Indonesian Throughflow: PACific Source Water INVestigation (PACSWIN)
An international ocean climate program


Abstract
Our understanding of the role of the Indonesian Throughflow (ITF) in the global climate system has improved due to progress made on observations and modelling in the last decade or so. The International Nusantara Stratification and Transport (INSTANT) program from 2004–06 measured the ITF simultaneously at several of the primary straits and showed a 20–30% increase of the ITF transport under relatively weak El Niño-Southern Oscillation (ENSO) conditions. This suggests that prior ITF transports could be underestimated. Further simultaneous observations encompassing a complete ENSO cycle are required for a more accurate estimate of the ITF transport. Climate monitoring requires cost-effective long-term measurement of the ITF on decadal or even centennial time scales. Currently, no such sustainable monitoring program exists for the Indonesian seas and adjacent region.

To address this need, a coordinated international program is necessary. Modelling the role of the ITF in global climate has primarily been along the line of switching the ITF on or off. The ITF has been established as affecting tropical wind stress, thermocline depth and precipitation in ocean general circulation and coupled atmosphere and ocean models. Teleconnection of the climate impact of the ITF with higher latitudes results from the westward shift of the western Pacific warm pool inducing changes in atmospheric deep convection. However, the role of the ITF in the global climate system has not been well addressed by the models, due to two distinct obstacles. First, there has been insufficient resolution of the complicated bottom topography and numerous narrow straits in the Indonesian seas. Second, the tidal mixing which blends all Pacific source waters into one Indian Ocean water-mass has been poorly resolved. As a consequence of mixing, the major ITF in the thermocline layer actually cools and freshens the eastern Indian Ocean. These observational, modelling and climate inadequacies provide the rationale for this newly proposed international ocean climate program, the Indonesian Throughflow: PACific Source Water INVestigation (PACSWIN), which will focus on the variability of the ITF passing through the Indonesian seas and straits. This new program aims to bridge the data gap in the Indonesian seas left by the current Argo program and to resolve various source waters (mainly of Pacific origin) and their teleconnections and pathways, thus supplementing the INSTANT moorings completed by the end of 2006.

1. Introduction
The United Nation (UN) Climate Change Conference, held in Bali, Indonesia, in December 2007, created a roadmap to continue the goals of the Kyoto Protocol after it ends in 2012. The conference sent strong messages about the critical need to effectively monitor climate change and provide accurate information of global warming to society. Nowhere is this more evident than in the Indonesian Throughflow (ITF) region between the Pacific and Indian Oceans. The ITF, draining water from the tropical Pacific
into the Indian Ocean, plays an important role in Australian and global climate. It is reasonable to expect that the potential dramatic climate change associated with the weakening of the ocean circulation in the northern and tropical North Atlantic could also affect the ITF and cause subsequent regional climate change in southeast Asia and Australia because the ITF is a choke point of the global ocean circulation affecting earth's climate.

The Indonesian Throughflow: PACific Source Water Investigation (hereafter PACSWIN) program is an international coordinated ocean climate monitoring program proposed to address the role of the ITF in regional and global climate change. Geographically, PACSWIN intends to cover the Indonesian seas and adjacent regions (Figure 1) including the entrance of the Pacific source waters east of Mindanao, north of Papua New Guinea (PNG) and the far western equatorial Pacific as well as the exit of the ITF in the eastern Indian Ocean (see dashed square in Figure 1; note that acronyms for currents and water masses used in the paper are defined in the caption of Figure 1). The aims are twofold: first, to improve identification of the various source waters from the Pacific and Indian oceans through the use of extended tracers including temperature, salinity, oxygen, nutrients and biological and chemical tracers and, second, to investigate the Indo-Pacific water mass exchange via the ITF linkage with current system east of Mindanao, north of PNG, the equatorial current and that in the eastern Indian Ocean. The second goal will be to coordinate activities with two other major international programs in the western tropical-subtropical Pacific, SPICE (Southwest Pacific Ocean Circulation and Climate Experiment) (Ganachaud et al. 2007) and NPOCE (Northwestern Pacific Ocean Circulation Experiment) (Hu, personal communication, 2007) as well as the global Argo (Array for Real-time Geostrophic Oceanography) program (Roemmich et al. 2009). We want to illuminate how various Pacific source waters are transformed into a unique mixture of the Indonesian sea water and how the new Indian Ocean sources, such as the transformation of Antarctic Intermediate Water (AAIW) to Indonesian Intermediate Water (IIW), are formed by tidal and vertical mixing processes within the Indonesian seas. A water mass moving from its formation region to another place carries an index of climate change signals.
PACSWIN is designed to better quantify the role of the ITF in global climate change.

Secondly, a climate-sensed teleconnection of the water-mass inventory of the Indonesian seas has to be established to link local water masses with their remote source formation regions. The Indonesian seas lie in a tropical region where no water mass can be formed locally by air/sea interaction. All water masses have to come from subtropical and high latitudes of the Pacific Ocean. The remote source waters at tropical and subtropical regions are marked in Figure 1. They are mainly high salinity and oxygen waters initially formed by Ekman subduction since they are ventilated at the tropical and subtropical convergence zones. Those intermediate waters are originally formed in the subpolar regions (see big black dots in Figure 1). However, significant transformation of these prototype source waters is necessary before they can cross the subtropical convergence zone at about 40°S and enter the subtropical latitudes. In the past, the contribution of marginal seas to the ITF has not been well accounted. PACSWIN has established a monitoring component of marginal seas input such as at the Kalimantan Strait where the South China Sea transports a significant amount of water from and into the Indonesian seas during reverse monsoons.

The PACSWIN initiative is motivated by four factors: 1) the need for continuous monitoring of the ITF across the major Indonesian straits subsequent to International Nusantara Stratification and Transport (INSTANT) program, 2) the paucity of Argo profiles in the region prompting consideration of a different monitoring strategy, 3) the inability of the INSTANT program to resolve the various source waters and their pathways and 4) the focus of the present wider global climate issue on the North Atlantic concerning the weakening or even halting of the meridional overturning circulation (MOC) but ignoring the role of the ITF in global circulation. Recent observational programs monitoring the MOC in the North Atlantic indicate high current variability that must be incorporated into any predictive models (Church 2007; Kanzow et al. 2007; Cunningham et al. 2007).

2. Aims and objectives

PACSWIN aims to bridge the data gap in the Indonesian seas left by the current Argo program, and to resolve various source waters (mainly of Pacific origin) and their teleconnection with the high latitude formation region and pathways and hence the climate. This will supplement the INSTANT moorings completed by the end of 2006. PACSWIN will provide a major international ocean climate monitoring network in the Indo and western Pacific for at least the coming decade and beyond. The objectives of PACSWIN are

- to strategically establish a long-term and cost-effective climate monitoring program including the priority components of moorings, submarine cables and modified floats, permitting data from the Indonesian seas to complement the Argo array in compliance with other global ocean monitoring programs such as that in the North Atlantic for the MOC
- to obtain accurate estimates of the ITF transport, heat and freshwater fluxes through the Indonesian seas
- to elucidate the various source waters entering the Indonesian seas, especially of Pacific origin, their pathways, transformations and teleconnections
- to identify forcing mechanisms such as wind, ENSO, monsoon and tides, etc, which affect the ITF and heat and fresh water fluxes
- to apply high resolution ocean and climate models to better simulate and predict the ITF and its climate impact.

PACSWIN also includes some components of topical studies aimed at resolving some important dynamical issues

- the association of ITF with the Pacific and Indian Ocean equatorial current system, low latitude boundary currents, eddies of Mindanao, Halmahera and eastern Indian Ocean
- the forcing of wind and equatorial waves including Rossby and Kelvin waves
• the interior mixing, topographic interaction and water-mass transformation within the Indonesian seas
• the various time-scales of intraseasonal, seasonal, interannual, annual and decadal variability and their interplay
• the dynamic correlation of the ITF with the Indian Ocean dipole, Pacific decadal Oscillation and North Pacific Gyre Oscillation.

3. Scientific background

Argo is designed to continuously monitor ocean climate, especially temperature and salinity in the upper 2000 m of the global ocean covered by ~3000 free-drifting floats (The Argo Science Team 1998). Argo started in 1999 as part of the Global Climate Observing System (GCOS), Global Ocean Observing System (GOOS), Global Ocean Data Assimilation Experiment (GODAE) and Climate Variability and Predictability Experiment (CLIVAR). Figure 2 shows the updated state of the Argo floats as of 15 March 2009, with a total number of 3325 floats now deployed. The important role of Argo in monitoring climate change and validating climate models has been increasingly recognised. However, there is a gap in the Indonesian seas due to the limit of the designed diving depth of 2000 m for open ocean, (see marked square area in Figure 2). Therefore, the Indonesian seas need a different strategy to monitor changes in ocean climate.

The Indonesian seas play a crucial role in global ocean circulation and climate. The Indonesian archipelago is the only low latitudinal connection of tropical oceans between the western equatorial Pacific and eastern Indian Ocean. Flow passing through the archipelago is the well-known ITF guided by geographically complicated basins and straits. From the Snelius expedition, van Riel (1932) was the first to suggest that the transport within the East Indies (now Indonesian) waters (ITF) was directed to the Indian Ocean (Parlungo et al. 2005). In the Indian Ocean, the inflow of the ITF can be identified as a jet-like flow westward along 12°S reaching the coast of eastern Africa, feeding the Agulhas Current from both sides of Madagascar and exiting in the southwest Indian Ocean. A small fraction of the escaped

ITF water from the Agulhas Retractation continues its journey to the South Atlantic via Agulhas rings/eddies, joining the global ocean circulation in the Benguela Current. Within the Indian Ocean, the ITF is a significant component of the northern and southern Indian Ocean gyre circulation. The former switches between cyclonic and anticyclonic circulation under monsoonal forcing. The water mass mixture of the Indonesian seas from various thermocline source waters can be identified as a low temperature and salinity tongue in the Indian Ocean, and is called Australasian Mediterranean Water (AAMW) (You & Tomczak 1993), a nomenclature reserved for its unique water mass property while the ITF is named for the surface current. In terms of basin-scale description of water-mass structure in the Pacific and Indian Oceans, AAMW is a sink resulting from the mixing of North and South Pacific thermocline waters predominantly from North Pacific sources and transformed through the "Indonesian Mix-Master" (IMM) (Gordon 2005) to be a new source of Indian Ocean thermocline water. The same scenario of water mass transformation is retained for the intermediate water layer. The Indonesian Intermediate Water (IIW) is
• the interior mixing, topographic interaction and water-mass transformation within the Indonesian seas
• the various time-scales of intraseasonal, seasonal, interannual, annual and decadal variability and their interplay
• the dynamic correlation of the ITF with the Indian Ocean dipole, Pacific decadal Oscillation and North Pacific Gyre Oscillation.

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![Figure 2 Argo stations on 15 March 2009. Note the gap in the Indonesian seas (outlined in square). Superimposed is the great ocean conveyor belt with the cold water route and warm water route.](image)

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thermocline waters are blended into a vertically rather homogeneous water mass (see Figure 4). For the intermediate water layer, NPIW at about 300 m (or 26.5σo) is well mixed and is no longer identifiable in the Timor Sea. AAIW enters the eastern Indonesian seas at about 600–1000 m (or 27.1–27.2 σo) but cannot be identified in the Banda Sea. A replaced IIW at 1000 m (or σo=31.96) is observed in the eastern Indian Ocean South Equatorial Current (SEC) (Talley & Sprintall 2005). The Indonesian seas act as a sink for various Pacific water masses and a source for the Indian Ocean (Table 1).

Table 1: Inventory of water masses in the Indonesian seas, their teleconnection with the Pacific source formation and transformation to new source of the Indian Ocean.

<table>
<thead>
<tr>
<th>Water mass</th>
<th>Property feature</th>
<th>Source formation region</th>
<th>Transformed Indian new source water mass and property feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPSW</td>
<td>high S (34.65), T (15°C), O2(9.0 ml/l), low nutrients</td>
<td>shallow subtropical North Pacific</td>
<td>AAMW low S (34.6), T (14°C)</td>
</tr>
<tr>
<td>SPSW</td>
<td>high S (34.75), T (14°C), O2(2.6 ml/l), low nutrients path: via Halmahera Sea</td>
<td>shallow subtropical South Pacific</td>
<td>AAMW low S (34.6), T (14°C) high silicate (38 mol kg^-1)</td>
</tr>
<tr>
<td>NPIW</td>
<td>S minimum (34.4), path: via Malakaar and Maluku Sea</td>
<td>Okhotsk Sea and Gulf of Alaska</td>
<td>AAMW low S (34.6), T (14°C) high silicate (38 mol kg^-1)</td>
</tr>
<tr>
<td>AAIW</td>
<td>S minimum (34.56), low nutrients path: via Maluku Sea, Seram Sea, Banda Sea to Timor Sea</td>
<td>southeast South Pacific</td>
<td>IIW silicate maximum (80 μmol kg^-1)</td>
</tr>
<tr>
<td>uCDW</td>
<td>high S (32.65) and nutrients</td>
<td>circumpolar region</td>
<td>none</td>
</tr>
</tbody>
</table>

When the water mass cannot be identified through potential temperature θ and S becoming obscured, nutrients and chemical tracers help to identify the various Pacific source waters. Gordon and Fine (1996) used chlorofluorocarbons (CFC-11 and CFC-12) to examine water mass stratification within the Indonesian seas. However, CFC-11 and CFC-12 do not delineate vertical water-mass structure. Oxygen generally has a high value in the South Pacific source and a low value in the North Pacific source below the upper
thermocline on isopycnal surfaces mapped by Hautala et al. (1996) to follow the major water mass cores. This situation is reversed in the upper thermocline. The North Pacific source shows relatively higher oxygen content. Within the Indonesian seas, Ffield and Gordon (1992) discovered that oxygen curves could not be used to distinguish between sources, suggesting that oxygen consumption may have to be considered. However, silicate is a major signal to identify the transformed Indonesian source waters for the Indian Ocean. Nutrients have so far been very poorly sampled in the Indonesian seas.

The thermohaline stratification and water-mass structure of the Indonesian seas (referring to Figure 4 and Table 1) can be summarised as upper thermocline water with a salinity maximum (>34.75) at 130 m (or 24.5σθ) (SPSW), main thermocline water with relative high salinity (~34.65) and oxygen (3.0 ml l⁻¹) but no extremas at 220 m (NPSW), a salinity minimum (<34.4) at 300 m (or 26.5σθ) (NPIW), a relative low salinity (~34.56) and oxygen (2.35 ml l⁻¹) but no extremas at 1000 m (or 27.25σθ) (AAIW) and deep water with a relative high salinity (~32.62) below 1500 m (or larger than 27.4σθ) (Iahude & Gordon 1996; Ffield & Gordon 1992; Hautala et al. 1996).

Note that the sill depths in the Maluku Sea and Lifamatola Strait are sufficient to allow passage of upper Circumpolar Deep Water (uCDW) from the Southern Ocean into the Banda Sea (see Figures 3 and 4). The pathways of the remote Pacific sources into the Indonesian seas are not well resolved, especially in the eastern route since the western route is dominated by North Pacific sources and is shallower with a sill depth of ~600 m (implying fewer water types involved). Both North and South Pacific sources flow into the eastern route. A teleconnection of the Indonesian water types with the remote Pacific source waters has yet to be established in extended property fields including nutrients and chemical tracers. For example, it is still unclear whether or not there is a shortcut by the North Pacific source from the Mindanao Current (MC) southward along a line east of the Sangahe Ridge to the Maluku Sea, and a circulatory path by South Pacific source to the North Pacific through the equatorial current system (Godfrey 1996), and how much South Pacific source water successfully crosses the Lifamatola Passage, although evidence is building up that South Pacific origin does get into the Halmahera and Maluku Seas (Cresswell & Luick 2001; Luick & Cresswell 2001; Talley & Sprintall 2005). The model results of Zenk et al. (2005) show that South Pacific waters not only feed the Halmahera Sea and Maluku Sea but probably also the southern Sulawesi Sea though the flow is strongly seasonally dependent.

The ITF transport (Figure 3) is based on the estimates by Gordon (2001, 2005). The new estimate from the INSTANT program has not yet been published but suggests a value 20–30% higher. The main throughflow path passes through the Makassar Strait within the thermocline layer with a transport of 8 Sv (1 Sv=10⁶ m³ s⁻¹) with an uncertainty of 1–2 Sv. 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 of this water flows 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 easterly 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, close to the mean of previous range of 2–22 Sv (Table 2) (Godfrey 1996; Fieux et al. 1994). Improved estimates are possible through recent mooring programs such as Arus Lintas Indonesia (ARLINDO) (Gordon & Susanto 1999). Using the World Ocean Circulation Experiment (WOCE) and other sections, Talley and Sprintall (2005) derive a range of 3–7 Sv for the ITF transport through the eastern route which, for a single water mass, is much larger than the estimate of 1.5 Sv for the entire strait throughflow.
Table 2 Inventory of the Indonesian Throughflow transport estimates.

<table>
<thead>
<tr>
<th>Method</th>
<th>Transport (Sv)</th>
<th>Author(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geostrophy, top 300 m</td>
<td>1.7</td>
<td>Wyrtki (1961)</td>
</tr>
<tr>
<td>Geostrophy, 11 unclosed Indian Ocean sections</td>
<td>10.0</td>
<td>Grech and Golding (1981)</td>
</tr>
<tr>
<td>Inverse, 43°S and 28°S Pacific section</td>
<td>&lt;10.0</td>
<td>Wunsch et al. (1983)</td>
</tr>
<tr>
<td>Freshwater budget, Pacific and Indian Oceans</td>
<td>14.0</td>
<td>Fiala and Gordon (1984)</td>
</tr>
<tr>
<td>Tritrunc budget, top 300 m</td>
<td>5.0</td>
<td>Fite (1985)</td>
</tr>
<tr>
<td>Inverse, Timor Strait</td>
<td>7.0</td>
<td>Fite (1986)</td>
</tr>
<tr>
<td>Salinity budget, West Pacific</td>
<td>&lt;5.0</td>
<td>Toole et al. (1988)</td>
</tr>
<tr>
<td>Current meter, Lombok Strait</td>
<td>1.5</td>
<td>Murray and Azief (1988)</td>
</tr>
<tr>
<td>Geostrophy from Levitus data, Australia – Sumatra</td>
<td>12.0</td>
<td>Grech and Golding (1981)</td>
</tr>
<tr>
<td>Inverse, 52°S Indian Ocean</td>
<td>7.0</td>
<td>Toole and Warren (1993)</td>
</tr>
<tr>
<td>Heat budget, closed box 14°S–165°E–10°N</td>
<td>0–8.0</td>
<td>Wijffels et al. (1992)</td>
</tr>
<tr>
<td>Geostrophy/current meter, Australia – Bali, JADE, August, 1989</td>
<td>18.6±7</td>
<td>Fieux et al. (1994)</td>
</tr>
<tr>
<td>Geostrophy/current meter, Australia – Bali, JADE, February 1992</td>
<td>-2.6±7</td>
<td>Fieux et al. (1996)</td>
</tr>
<tr>
<td>Geostrophy, XBT time series, peak-to-trough, top 400 m</td>
<td>5.0</td>
<td>Meyers (1996)</td>
</tr>
<tr>
<td>Mooring, Timor Strait</td>
<td>3.4–5.3</td>
<td>Molcard et al. (1996)</td>
</tr>
<tr>
<td>Tidal-induced residual transport, Seram–east Banda</td>
<td>3.8</td>
<td>Hatayama et al. (1996)</td>
</tr>
<tr>
<td>Mooring, Makassar Strait, 1997</td>
<td>8.0±2</td>
<td>Susanto and Gordon (2005)</td>
</tr>
<tr>
<td>Current meters, Moluccas Sea</td>
<td>7.0</td>
<td>Luick and Cresswell (2000)</td>
</tr>
<tr>
<td>Current meters, Halmahera Sea</td>
<td>1.5</td>
<td>Cresswell and Luick (2001)</td>
</tr>
<tr>
<td>Current meter, Lifamatola</td>
<td>1.5</td>
<td>van Aken et al. (1988)</td>
</tr>
<tr>
<td>Heat, freshwater, oxygen and silica budget, Lifamatola</td>
<td>&gt;5.0</td>
<td>Talley and Sprintall (2005)</td>
</tr>
<tr>
<td>XBT, 20-year mean of geostrophic transport, reference to 750 m</td>
<td>8.9±1.7</td>
<td>Wijffels et al. (2005)</td>
</tr>
</tbody>
</table>

In Table 2, the various estimates of the ITF transport show a number of shortcomings, i.e. they lack temporal and spatial coherence since the data used cover different time periods and depths that lead to ambiguity in the ITF transport estimates. Even the transformation of the thermohaline can be misinterpreted. The aim of the INSTANT program was to resolve these shortcomings and derive a more accurate estimate of the ITF transport. The INSTANT program (Sprinwall et al. 2004) is a coordinated endeavour by Indonesia, Australia, France, The Netherlands and United States, deploying 11 moorings in the major straits of the interior Indonesian seas to simultaneously and contemporarily measure the throughflow currents over three years (see Figure 3). The field measurements were completed in 2006. According to Gordon et al. (2006), who reported on the first year and a half years of data, the estimated Makassar Strait transport is about the same as that observed in 1997 during the Arlindo program at 8–9 Sv (Table 2) (Susanto & Gordon 2005). The complete three-year mooring data of INSTANT indicate an average increase of the ITF transport by 25% (Gordon et al. 2008). The ITF across the major straits reveals strong variability with a wide range of temporal scales, marked by month-long periods of significant imbalance between the inflow and export, implying substantial convergence and divergence within the interior seas.

The most recent report of the final results of the INSTANT mooring analysis confirms a 20–30% of increase in the total ITF transport (Gordon et al. 2008). This transport is derived under a relatively weak El Niño – Southern Oscillation (ENSO), suggesting that the mean of the previous individual estimates of the ITF transport could be underestimated. Under a strong ENSO condition, the ITF transport is likely much higher than previously thought. From the water-mass point of view concerned here, INSTANT is a program for measuring transport of the ITF within the
Indonesian straits. The program cannot address water mass content, the Indo-Pacific source waters or their route to the Indonesian seas. One of the aims of PACSWIN is to resolve the water-mass properties of various sources with a significant Pacific origin entering the Indonesian seas, their en route pathways, transformation, mixing, variability and constituents in the Indonesian seas.

Another ITF pathway for waters below the lower thermocline of South Pacific origin, the intermediate and deep waters, is derived through the eastern route, via the Maluku (or Molucca Sea) and Halmahera Seas into the Banda Sea (Cresswell & Luick 2001). Since the western side of the Indonesian seas is connected with the eastern Indian Ocean by a sill depth of over 1500 m, an influence of Indian water seems inevitable, especially during La Niña (Molcard et al. 1996). This Indian Ocean reverse flow was observed in recent moorings (Gordon et al. 2006). With careful examination of deep topographic barriers, Gordon (2001) and Gordon et al. (2003) proposed three possible paths of Pacific water into the Indonesian Seas (Figure 3).

Many ocean general circulation models (OGCMs) and coupled atmospheric and oceanic models (AGCM or CGCM) have simulated a closing down of the Indonesian straits resulting in a significant global and regional impact on climate. This kind of experiment treats the ITF as a pipe flow regardless of the horizontal and vertical resolution. Various model results show a positive heat transport of 0.6–0.9 PW (1 PW = 10^{15} Watt) contributed by the ITF to the Indian Ocean (Godfrey 1996; Hirst and Godfrey 1993; Schneider & Barnett 1997; Schneider 1998; Gordon 2001; Vranes et al. 2002). Modelling of the water mass of the Indonesian seas and the ITF is challenging because of the complicated boundary conditions. To resolve the ITF, sufficient resolution of the narrow straits in OGCMs is essential.

The consistent positive heat flux from the Pacific to the Indian Ocean illustrated in ocean models and other previous studies may be misleading, as argued recently by Gordon (2003) who points out that the positive heat flux can only be referred to be the value at the exit point when the water flows out of the Indian Ocean from south of Africa, while the net heat flux is actually negative. Gordon clarifies the concept by stating:

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: yes, yes; I think so.

The ITFs heat flux contributes to cooling rather than warming in the eastern Indian Ocean as can be seen in Figure 1 of Gordon (2005) of the upper thermocline temperature and salinity across the Pacific and Indian oceans. You and Tomczak (1993) showed a low temperature and salinity AAMW tongue in the ambient Indian Ocean water in the upper 500 m (see their Figures 2 and 3). Gordon (2005) pointed out that strong tidal-induced mixing by the IMI allows various inflow waters to be mixed into a unique Indonesian seas water, i.e. AAMW. Some of those inflow waters have not been well accounted. For example, the inflow of cool, fresh water (due to precipitation and run-off) from the marginal seas, the South China Sea and the Bay of Bengal via the shallow Gulf of Thailand and the Sunda Shelf was regarded as being too small. Another major source, usually neglected, is the NPIW. The NPIW shoals substantially to 300 m in the Indonesian seas and freshens as well as cools the main thermocline in the Banda Sea, Timor Sea and eastern Indian Ocean. NPIW contributes significantly for about 2.7 Sv of transport to the Indonesian seas (You 2003).

4. Scientific issues and proposal for investigation

The proposed PACSWIN program consists of various components covering broad scientific issues and monitoring techniques. To carry out the ocean climate monitoring in the region, three priority monitoring infrastructures have been defined, i.e. submarine cables, floats and moorings, although other monitoring components are also of interest.

4.1 Priority monitoring programs

4.1.1 Moorings

The objective of the INSTANT mooring program was to better quantify the ITF volume transport and to contribute to a future long term monitoring
strategy (Gordon et al. 2006). The 11 moorings (see Figure 3 for INSTANT mooring locations) were first deployed from August 2003 to January 2004 and finally recovered at the end of 2006 with mid-term recovery/redeployment in summer 2005. The first ever contemporary measurement of the ITF from the first half phase of INSTANT shows a similar and slightly larger transport in the western route in the Makassar Strait at 8–9 Sv than the Arlindo but a much larger transport in the eastern route across the Lifamatola Strait at 2.9 Sv compared to 1.5 Sv observed previously (van Aken et al. 1988). As mentioned above, the final results of the three-year INSTANT moorings have indicated about 20–30% increase of the ITF transport under a weak ENSO period (Gordon et al. 2008). With respect to resolving source water mass transport, INSTANT had only one mooring at the Lifamatola Strait. One mooring is insufficient in such a wide and deep strait. There was no mooring deployed to record the inflow of South Pacific water through the Halmahera Sea. Thus, the INSTANT mooring results suggest that a continuing and improved mooring program should be pursued as part of PACSWIN. After INSTANT, there has been only one mooring funded by NOAA to continue the measurement of the ITF at the Makassar Strait (Gordon, personal communication, 2008).

As shown in Figure 5, PACSWIN mooring component retains the INSTANT 11 moorings plus five additional moorings, one more at the Lifamatola Strait, two new moorings between Obi and Lifamatola for measuring the South Pacific source and two new moorings at the entrance for measuring the low latitude western boundary transport. The strategy for new moorings is to better address the South Pacific source water via the Halmahera Sea and the mixed source of North and South Pacific through the Maluku Sea. Since there is a deep strait between Halmahera island and Lifamatola (over 2000 m deep), moorings are placed in a deep inlet between Obi and Lifamatola rather than between Halmahera and Sorong. Such a mooring distribution would not only provide comparable transport with INSTANT moorings but better resolve water mass transport in the eastern route for the South Pacific source through the Halmahera Sea and mixed source through Maluku.

4.1.2 Submarine cables
A submarine cable is a cost-effective tool to measure ocean current transport. The ITF flowing through a strait or channel above a cable acts as a conductor cutting the vertical lines of the Earth's magnetic fields and thus generating a horizontal electric field that can be measured as motion induced voltage (MIV) from the cable. The theoretical development of electromagnetic fields for oceanographic application was first advanced by Stommel (1948). For monitoring of the ITF in a particular strait, only a voltage recorder and a computer are needed for net transport of the ITF except for calibration costs. Note that the cable base and ground facility are very expensive. Cables can satisfy both present and future needs for implementing a long-term ocean climate monitoring of the ITF and a global network in generally supplementing the Argo array. Indeed, the technique complements the Argo program, which leaves most straits and marginal seas and water deeper than 2000 m unobserved, as, for example, within the Indonesian seas.
(E-field sensor/inverted echo sounder) for the straits without cables (grey star) for undertaking the same job (Sanford, personnel communication, 2007) and c) the global vertical magnetic component (www.geomag.bgs.ac.uk/earthmag.html). As seen, the magnetic equator (zero line) lies well north of the Indonesian seas existing cables at Mindanao. This means that submarine cable measurement of the ITF should be a valid exercise.

A submarine cable has been utilised to monitor the Florida Current transport since the 1980s and others have been used elsewhere, including in the region of the Kuroshio between Taiwan, Luzon and Okinawa as well as at the Izu Islands; the Tsushima Current in the Korea Strait; transports between Gran Canaria and Tenerife; in the Baltic Sea and in channels on the Portugal continental shelf. However, so far, the application of a submarine cable to current measurement has been carried out for only a minor portion of the existing cable networks (see Figure 6a) and, as yet, the technique has not been given enough attention by the ocean climate community.

The western Pacific includes many of the marginal seas and straits of the world’s oceans. Thus, submarine cables could be a useful tool for the region, especially in the Indonesian seas. It is very costly to maintain a set of moorings for monitoring the ITF continuously for timescales longer than a decade and, indeed, there is no guarantee of funding for such long-term monitoring. However, a submarine cable can satisfy the requirement for monitoring the ITF continuously for a century or longer. Several submarine cables cross the ITF passages (see Figure 6b). In particular, two cable routes cross the Makassar Strait, a main ITF pathway. PACSWIN has chosen submarine cables as one of its priority monitoring infrastructures along with moorings and floats. The cable routes in the Indonesian seas avoid the magnetic equator which lies at Mindanao (see the zero line in Figure 6c).

A first submarine cable workshop was endorsed by CLIVAR on 23 April, 2008 and held in Taipei on 9–10 September 2009. The proposed workshop will provide an opportunity to update the community and to review and promote the technique. It will enable exchanges to take place among users and the opportunity to share the technique with non-users. Since meaningful
current transport measurements from cables depend upon accurate determination of parameters such as tides, sediment condition, local magnetic field and intercomparison of real current measurements, the workshop will standardise the methodologies to be used and intercomparison technology. Another task of the workshop is to design the PACSWIN cable component using the existing Indonesian seas cables (Figure 6b) for cost-effective long-term monitoring of the ITF.

On the other hand, a new technique has been developed recently to combine inverted echo sounder (IES) with E-field sensor (EFS) (Tom Sanford, personal communication, 2007) and will be available for those straits without existing cables. The workshop will provide technical support and design for the PACSWIN cable component and also set a road map for building a global network and open-access data bank.

4.1.3 Floats

Argo

Argo started in 1999 and by November 2007 had reached its target of 3000 floats. Currently, Argo has 3325 floats as of 15 March 2009 (see Figure 2). Argo floats are useful in PACSWIN for tracking the North and South Pacific source waters and the pathways on the Pacific side entrance of the Indonesian seas. In the eastern Indian Ocean, Argo will help tracing the components of the ITF as transformed Pacific source waters spread in space, depth and time. The existing Argo floats are ready to use for the purpose of PACSWIN in a broad equatorial current system. However, Argo has limitations for inshore currents within 100 km from the coast since Argo floats spend 5–10 hours on the surface transmitting data and may be swept up on shore or caught in strong near-shore currents. Another problem may be relevant to marine jurisdiction permission and EEZ (Exclusive Economic Zone) sovereign rights. In this latter context, Argo floats for Lagrangian tracing of Pacific source waters may be released offshore while inshore measurement is implemented by other means such as gliders and hydrographic survey sections applying a CTD.

Gliders

Autonomous underwater gliders (Davis et al. 2002) operate in a depth range of 200 to 1500 m over time periods from a few weeks to several months, and measure current velocity and water properties.

PACSWIN hydrographic sections

Figure 7 The PACSWIN hydrographic sections including the survey sections at the Pacific side entrance and Indian side outflow regions.

Several glider sections are planned for the main straits of the Indonesian seas and north-west Australia (see dashed line in Figure 7). A glider’s (Figure 8) position is located by GPS at the surface where data are transmitted to satellite and instructions are provided for the glider’s continued mission. This new type of instrument has been successfully used around the world’s oceans. As mentioned above, gliders may also be used to measure the inshore currents along the Pacific survey sections Pac1 to Pac9. However, since glider
speeds are about 25 cm s⁻¹; they are perhaps too slow to overcome the strong, low latitude western boundary currents such as those currents through the Vitiaz Strait. In sections with strong boundary or throughflow currents, other measurement tools such as ADCP, LADCP and current meters have to be used.

Figure 8 Schematic display of the main components of the Spray glider. The 6061 aluminium pressure case is made in three pieces and houses batteries, hydraulic system, compass, attitude sensor, GPS receiver, Iridium transceiver and the microprocessor controller. An aft flooded bay houses the external bladders that expand to increase buoyancy. This bay also houses the sensor suite selected for each mission. Sensors that have been used include: Precision Measurement Engineering CTD; Sea Bird 41 CP CTD with seawater pump; Sea Point Optical Backscatter Sensor; Sea Point Chlorophyll Fluorometer; Tritech PA200 acoustic altimeter for bottom avoidance; and Sonieck Argonaut-SGP 750-kHz Acoustic Doppler Current Profiler (see spray.ucsd.edu or Davis et al. 2002 for details).

Lagrangian tracking technique of Pacific source waters
The application of Lagrangian techniques is one way to fill the ARGO gap (Figure 2) and to overcome the spatial problem of Eulerian observations. Surface drifters with deep drogues are one possibility for near-surface current observations. Unfortunately, they often become the subject of vandalism especially in regions in reach of archipelagos. Sub-surface floats can also be used as roving current meters. They are much more protected against severe weather conditions and human interference. This is particularly important for the Indonesian seas.

Figure 9 A typical RAFOS device structure. While freely drifting at a pre-ballasted pressure level, this eddy resolving subsurface drifter is tracked acoustically with daily resolution. The glass housing is about 1.5 m long. After a pre-programmed time, the instrument drops a weight and returns to the surface. Since its upper half is then exposed above the sea surface, it can upload recorded data via satellite transmission.
RAFOS floats (Rossby et al. 1986) are acoustically tracked devices (Figure 9), which can be used to track the source water pathway in the western equatorial Pacific. Since the core of the ITF is supposed to lie in the main thermocline, sub-surface floats appear more suitable than surface drifters. Once an array of RAFOS sound sources has been installed, an unlimited number of RAFOS floats can be deployed and be part of the system (cf. a radio station on land with any number of receivers). RAFOS floats are about three times less expensive than Autonomous Profiling Explorer (APEX) etc. floats. This brings up the issue of the number of sound sources to be moored. In principle, two moorings are sufficient for an ocean basin, three are better. Since the western tropical Pacific is divided into several basins, the number of sound sources depends critically on the suspected region of the source waters of the ITF. A RAFOS sound array can be also used for Eulerian observations at strategic locations (mooring of opportunity). The RAFOS technology has been successfully applied to track the AAIW paths in the Bismarck Sea by Zenk et al. (2005). Lagrangian observations with eddy resolving RAFOS floats and extended model simulations at the source region of this ITF branch have identified a region of enhanced mixing at an intermediate level of 27.2–27.3 ρ0 (~580–600 m depth) in the equatorial western Pacific. The apparently increased eddy kinetic energy (EKE) may play a major role in the preconditioning process of this ITF source, augmented directly from the South Pacific. It reflects strikingly the convergence zone of the New Guinea Coastal Undercurrent (NGCUC) compared with the Equatorial Intermediate Current (EIC). Analogous particle tracking experiments with monthly resolution in this inter-hemispheric source region demonstrate great seasonal differences. Towards the Maluku and Sulawesi seas, an enhanced outflow from the south Pacific seems to develop in late summer (Figure 10). The pathway through the Halmahera Sea is probably of secondary importance (Zenk et al. 2005).

Up to 200 RAFOS floats would be released at the eastern entrance of the Indonesian seas on the Pacific side during the PACSWIN operation (Figure 11), which should be adequate to track the various Pacific source waters at different density levels.

Figure 10 Map showing trajectories from a cluster of model floats all started at the same location in the Bismarck Sea (a big dot). These model markers were injected in the New Guinea Coastal Undercurrent at the level of the Antarctic Intermediate Water. The grey colour code applied to the drift paths (see grey colour bar) indicates the elapsed drift time from the start. Observed RAFOS tracks were reasonably reproduced by the model path ways shown (Zenk et al. 2005).

2 Other monitoring programs

2.1 Hydrographic survey

The last systematic hydrographic survey in the Indonesian seas was conducted 15 years ago during the ARLINDO program in 1993–94. However, the data measured were mainly CTD/CFC but not nutrients (Jahude & Gordon 1996; Gordon & Fine 1996). Nutrients and other biochemical tracers are very much needed for PACSWIN in order to identify various Pacific source waters. In the past, nutrients were poorly sampled in the Indonesian seas.
The hydrographic survey sections are designed for several parts (Figure 7). The Pacific side consists of Pac1 to Pac9 for tracing the North and South Pacific source waters via the Viti Levi Strait, St George channel and New Ireland to Solomon Islands and east of Mindanao. In the Indonesian seas, the survey sections follow roughly the pathways of the North Pacific source in the western route (Pac1), the South Pacific source in the eastern route (Pac3) and the mixed North and South Pacific sources in the middle route (Pac2). These sections align mostly with the Indonesian sea lane (Figure 12). Other sections in the Indonesian seas are the repeat survey along the submarine cables for intercalibration (Pac1–4) and a glider mission at critical straits/channels (Pac1–7 in dashed line). In the outflow region in the eastern Indian Ocean, three sections west and east of Timor and at JADE (Pin1–3) are perpendicular to the ITF. These sections can further trace the transformed Pacific source waters to the eastern Indian Ocean through the Indonesian seas.

Except for traditional surveys by CTD and ship mounted ADCP, various nutrients, CFC and biochemical tracers will be sampled with Rosette bottle samplers such as dissolved oxygen, phosphate, silicate, nitrate, CFC11, CFC12 etc. These surveys will be conducted in each season for the first year and repeated for another year if possible.

4.2.2 ADCP/LADCP: using commercial freight ships for long-term measuring of the ITF and variability

It has long been practice for oceanographers to use commercial freight ships installed with a downward-looking acoustic Doppler current profiler (ADCP) mounted to the hull to routinely measure currents. One of the success stories is the Olenander project started in 1992 with weekly round trips between Elizabeth, New Jersey and Hamilton, Bermuda (Flagg et al. 1998) (Figure 13). To facilitate the data collection and dissemination, an autonomous data collection system called AutoADCP has been developed to
allow wireless internet data connection as soon as a freight vessel arrives ashore. This important upgrade makes the monthly trips to the ship to collect the data unnecessary. The time period of data availability is shortened from over a month to a week or so. The new data processing system handles different data formats.

![Atlantic Climate Change: The Oleander Project](image)

**Figure 13** The Oleander ADCP project between the port of Elisabeth, New Jersey and Hamilton, Bermuda since 1992.

Using the technique in the Indonesian seas and for ITF monitoring strategy is effective because there are many regular container and freight ships navigating through the Indonesian archipelago, along and across the ITF. The Indonesian archipelagic sea lanes can be used by international freight ships with ADCP installed to measure the ITF regularly. On the other hand, Indonesia is the largest archipelagic country in the world. There are numerous passenger shipping/ferry lines in the Indonesian archipelago (Figure 14a), which are potentially large resources for installing ADCPs for long term climate monitoring.

In Figure 14b, only a portion of the Indonesia domestic container shipping lines from Jakarta and Surabaya are presented. The adjacent Darwin link with Asian ports is a perfect example for using the Oleander project model. We haven’t shown other numerous international freight shipping lines, especially for the western Pacific and Asian countries. It can be anticipated that an international network of AutoADCP can be established to support the simultaneous monitoring of the ITF. ADCP measures currents down to below 400 m, which covers a depth range of the thermocline and NPIW in the Indonesian seas. Since the major source waters in the ITF are derived from the North Pacific, the depth counts for at least 80% of the total ITF transport. In conclusion, the commercial ship ADCP is considered a cost-effective long-term means for monitoring the ITF. This new technique is under consideration by SCOR/IAPSO working group (known as SCOR WG#133 or OceanScope) for exploring ways of developing a new paradigm for working with the merchant marine shipping industries (Rossby, personal communication, 2009).

### 4.2.3 Expendable Bathythermographs (XBT)

The above subsection calls for the traditional Expendable Bathythermographs (XBTs) to be considered by PACSWIN. The XBTs are devices to measure the temperature of the upper ocean using moving vessels including the aforementioned merchant vessels. XBT can measure temperature down to 800 m. Combined with the ADCP/LADCP, one can obtain a time series profile of velocity and temperature and the transport and heat flux in the upper ocean.
Since TOGA in 1983, CSIRO initiated an XBT network in the Indonesian seas and adjacent region. After 1997, the project was jointly supported by CSIRO, the Joint Australian Facility for Ocean Observations (JAFEOS) and Australia's Bureau of Meteorology (BOM). Currently, there are three frequent XBT lines (12–18 times per year) across the ITF from Australia to the Indonesian shelf; one from Perth to Java (IX1), a second one that is a quasi-zonal line from Java to the Banda Sea in the east (PX2) and a third one from Port Hedland to the Banda Sea, Maluku Sea and then east of Mindanao (IX22). These XBT lines have been running for 25 years and have provided the only long time series of information on ITF transport and other watermass characteristics. Recently, Wijffels et al. (2008) estimated a 25-year mean of ITF transport from these XBT lines above 750 m of 8.9±1.7 Sv. The XBT program satisfies the target of PACSWIN pursuing a cost-effective long-term climate monitoring of the ITF. PACSWIN will use vessel opportunities to continue the Indonesian seas' XBT sampling.

4.2.4 Satellite altimetry and scatterometry

With their superior spatial coverage, satellite observations (e.g., altimetry and scatterometry) are complementary elements to the in situ elements of the PACSWIN program. Dominant variability of the ITF and related marginal seas are primarily driven by wind forcing, which can be monitored by scatterometers (e.g., SeaWinds on QuikSCAT and ASCAT on Metop). Scatterometer-derived wind measurements can be used to estimate near-surface Ekman transport as well as to diagnose signals in the thermocline or deeper layers in response to Ekman pumping. The latter not only generates local variability in the ITF region but can cause perturbations in the Pacific and Indian oceans that propagate into the ITF region to affect property transports. Oceanic responses to local and remote Ekman pumping have signatures in the variation of sea surface height (SSH), which can be measured by altimeters (e.g., JASON-1, ENVISAT, GFO). Altimetry data will be used to determine the Indonesian seas' sea-level and ocean-bottom-pressure (OBP). Song (2006) and Qu and Song (2009) recently proposed a method that allows the use of satellite-observed sea level and OBP for estimating the transport through a strait. Although the method has its
limitations due to the simplified formula and the satellite data resolution, it may provide a useful upper bound of strait transport in the Indonesian seas. Therefore, satellite altimetry and scatterometry provide important sources of information to help diagnose the physics of circulations in the ITF region, for instance, to evaluate the relative role of local, Pacific and Indian Ocean forcing. Moreover, satellite observations can help interpret in situ observations and constrain ocean model and assimilation systems.

4.2.5 Process monitoring components

Other monitoring components of PACSWIN are process studies including 1) marginal sea effects, 2) biochemical tracers and 3) tides and tidal mixing, which are briefly described here but will be detailed in an operation plan. These components require some special measurements and monitoring. For example, the marginal sea input of mass and property through the Sunda shelf is monitored through the Kalimantan Strait section by hydrographic surveys, gliders and cables. Monitoring of biochemical tracers is through hydrographic survey and ship cruises from Rossette bottle samplers. Monitoring of tides and tidal mixing is realized through tidal gauges, tidal stations and the high resolution of CTD surveys. These components have an important impact on the ITF and associated variability in transport, heat and fresh water fluxes and ecosystem. They resolve some concerns of processes relevant to the ITF. The South China Sea (SCS) and Celebes Sea are known to have a great impact on the ITF, particularly during the winter monsoon. Qu et al. (2006) estimated that up to 0.2 FW of heat and 0.1 Sv of freshwater are transported into the Indonesian seas from the SCS. Gordon (2005) conjectured up to 1 Sv of total marginal sea input to the ITF during the boreal winter monsoon. Though the volume transport of the SCS throughflow is small in comparison with the ITF, its impact on the Pacific-to-Indian Ocean heat transport is hypothesized to be large (Qu et al. 2005). Tózuka et al. (2007) recently conducted a numerical experiment and provided a better insight into this hypothesis. The results demonstrated that the SCS throughflow reduces the ITF heat transport by as much as 47% in the model, thereby playing a potentially important role in regulating the SST pattern in the tropical Indo-Pacific Ocean.

A project called South China Sea – Indonesian Seas Transport/Exchange (SITE) has been carried out, a collaboration between the LDEO-Columbia University, BRKP-Indonesia and FIO-China. Five moorings (three moorings at the Kalimantan Strait and two moorings in Sunda Strait) were deployed in December 2007 and November 2008 to measure the flow between the SCS and Java Sea and Indian Ocean (Susanto, personal communication, 2009). Measurement of the SCS throughflow via the Kalimantan Strait and Celebes and Sulu Seas is considered in the hydrographic survey sections and glider mission (Figure 7).

The Arlindo CFC survey showed stratification of CFCs in the vertical structure of the Indonesian seas' water column, consistent with the thermohaline stratification of the water mass (Gordon & Fine 1996). Spatial and vertical fluxes of biochemical tracers are crucial to the study of the Indonesian seas' ecosystem. On the other hand, without understanding the physical process of the ITF system, many ecosystem phenomena are difficult to interpret. This is because the Indonesian seas ecosystem is a consequence of many environmental conditions such as ITF, tides/tidal mixing, upwelling/downwelling, heat/fresh water fluxes, the monsoon and ENSO. The large marine ecosystem is considered a Class II, moderately high (150–300 grams of carbon m²/year) productivity ecosystem based on SeaWiFS global productivity estimates (NOAA 2008). The Indonesian seas' ecosystem is vulnerable to environmental change. Human activity and pollution as well as climate change are threatening the Indonesian seas' ecosystem. This topic, as a component of PACSWIN, could be better addressed under high priority monitoring components.

Tides and tidal mixing play a crucial role in the Indonesian Mixing Master (Gordon 2005). Various source waters from the Pacific and marginal seas are mixed and blended by tidal forcing into a single Australasian Mediterranean Water (AAMW) (You & Tomczak 1993) feeding the Indian ocean thermocline and intermediate water masses. Tides and tidal mixing in the Indonesian seas are most complicated. Tides from the Pacific and Indian oceans meet in the Indonesian seas, interact with the intricate bottom topography, numerous islands, deep and shallow straits, shore lines and shallow shelves inducing barotropic and baroclinic tides as well as small-scale
internal tides (Robertson & Ffield 2008). The monitoring component of PACSWIN on tides and tidal mixing will rely on existing tidal gauges, the aforementioned mooring observations and high resolution CTD and XBT data along the hydrographic sections (Figure 7).

4.3 Scientific studies

4.3.1 Lagrangian characterisation of archipelago strait dynamics

In addition to the observational phase for tracing the Pacific source waters with Lagrangian techniques proposed in section 4.1.3.3, here we propose a comprehensive study of archipelago strait dynamics for PACSWIN using combined Lagrangian and other observational tools and laboratory experiments. We aim (1) to collect and analyse novel and exploratory Lagrangian velocity and stratification measurements to characterise the time- and space-dependent mesoscale variability in and around two specific Indonesian straits (Figure 15) and (2) to synthesise these observations with idealised laboratory simulations to elucidate the underlying dynamics and to facilitate assessment of more complex numerical simulations and predictions. Our goal is to determine not only what makes each strait unique but also to identify fundamental processes and dynamical regimes with relevance to other locations.

The proposed study focuses on the meso- and submesoscale circulation within two structurally different but adjacent Indonesian straits, Makassar and Lombok, as well as the region between these straits and the areas immediately up- and downstream of each. The major study will focus on three main topical areas. These are, in order of emphasis:

1) Exploratory measurements of horizontal flow patterns, including detailed descriptions of meso- and submesoscale variability and investigation of the responsible dynamical processes

2) Measurements of the temporal and spatial variation of upper-ocean stratification and horizontal velocity shear using temporal sampling resolution appropriate to the detection of internal waves and solitary waves

3) Estimates of low-frequency acoustic transmission loss and relationships to mesoscale variability, coherent features and topography.

In addition to providing unparalleled horizontal and temporal sampling coverage, Lagrangian measurements are uniquely capable of addressing fundamental questions regarding intrinsic time and length scales, the influence of topography on both the mesoscale and low-frequency circulation, and the relationship of coherent structures (eddies, filaments, etc) to upstream dynamic conditions. Float and drifter trajectories, either singly or in clusters, provide access to estimates of horizontal or isopycnal dispersion and may be directly compared with and/or assimilated into numerical ocean models. We propose to focus our measurements on the time-varying mesoscale velocity field, including explicit resolution of the
additional 30 isobaric RAFOs floats are proposed for measuring the horizontal circulation at a depth of 800 m (shallower than the controlling sill in the Makassar Strait). To resolve the semidiurnal tide, acoustic positions will be obtained eight times per day. Based on recent work in the Luzon Strait (e.g. Ramp et al. 2004) we expect internal waves to be generated by the interaction of strong tidal or mesoscale velocities with topography. The isopycnal floats will measure temperature and pressure hourly and provide estimates of thermocline excursions associated with internal waves and solitons. To improve temporal resolution, we will burst sample T & P at approximately one minute intervals several times per day. The buoys will alternate between acoustically tracked isopycnal drift (using active ballasting) and rapid 0–500 profiles of temperature and salinity. These floats will yield unique records of temporal and spatial variability including the Lagrangian evolution of potential vorticity.

In parallel with the observational program, we will conduct idealised laboratory modelling in order to identify the fundamental dynamics governing inertial flow through archipelago straits. The laboratory results will bring dynamical insight on a wide range of straits, including but not limited to those addressed by this proposal. In fact, the laboratory modelling will provide a dynamically consistent means to transfer the understanding gained during this field program to the multitude of other strategically relevant archipelago straits in the western Pacific and globally. The laboratory experiments will be highly quantitative, using both particle tracking and particle image velocimetry. Both stationary and rotating tank experiments will be performed. For this effort, three nondimensional parameters will be varied: the ratio of the channel width, $W$, to the Rossby radius of deformation, $R_d$, the Froude number, $Fr$, and the Reynolds number, $Re$. The external parameters controlling the ratio $W/R_d$ will be varied to examine three regimes: $W < R_d$, $W = 0(R_d)$ and $W > R_d$ and, by varying the velocity of the inertial flow through the strait, we will span different values of $Fr$ and $Re$. We hypothesise the occurrence of at least three regimes: laminar (low $Re$ and $Fr$), hydraulically controlled (for $W < R_d$, $Fr > 1$, and low $Re$) and mesoscale eddies (for $W < R_d$ and large $Re$).
Laboratory models, while highly complementary with numerical simulations, are particularly desirable in this instance because they use real fluids, with known viscosities and diffusivities. There is a true no-slip boundary condition at the bottom, and dynamics are fully nonlinear with no approximations involved. Fully turbulent flows with large Reynolds numbers are possible, with all scales of motion (within the tank) fully resolved. Direct comparison with in situ observations will be possible using synthetic floats in the laboratory. We anticipate that such comparisons will both aid in the interpretation of the field results and help guide observational strategies.

4.3.2 Other topical studies

Other major topical studies related to the ITF include 1) low latitude western boundary currents, 2) the equatorial current system, 3) ENSO and the 4) monsoons. The low latitude western boundary currents (LLWBCs) are defined as those western boundary flows that are directly connected to the strong wind-driven zonal flows of the tropics and an important component of the equatorial heat and mass budgets, contributing to fraction of the cross-equatorial transport of mass, heat and salt. Thus they are an important element of the global climate system (Lukas et al. 1996). Since the major sources of North and South Pacific origin are carried by the equatorward LLWBCs, the Mindanao Current and New Guinea Coastal Undercurrent (NGCUC), it is particularly important to study these currents, transport and water-mass properties from the hydrographic survey along the Pacific sections Pacc to Pacc9. In addition to physical properties such as temperature and salinity, nutrients and biochemical tracers will also be used to identify the source waters. Analysis of water-mass properties in the LLWBCs' water will distinguish different sources. Hu et al. (1992) discovered the Mindanao Undercurrent, which may imply the pathway of the cross equatorial South Pacific source waters. However, its northward intrusion in the western North Pacific is an issue of debate. The open question as to whether or not the South Pacific sources cross the equator northward may help to identify the pathway of South Pacific-originating water along the middle route (Figure 7).

The LLWBCs are connected with the equatorial current system as seen in Figure 1. The North and South Pacific sources brought to the far western equatorial Pacific by LLWBCs are regulated by two prominent eddies, the Mindanao and the Halmahera Eddy, which draw the source waters eastward to the equatorial interior in the North Equatorial Counter Current. It is unknown how the eddy and equatorial current system controls the source waters of North and South Pacific origin, partly effectively entering the Indonesian seas and partly removed away from the entrance into the equatorial interior. In the eastern Indian Ocean, the blended Indonesian water (AAMW) is mainly contained in the westward South Equatorial Current (Figure 1). However, it is unclear how the southward Sumatra-Java Current interplays with the outflow.

It is well understood that the ITF contains an ENSO signal showing an interannual variability with a phase of the ENSO cycle. During El Niño, ITF transport is usually smaller and larger during La Niña. One of the obvious reasons is that sea level during El Niño is lower than that during La Niña affecting the Indo-Pacific geopotential levels. Gordon et al. (2008) observed a strong ENSO suppression on the Makassar Strait throughflow resulting in a 2004–06 transport and temperature of 27% and 1°C higher than 1997 at 11.6±3.3 Sv and 15.6°C. During INSTANT, ENSO is weak from a transition of the El Niño phase to the La Niña phase. However, the simultaneously measured ITF transport by main strait moorings show a three year mean 20–30% higher than the previous averaged value based on individual estimates from various means (Gordon et al. 2008, unpublished manuscript). For a La Niña suppressed phase, the total ITF transport could be expected to be much higher. Nevertheless, the INSTANT result urges an ENSO monitoring component and the PACSWIN program in general.

The dominant seasonal forcing in the Indonesian seas and adjacent region are the monsoons since the region lies in the Intertropical Convergence Zone (ITCZ). The Indonesian seas are covered by the Asia-Australia monsoon with a much stronger winter monsoon than summer monsoon. The winter (north-west) monsoon can force the surface currents of the ITF to reverse (Gordon 2005). The imbalance of the monsoon forcing induces intra-seasonal variability of the upper ITF transport. The most significant impact of
monsoon forcing on the ITF is a winter monsoon that drives cool/fresh water out of the marginal seas into the Indonesian seas and intensifies mixing. In the boreal summer, the cool/fresh Indonesian seas water flows back to the South China Sea and Sulu Sea. The total cool/fresh water transport from the marginal seas contributing to the ITF is conjectured as roughly 1 Sv (Gordon 2005). Monitoring of the monsoon as one of the PACSWIN components is important not only to the ITF volume transport but also for heat and fresh water fluxes. The PACSWIN observational programs outlined above should satisfy the need for monsoon monitoring.

4.4 Modelling of the ITF and its role in global climate change

There have been many attempts to estimate the magnitude of the volume and heat transport associated with the ITF and its pathways within the Indonesian archipelago (see reviews by Godfrey 1996; Gordon 2001). Results demonstrate a wide spread of the values even for the mean magnitude, with significantly large amplitude variations at the seasonal and interannual timescales. The difficulty in simulating the ITF lies in the complex geometry and bottom topography in the region and the strong mixing generated by tidal currents. For example, with a 1/6 degree resolution global Parallel Ocean Program (POP) model, Gordon and McLean (1999) found that, due to the sill depth being almost 400 m shallower in the model than observed in the Makassar Strait, only the upper 250 m (sill depth in POP) current was correctly simulated. Using a recent higher-resolution ocean general circulation model (OGCM), called OFES, Masumoto et al. (2008) indicate that magnitude of the ITF is reasonably simulated with a mean transport of about 11 Sv. However, they also demonstrated that the water mass properties within the Indonesian archipelago are quite different from those observed due to the lack of a tidal mixing parameterisation in the OFES. A recent modelling effort by Koch-Larroque et al. (2008a, 2008b) successfully reproduced the water mass properties by including the effect of tidal mixing in the Indonesian archipelago, confirming the importance of mixing in this particular region. However, detailed volume, heat and salt transports through each major ITF passages and their relationships to the Pacific inflows and the Indian outflows are not yet well understood. For example, the simulated large positive heat flux of the ITF into the Indian Ocean, contrary to observation, is probably due to an unresolved mixing of the IIM mechanism and the omission of some Pacific source waters such as NPIW in numerical models.

Influences of the ITF on the global climate system cannot be correctly addressed without considering air-sea interaction. Only when ocean and atmosphere feedbacks are accounted for in a coupled general circulation model (CGCM) can the full global impact of the ITF on the climate system be assessed. In general, the ITF tends to warm the upper Indian Ocean and deepen the thermocline there due to the warm water flowing from the western tropical Pacific to the eastern Indian Ocean, while the opposite situation occurs in the western tropical Pacific where water gets cooler due to the loss of heat to the Indian Ocean. By blocking the ITF in a CGCM, an ENSO-like response is produced over the equatorial Pacific and there is a dipole mode signature over the Indian Ocean (Hirst & Godfrey 1995). They also demonstrated that there was a significant difference in the surface heat flux distribution between the open and closed ITF cases. With the opening of the Indonesian straits, the net surface heat flux from the Pacific to the Indian Ocean is doubled in contrast to an ocean-only simulation (Wajcowicz & Schneider 2001). An open ITF in the CGCM also shows an accelerated equatorial undercurrent in the Pacific Ocean and a decreased Indian Ocean response to a change of wind stress and meridional and zonal thermocline gradients (Schneider 1998). Using the Geophysical Fluid Dynamics Laboratory (GFDL) CGCM, Song et al. (2007) restate a mean condition by closing the ITF — that is, SST in the eastern Pacific (Indian) is warm (cool), the near-equatorial Pacific (Indian) thermocline flattens (shoals), the Indo-Pacific warm pool precipitation shifts eastwards, the tropical Pacific trade wind relaxes and anomalous easterlies occur over the equatorial Indian Ocean. When their CGCM permits interannual diagnostics, interannual variability intensifies in the equatorial Pacific and the eastern Indian Ocean and ENSO becomes more energetic and frequent.

Considering the proposed intensive observations of PACSWIN, that will provide an invaluable data set in and around the Indonesian archipelago, and the recent capability of high-resolution OGCMs and CGCMs, now is the
time to revisit the evaluation of the detailed transport and property distributions, the ITF pathways and its impact on the regional, basin-scale and global ocean circulations and climate.

The PACSWIN model components comprise studies utilising ocean-only models, atmosphere-ocean coupled models, fully coupled climate models and paleoclimate models. In addition to outputs from prognostic models, results from ocean state estimations with a data assimilation scheme will be used.

For the ocean component, current high-resolution models can reach a horizontal resolution of 0.1 degree or higher, such as POP and OFES, which is crucial for resolving the narrow Indonesian straits and the complicated bottom topography. A locally enhanced high-resolution model nested in a global model with less high resolution is also utilised for studying the global climate impact on the ITF. Such a model has been developed by Australia’s CSIRO and BOM under the BlueLink program. The model has a regional resolution of 10 km, resolving the mean and eddy flow fields but, outside of the Australia-Indonesia seas' region, the model has a coarse resolution. The INSTANT moorings provide a benchmark for various modelling validation tests of the PACSWIN modelling components. With recent advances in ocean observations, including Argo, surface drifting buoys and tropical mooring arrays, and especially the improved measurement of the ITF from INSTANT, high-resolution data assimilated models would provide a reasonably good simulation of the three-year mooring results.

The initial task of PACSWIN modelling will be to use high-resolution model outputs and to assess and validate the PACSWIN observational projects on the pathways and transports of the ITF and circulation in the western tropical Pacific Ocean, as well as the water mass distributions associated with the ITF system. The focus will be on the three-year mean condition, mean seasonal variations, interannual variations associated with El Niño–Southern Oscillation and Indian Ocean Dipole mode, and intraseasonal variability in and around the Indonesian archipelago. High-resolution, eddy resolving models can reproduce meso-scale eddies and ocean frontal structures generated by internal instabilities in the ocean. The roles of such an oceanic instability on the large-scale ITF system will be investigated. All models will be further adjusted and improved as PACSWIN develops in the coming decade.

For coupled model and climate model components, the impacts of the ITF on the regional, basin-scale and global ocean circulation and climate systems will be one of the main targets to be studied. At the same time, the impacts of many climate variations in remote areas on the ITF will be investigated.

At the completion of the PACSWIN program (in 5–10 years), our understanding of the mean condition of the ITF and its variability will be enhanced significantly, and the target model should attain optimal performance in simulating the ITF and associated ocean and climate conditions.

5. Programmatic development

5.1 An international coordinated program

A successful PACSWIN requires a truly strong international effort. The survey plans, instruments and technologies must be well coordinated among the many participating countries and international organisations, especially those in the Asia-Pacific region. A time span of about two years for pilot studies and between three and five years for operation is currently suggested. Some long-term monitoring projects such as submarine cables will be needed for as long as possible.

PACSWIN has set three priority monitoring projects: submarine cables, floats and moorings. An international submarine cable workshop on cable voltage measurement to monitor transport of ITF has been planned. PACSWIN will integrate with other two proposed ocean programs, SPICE and NPOCE, to constitute a major ocean climate monitoring network in the Indo and western Pacific for at least the coming decade.

Sponsorship will be sought for the PACSWIN program from individual participating national governments and funding agencies including governmental and intergovernmental sectors and other international organisations such as CLIVAR, IOC, SCOR and APEC as well as the private sector. Support from the Indonesian scientific community and government
and collaboration with the international community will be crucial to ensure the success of this international program. A memorandum for joint funding will be submitted to participating national funding agencies.

5.2 CLIVAR endorsement

CLIVAR (www.clivar.org) is one of the World Climate Research Programme (WCRP) (wcrp.wmo.int) projects, which addresses Climate Variability and Predictability with a particular focus on the roles of ocean-atmosphere interactions in climate and of biochemical cycles. PACSWIN in many ways meets the interests of CLIVAR, for example, the First PACSWIN Submarine Cable workshop in Taipei on 9–10 September 2009 endorsed by CLIVAR on 23 April 2008. The CLIVAR endorsement will not only allow PACSWIN to become an officially recognised program but help make it an international coordinated endeavour to satisfy the need for accurate ocean climate information from the region.

A roadmap towards CLIVAR endorsement has been drawn up. PACSWIN was proposed at the CLIVAR Pacific panel meetings in Guang Zhou, China, on 29–30 November 2007 and in Perth, Australia, on 27–28 March 2009. PACSWIN was also proposed to the CLIVAR Indian Ocean panel meeting in Bali, Indonesia on 12–14 May 2008. The progress of PACSWIN was reported to Pacific Panel Meeting 5th session in Perth. A further progress report of PACSWIN along with this document will be submitted to CLIVAR Pacific and Indian panel sessions for review and feedback.

6. Towards a PACSWIN implementation plan

This is the initial report on the PACSWIN scientific description aimed at providing a state-of-the-art ocean climate monitoring program in the Indonesian seas and adjacent regions. The chapter brings an up-to-date view of the scientific proposal from individual program component chairs/co-chairs for future operation. To develop PACSWIN into an international coordinated program, the proposed program components will be agreed upon through the participating country chairs and the wider community in their own countries. Each country chair leads at least one component of PACSWIN. Each component will involve a number of participating countries and scientists. To make PACSWIN operational, participating countries and scientists need to apply for funding from their own government funding agencies. Therefore, PACSWIN will be achieved by coordinated international efforts including personal, technical and funding resources. Detailed operation and activities will appear in future reports.

References


**Appendix 1: Acronyms**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>AAMW</td>
<td>Australasian Mediterranean Water</td>
</tr>
<tr>
<td>AC</td>
<td>Agulhas Current</td>
</tr>
<tr>
<td>ADCP</td>
<td>Acoustic Doppler Current Profiler</td>
</tr>
<tr>
<td>AGCM</td>
<td>atmosphere general circulation model</td>
</tr>
<tr>
<td>APEC</td>
<td>Asia-Pacific Economic Cooperation</td>
</tr>
<tr>
<td>APEX</td>
<td>Autonomous Profiling EXPLorer</td>
</tr>
<tr>
<td>Argo</td>
<td>Array for Real-time Geostrophic Oceanography</td>
</tr>
<tr>
<td>ARLINDO</td>
<td>Arus Lintas Indonesia</td>
</tr>
<tr>
<td>ASCAT</td>
<td>advanced scatterometer</td>
</tr>
<tr>
<td>BOM</td>
<td>Bureau of Meteorology</td>
</tr>
<tr>
<td>CC</td>
<td>California Current</td>
</tr>
<tr>
<td>CGCM</td>
<td>coupled atmosphere and ocean general circulation model</td>
</tr>
<tr>
<td>CLIVAR</td>
<td>Climate Variability and Predictability Experiment</td>
</tr>
<tr>
<td>CSIRO</td>
<td>Commonwealth Scientific and Industrial Research Organization</td>
</tr>
<tr>
<td>CTD</td>
<td>conductivity-temperature-depth</td>
</tr>
<tr>
<td>EAC</td>
<td>East Australia Current</td>
</tr>
<tr>
<td>EEZ</td>
<td>Exclusive Economic Zone</td>
</tr>
<tr>
<td>EFS</td>
<td>E-field sensor</td>
</tr>
<tr>
<td>EIE</td>
<td>Equatorial Intermediate Current</td>
</tr>
<tr>
<td>EKE</td>
<td>eddy kinetic energy</td>
</tr>
<tr>
<td>ENSO</td>
<td>El Niño – Southern Oscillation</td>
</tr>
<tr>
<td>ENVISAT</td>
<td>Environmental Satellite</td>
</tr>
<tr>
<td>GAIW</td>
<td>Gulf Alaska Intermediate Water</td>
</tr>
<tr>
<td>GCOS</td>
<td>Global Climate Observing System</td>
</tr>
<tr>
<td>GFDL</td>
<td>Geophysical Fluid Dynamics Laboratory</td>
</tr>
<tr>
<td>GFO</td>
<td>GEOSAT (Geophysical/Geodetic Satellite) Follow-On</td>
</tr>
<tr>
<td>GODAE</td>
<td>Global Ocean Data Assimilation Experiment</td>
</tr>
<tr>
<td>GOOS</td>
<td>Global Ocean Observing System</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>HE</td>
<td>Halmahera Eddy</td>
</tr>
<tr>
<td>IAAIW</td>
<td>Indian Ocean Antarctic Intermediate Water</td>
</tr>
<tr>
<td>IAPSO</td>
<td>International Association for the Physical Sciences of the Oceans</td>
</tr>
<tr>
<td>ICW</td>
<td>Indian Central Water</td>
</tr>
<tr>
<td>IES</td>
<td>inverted echo sounder</td>
</tr>
<tr>
<td>ITIW</td>
<td>Indonesian Intermediate Water</td>
</tr>
<tr>
<td>IMM</td>
<td>Indonesian Mix-Master</td>
</tr>
<tr>
<td>INSTANT</td>
<td>International Nusantara Stratification and Transport</td>
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<tr>
<td>IOC</td>
<td>Intergovernmental Oceanographic Commission</td>
</tr>
<tr>
<td>ITCZ</td>
<td>Intertropical Convergence Zone</td>
</tr>
<tr>
<td>ITF</td>
<td>Indonesian Throughflow</td>
</tr>
<tr>
<td>JADE</td>
<td>Java Australia Dynamic Experiment</td>
</tr>
<tr>
<td>JAFOS</td>
<td>Joint Australian Facility for Ocean Observations</td>
</tr>
<tr>
<td>JASON</td>
<td>Joint Altimetry Satellite Oceanography Network</td>
</tr>
<tr>
<td>KS</td>
<td>Kuroshio</td>
</tr>
<tr>
<td>LADCP</td>
<td>Lowered Acoustic Doppler Current Profiler</td>
</tr>
<tr>
<td>LC</td>
<td>Leeuwin Current</td>
</tr>
<tr>
<td>LCDW</td>
<td>lower Circumpolar Deep Water</td>
</tr>
<tr>
<td>LLWBCs</td>
<td>low latitude western boundary currents</td>
</tr>
<tr>
<td>MC</td>
<td>Mindanao Current</td>
</tr>
<tr>
<td>ME</td>
<td>Mindanao Eddy</td>
</tr>
<tr>
<td>MOC</td>
<td>meridional overturning circulation</td>
</tr>
<tr>
<td>NGCUC</td>
<td>New Guinea Coastal Undercurrent</td>
</tr>
<tr>
<td>NICW</td>
<td>North Indian Central Water</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td>NPCW</td>
<td>North Pacific Central Water</td>
</tr>
<tr>
<td>NPIW</td>
<td>North Pacific Intermediate Water</td>
</tr>
<tr>
<td>NPOCE</td>
<td>Northwestern Pacific Ocean Circulation Experiment</td>
</tr>
<tr>
<td>NPSW</td>
<td>North Pacific Subtropical Water</td>
</tr>
<tr>
<td>OGCM</td>
<td>ocean general circulation model</td>
</tr>
<tr>
<td>OIW</td>
<td>Okhotsk Intermediate Water</td>
</tr>
<tr>
<td>pAAIW</td>
<td>Pacific Ocean Antarctic Intermediate Water</td>
</tr>
<tr>
<td>PACSWIN</td>
<td>INvestigation</td>
</tr>
</tbody>
</table>
Appendix 2: Available resources and technique for PACSWIN from participating countries and institutes

University of Sydney
National facility: R/V Southern Surveyor
National facility: Gliders, moorings
Australian Centre for Field Robotics

University of Rhode Island, www.gso.uri.edu/
Research vessel: 185 foot R/V Endeavor
RAFOS floats and sound sources (Tom Rossby)
The Inverted Echo Sounder (IES) (Randy Watts)

BPPT (Agency for the Assessment and Application of Technology)
Research vessels: R/V Baruna Jaya I to IV

JAMSTEC (Japan Agency for Marine-Earth Science and Technology)
Research vessels: R/V Natsushima, R/V Kaiyo, R/V Yokosuka, R/V Mirai,
R/V Kairei, R/V Hakuyo Maru, R/V Tansui Maru
Submersible Shinkai 6500
Deep-Sea Drilling Vessel: Chikyu
Other Vehicle: Deep-Sea cruising AUV Urashima; Deep-Sea Survey System:
Deep Tow: 3000m remotely operated vehicle: Hyper-Dolphin; 7000m Class
remotely operated vehicle: Kaiko 7000II
Observation facility: Doppler Radar, Radiosonde, TRITON Buoy, CTD,
ADCP, Argo, POCS
Earth Simulator

Scripps Institute of Oceanography
Research vessels: R/V Roger Revelle, R/V Melville, R/V New Horizon, R/V
Robert G Sproul
Floating Instrument Platform (FLIP)
Underwater plane
Weather buoy
3D Sea Scan
Gliders, Argo, moorings

Institute of Oceanography, Chinese Academy of Sciences
Research vessel: R/V Kexue-I, R/V Kexue-III, R/V Jinxing-II
Flow Cytometer, Marine Gravimeter, towed oceanographic vehicle, marine
CTD winch
Other facility: network server SGI3400, stable isotope MS system, modern
gas chromatography-mass spectrometry, ICP-MS, X-ray diffractometer, 500
M nuclear magnetic resonance spectrometer

I.DEO, Columbia University
Research vessel: R/V Marcus G. Langseth
OTIC, CICAR, Environment Tracer Group, ICPMS, ICSN, MARGINS

Woods Hole Oceanographic Institution
Research vessels: R/V Atlantis, R/V Knorr, R/V Oceanus, R/V Tioga
National Deep Submergence Facility: HOV Alvin, ROV Jason/Medea, AUV
ABE/Sentry
Observing systems: moorings, buoys, floats, drifters
Instruments: Sensors/samplers, Seafloor mapping system, Lighting and
camera system, Communication tools, MISOM
Underwater vehicles: HROV Nereus, AUVs, Towed vehicles

Marine Science Institute, University of the Philippines
Research vessel: MV DA-BFAR
Specialise on tropical marine sciences

Institute of Oceanography, National Taiwan University
Research vessel: R/V Ocean Researcher I, R/V Ocean Researcher II, R/V
Ocean Researcher III
CTD, ADCP

Korea Ocean Research and Development Institute (KORDI)
Research vessels: R/V Oumuri, R/V Eardo
Observational equipment: wave meter, CTD, ADCP, Gravity meter, Precise
depth recorder

Institut Français de Recherche pour l’Exploitation de la Mer
(IFREMER)
Research vessels: R/V Pourquoi pas? R/V L’Atalante, R/V Thalassa, R/V Le
Suroit, R/V L’Europe, R/V Gwen Drey, R/V Thalía
Underwater systems: Nautilus, Victor 6000, AUV Aster x, SAR, Scampi,
MIMOSA, ADELIE, VEMO+, POSIDONIA
Acoustic facilities: Multibeam echo-sounders – Simrad EM12/Dual 13khz,
Simrad EM1000, Simrad EM300 30 khz; Doppler current met Button
Doppler – RDI 300 khz, RDI 150 khz, RDI 75 khz; Towed sonar – Edge
TechDF10; Sediment sounders – Elics 2 khz, EDO 3.5 khz; Pingers –
Genesa, Suber; Fishing sounders and sonars; Trawl ing – Scanmar 42 khz,
TMS Pach 2000, Geonet; Acoustic environment – Censea Orca, Sabrina
Seismic survey methods used by the Ifremer fleet. (English Version – pdf
format): Multitrace seismic survey (SMT), High Resolution Seismic Survey
(HR), Rapid digital seismic survey (SIRAP)
PENFELD penetrometer
Other facilities: Gravimeters - KSS30, Lockhead BGM5; Magnetometers –
Baringer M244; Thermosalinometer – Seabird 21, SIS CTD 1000;
Fluorometer; Sea water temperature – TQP, TPP; Bathythermographs –
Sippican MK12; Weather unit – Vaisala Milos 5, Andersa, Informedfic
(NOAA/METEOR), Batos Meteo France
International Pacific Research Center, School of Ocean and Earth Science and Technology, University of Hawaii
Research vessels: R/V Ka‘imikai-O-Kanaloa, R/V Kilo Moana
two research submersibles, the Pisces IV and Pisces V (2000 meters), and the ROV RCV-150 (914 m)
ADCP/LADCP

RSMAS/MAC, University of Miami
Research vessel: R/V FG Walton Smith
Mobile instruments: Air Sea Interaction Buoys, 94-GHz Doppler Cloud Radar, X-Band Cloud Radar, 915 MHz Wind Profiler, Marine-Atmosphere Emitted Radiance Interferometer (M-AERI)
State-of-the-art instruments including a salt-water wave tank, an isotopic mass spectrometer, five-tank Conditioning and Spawning Systems, multi-tank Aplysia Culture Laboratory, Controlled Corals Climate Tanks, Applied Biosystems 3730xl DNA Analyser, Evolution 3 automated liquid-handling system

University of Tokyo
Research vessels: R/V Keikaku, R/V Hakuho

School of Oceanography, University of Washington
Research vessels: R/V Thompson, R/V Barnes
Argo program, SeaGlider system, OOI/RSN

California Institute of Technology, JPL
Various satellite data and products such as altimetry and scatterometry