance

4.1 Significance and innovation: The ITF is considered as a key component of the Pacific and Indian (perhaps global as well) ocean circulation, heat and freshwater transport, ENSO and of the climate system. The global significance of ITF is largely synthesized from large-scale models or theoretical conjecture, but less tested systematically from a hydrography. Understanding the water-mass composite and origin of ITF is a prerequisite to discuss and predict ITF's role in a global context. The PACSWIN targets these issues by addressing ITF's source waters back to their Pacific origin, therefore establishing a connection and evolution of water types from one end to another. To accomplish the objectives, the PACSWIN uses novel 3-D Indo-Pacific source water mixing and transformation models, accurate neutral density surface frames and updated hydrography.

4.2 Advancing the present knowledge: The study of ITF is currently undergoing a significant transition to simultaneous measurement of transport such as the INSTANT project. However, a full understanding of ITF transport and variability is beyond the scope of the Indonesian seas themselves. The required knowledge as to how many sources are composed of ITF and where they come from and how they get into the Indonesian seas is lacking. A conventional T-S diagram cannot resolve well the real number of Pacific source waters and paths. CFC11 and CFC12 show general stratification but do not delineate well the vertical water-mass structure. This is because source waters come from the remote Pacific origins and become obscure in their property signals as water types have evolved from one end at formation region to another end in the Indonesian seas. A typical example is the NPIW whose core density is transformed

from an origin of $26.5\sigma_\theta$ in the subpolar North Pacific to subtropical gyre of $26.8\sigma_\theta$ and back to $26.5\sigma_\theta$ in the Indonesian seas. Understanding of this NPIW component in ITF requires a full understanding of how NPIW is formed and transformed to the ITF. This scale of in-depth study has not been achieved. Endeavor made to clarify water-mass structure and paths in a local environment of the Indonesian seas has proved difficulty (Ffield and Gordon, 1992; Hautala et al., 1996). With gathering hydrographic data in the last decade or so, in particular following the complete of the ARLINDO program, the PACSWIN will facilitate full utilization of the potential synergy of knowledge about ITF and an unprecedented data set.

4.3 Long term perspective: Since the PACSWIN will connect the local water-mass signals with remote Pacific origins by 3-D Indo-Pacific source water mixing models, the ITF can be discussed in a broad global scale view. The expected results may offer future perspective for a long term monitoring of the ITF such as using autonomous ARGO floats and provide constraints for sophisticated ocean and climate models. The variability of ITF interocean heat and freshwater transport, in principal, may be monitored by investigating the temporal T/S changes of its sources. Since the project combines physical data with chemical data to solve water mass mixing problem, it advances the knowledge base of discipline. Also the project includes a graduate student involving in research which will promote both research and education.

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(INSTANT) program was established to directly measure the ITF. Scientists from Indonesia, France, the Netherlands, United States and Australia make up the collaborative INSTANT partnership. The INSTANT field program began in December 2003 [a single mooring near East Timor was deployed in August 2003], and consists of a three-year deployment of an array of moorings and coastal pressure gauges which will directly measure sea level and full depth *in situ* velocity, temperature and salinity of the ITF. For the first time, simultaneous, multi-passage, multi-year measurements will be available and allow the magnitude and properties of the inter-ocean transport between the Pacific and Indian Oceans to be unambiguously known. Most of the INSTANT moorings were deployed from December 2003 to January 2004. The CTD data collected during the 4 deployment cruises are presently being processed and studied. The deployment phase that included the moorings most directly associated with A.L.Gordon are in the 2 Makassar Strait, set out during Leg 3 [both deployed 18 January 2004]:

	Lat S	Long E	Depth m
Makassar East	2°51.222'	118°37.734'	1613
Makassar West	2°51.888'	118°27.276'	2147

A.L.Gordon is presently working on scheduling the rotation cruise for June/July 2005.

An article is in press in AGU's EOS: "A New International Array to Measure the Indonesian Throughflow: INSTANT" *Janet Sprintall, Susan Wijffels, Arnold L. Gordon, Amy Ffield, Robert Molcard, R. Dwi Susanto, Indroyono Soesilo, Jan Sopaheluwakan, Hendrik M. van Aken.*

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