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The Indonesian Throughflow, 3-year INSTANT composite view

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The transfer of tropical water from the Pacific to the Indian Ocean through the Indonesian seas is considered to be a first order factor in the heat and freshwater inventories of these oceans, and as such are linked by sea-air fluxes to the larger scale climate system (Godfrey, 1996), specifically to El Niño-Southern Oscillation (ENSO), the Asian Monsoon, the Indian Ocean Dipole (IOD). The interocean exchange within the multiple passages of the Indonesian seas is a challenge to observe as well as to simulate accurately within numerical models. For the first time, simultaneous measurement of the flow through the principal pathways within the Indonesian seas, collectively referred to as the Indonesian Throughflow (ITF), was achieved from 2003 to 2006 by the INSTANT program.

Indonesian Throughflow, ITF

The Indonesian seas represent a complex array of passages linking shallow and deep seas (Figure 1). The literature, dating to 1961 (Wyrtki, 1961), offers a wide range of annual mean transport values for the ITF, from near zero to 25 Sv (Sv = 10^6 m^3/sec). Estimates based on observations obtained from the mid-1980s and mid-1990s suggest a mean ITF of ~10 Sv (Gordon, 2005; Figure 1) with interannual and seasonal fluctuations, as well as energetic intraseasonal (<90 days) variability and tides (Gordon, 2005; Qiu et al. 1999; Wijffels et al. 2004; Susanto et al. 2000; Sprintall et al., 2000; Egbert and Ray, 2001; Ray et al., 2005). The ITF is a response to ocean-scale wind stress as characterized by the "Island Rule" (Godfrey, 1989), and to the phase of ENSO (Meyers, 1996; England and Huang, 2005; Wijffels et al., in press) and its Indian Ocean "cousin", the Indian Ocean Dipole, IOD (Saji et al., 1999; Wijffels et al., in press; Potemra, and Schneider, 2007) as well as the regional monsoonal wind pattern over southeast Asia (Gordon et al., 2003; Susanto et al., 2007).

There have been many model studies investigating the ITF impact on the Indian and Pacific heat and freshwater budgets and on the ITF role in the climate system (Hirst and Godfrey, 1993; MacDonald, 1993; Maes, 1998; Murtugudde et al., 1998; Wajsowicz and Schneider, 2001; Wajsowicz, 2002; Schott and McCreary, 2001; McCreary and Lu, 2001; Lee et al., 2002). The model dependent results indicate changes in the ocean surface temperature and meridional circulation within the Indian and Pacific Oceans according to the presence (or not) of an ITF. The ITF affects atmosphere-ocean coupling with potential impacts on the ENSO and monsoon phenomena (Webster et al., 1998).

The water within the thermocline of the Indonesian seas is derived for the most part from the North Pacific Ocean by way of Makassar Strait, while the source water for lower thermocline is drawn from the South Pacific via the Halmahera Sea (Gordon, 2005; Figure 1). Lifamatola Passage east of Sulawesi, with a sill depth of ~2000 m channels spillover of dense water into the depths of the Banda Sea (van Aken et al., 1988).

The Indonesian seas do not simply provide a passive conduit for interocean exchange, as the stratification of the inflowing Pacific is altered before its export into the Indian Ocean. During the ~1 year residence of the Makassar transport ~10 Sv within the Banda Sea (above the sill depth of Makassar Strait, ~700 m), the inflowing Pacific stratification is modified by mixing, with energy derived from dissipation of powerful tidal currents (Ffield and Gordon, 1992, 1996; Egbert and Ray, 2001; Koch- Larrouy et al. 2007), by Ekman pumping (Gordon and Susanto, 2001), as well as heat and freshwater flux across the sea-air interface. This results in a unique Indonesian tropical stratification with a strong, although relatively isohaline, thermocline. The formation of the Indonesian stratification is further complicated as the inflow and outflow at the intraseasonal to seasonal time scales are not necessarily in balance, with water accumulating and modified within the Banda Sea from February to June and released during the rest of the year (Gordon and Susanto, 2001; Qu et al., 2008).

The Indonesian water is exported into the Indian Ocean within the three major passages along the Nusa Tenggara archipelago: Timor Passage, sill depth ~1890 m; Ombai Strait, sill depth ~3250 m; and Lombok Strait, sill depth ~300 m (Figure 1). The waters of the ITF are apparent within the thermocline as a relatively cool, low-salinity streak across the Indian Ocean near 12°S (Gordon, 2005) and at intermediate depths as a band of high silicate (Talley and Sprintall, 2005).

The interocean fluxes of heat and freshwater induced by the ITF does not depend on just the net transport, but also on the form of the velocity, temperature and salinity profiles (Potemra et al., 2003; Song and Gordon, 2004). The annual mean transport may not change, but if the transport profile varies relative to that of temperature and salinity, then the interocean heat and freshwater transports would change accordingly.

INSTANT

In the past, the main throughflow passages have been measured over different years and for varied lengths of time, making it impossible to assemble a reliable synoptic picture of the ITF. Is the ITF transport pattern as shown in Figure 1 faithful to the climatic (long-term) patterns or simply reflecting "noise" due to higher frequency variability?

The International Nusantara Stratification and Transport (INSTANT) program (Sprintall et al., 2004) was established to directly measure the depth dependent ITF from the intake of Pacific water at Makassar Strait and Lifamatola Passage, to the Nusa Tenggara exit channels into the Indian Ocean. The collective merit of the INSTANT program over prior measurements of the ITF is the simultaneous, multi-year measurements in all the major inflow and outflow passages (Figure 1). This was only possible by the coordinated effort of an international group of researchers, working in collaboration with Indonesian colleagues. Each had specific responsibilities: United States: Makassar Strait; Lombok, Ombai Straits; The Netherlands: Lifamatola Strait; Australia and France: Timor Passage; Indonesia: CTD observations and ship support.

Three years cannot capture the climate mean ITF (low frequency fluctuations of the climate system make this effectively impossible), but the simultaneous measurements within the key passages capture the state of the ITF and its profile over a specific time period, revealing its tidal, intraseasonal to annual cycles, with a glimpse of interannual variability. INSTANT fieldwork began in December 2003/January 2004 and was completed in November/December 2006. ENSO during the three year INSTANT period was in a weak El Niño state, with a La Niña phase in late 2005 into early 2006 (Figure 2), providing some confidence that the three year ITF mean might be a fairly good representation of a longer term mean. The IOD during the INSTANT period was near zero, but with a substantial positive phase in the latter half of 2006 (Vinayachandran et al., 2007). The role of IOD in influencing the ITF transport independent of ENSO is not clearly established.

INSTANT Speeds

A composite view of the along-channel velocity time series at various depths reveals much variability (Figure 3). Detailed analysis is underway, but a few features are revealed by simple inspection of the time series. At all levels Makassar and Timor throughflow are relatively steady, in comparison to Lombok and Ombai, which are rich in intraseasonal oscillations. These features are likely related to Kelvin waves that propagate from the Indian Ocean along the southern coast of Sumatra and Java (Sprintall et al., 2000; Wijffels and Meyers, 2004). The inflow and outflow pattern of the along-channel speeds do not rise and fall in tandem, suggesting either an imbalance due to internal storage of water within the stratum of the interior seas of Indonesia, most likely within the large Banda Sea, or vertical transport between layers. Both of these processes may occur, although continuity constrains full depth imbalance to relatively short time periods. The partitioning of the speeds into the Indian Ocean among the three export channels varies substantially with time.

The surface layer (represented by the 50 m panel of Figure 3) shows near zero and even flow reversals during the northwest monsoon (boreal winter) at all passages. Significant reversals of up 0.5 m/s at Lombok and Ombai Straits are also observed in June 2004 and April 2006. Lombok and Ombai exhibit the greatest range of speeds, from +0.7 to –1.1 m/s. Makassar and Timor have equivalent speeds at 50 m of ~0.4 m/s. However, during the southeast monsoon (boreal summer) Makassar speeds at 50 m exceed that of Timor by a factor of 2.

Within the thermocline (the 150 m panel of Figure 3) the intraseasonal fluctuations are somewhat subdued relative to that in the surface layer, although Ombai continues to display the most vigorous variability. The Makassar thermocline speeds are about 50% larger than that of the surface layer, and are about two to three times the thermocline speeds in Timor Passage. Thermocline intensification of Makassar Strait throughflow was also observed in 1997 (Gordon et al., 1999) leading to a cooler then expected heat flux (Gordon et al., 2003). The lack of a sustained thermocline intensification in the outflow indicates that the presence of net upwelling within the Banda Sea.

In the lower thermocline (the 350 m panel of Figure 3) there is reduced along-channel flow. Lombok, Timor and Lifamatola speeds are generally less than 0.1 m/s, though at Timor the speeds rise to 0.2 m/s towards the Indian Ocean from February to April in each of the INSTANT years, and Lifamatola displays a preference to flow towards the Pacific Ocean of ~0.1 m/s from August 2005 to June 2006. Ombai continues to display the most variability. The Makassar speeds at 350 m are slightly more variable than observed at 150 m.

Within the deep layers, >750 m, the 'stand-out' is the vigorous overflow into the Banda Sea through Lifamatola Strait, with speeds of about 0.5 m/s, and up to 0.75 m/s, at 1750 m, about 250 m above the sill depth. The speeds at the other passages are generally less than 0.2 m/s, but Ombai speeds reach 0.4 m/s in the early stages of both the northwest and southeast monsoon, with the exception of the southeast monsoon of 2006. The 750 and 1500 m time series in Makassar, both below the 680 m topographic sill depths average near zero, with intraseasonal fluctuations distinctly out of phase.

It is premature to present the INSTANT ITF transport values, as its estimation requires further processing the data, tackling such issues as extrapolation to the sea surface and to the sidewalls. However, initial analysis suggests that the mean ITF transport during the 2004-06 INSTANT periods appear to be larger, by perhaps 20 to 30% over those estimated for pre-2000 observations (Figure 1). There is a clear semi-annual signature to the ITF transport, and at Makassar Strait a 1 month delayed response to ENSO is suggested. The increased speeds in 2006 (Figure 3), particularly at the 150 and 350 m depths at Makassar, may be related to the occurrence of La Niña in boreal winter 2005/06 (Figure 2), and perhaps with the positive IOD in the latter half of 2006.

What Next?

Now that we have a synoptic view of the ITF over three years, 2004-2006, what next? Beside the underway thorough analysis of the INSTANT data set in conjunction with other regional data as drawn from satellite and ocean observations systems, two actions are suggested: 1) to evaluate model simulations of the ITF and 2) to build a cost-effective ITF monitoring system.

Model Evaluation: Quantitative comparison of ocean observations and model output is very much needed. As observations improve, covering more of the spatial and temporal scales, and as models incorporate more realistic physics and fluxes, and move towards higher spatial resolution (even tackling such high frequency as tides), such comparison is becoming increasingly feasible. The INSTANT observations offer an ideal and challenging opportunity to investigate the validity of model simulation of the ITF. The premise is: if models can get the 2004-2006 ITF "right", then they offer a useful research tool for study of the ITF role in the regional and larger scale ocean and climate system, including reliable prediction. The complexity of the ITF represents a challenge to large scale numerical models, where the grid resolution is hardly more that the width of various passages funneling the ITF to the Indian Ocean. Furthermore, the simulation of tides and their resultant mixing is only beginning to be included in such models.

Quantitative comparison of INSTANT observational data to model output was initiated at a workshop held at Lamont-Doherty Earth Observatory on 28-30 May 2008. The major groups of global and regional modeling were represented. The comparisons were encouraging, models with the finer spatial resolution and the more realistic bottom topography, did quite well in simulating the INSTANT data. Inclusion of tides (explicitly or parameterized) helps the realism of the simulation.

One task identified at the workshop is to consider a set of metrics defining the ITF conditions to help provide structure for quantitative comparison of observational and model based data. Metrics include the transport through defined channels, and the

ITF velocity, temperature and salinity profiles, their mean state and their variability across the wide range of temporal scales. A discussion of effective metrics is at: http://www.marine.csiro.au/~cow074/instantmetrics.htm.

Long Time Series Observations: The INSTANT data set provides the first simultaneous measurement of the major streams of the ITF. However, the INSTANT observations extend only over a 3-year period. How characteristic are these three years of the longer term mean? What is the relationship of the ITF to larger scale climate variability? There are also other topics, such as the regional marine ecosystem, which is likely to dependence on the ITF. While models can help delve into these topics, for the foreseeable future a direct observational array of the ITF is needed, if only to valid model output.

In order to provide a link between INSTANT and future monitoring systems a current mooring was deployed in Makassar Strait at the time the INSTANT moorings were recovered in 2006. The Makassar mooring will be maintained and serve as an important component of an ITF monitoring array. What might be other components? Shallow pressure gauges (Figure 1) offer a method to capture the surface layer flow (Sprintall et al., 2003). Repeat XBT and XCTD sections offer snapshot views of the ITF stream entering the Indian Ocean (Meyers, 1996; Wijffels et al., in press). Data telemetry from instrumented drifters and Argo profiles (see: http://www.argo.ucsd.edu/) offer regional views for the ocean condition. Regional characteristics are also obtained from satellite, such as altimeter (Potemra, 2003) and ocean color (Susanto et al., 2006).

The exact form of a cost-effective ITF monitoring system needs to be developed. The INSTANT data set will be central in defining the elements of such a system. The Ocean Observations Panel for Climate (OOPC) http://ioc3.unesco.org/oopc/about/index.php and the CLIVAR Indian Ocean Panel http://www.clivar.org/organization/indian/IndOOS/obs.php are considering a sustained ITF ocean observing system.

The INSTANT program's three year record of the ITF provides an opportunity for further exploration of the interactive relationship of the ITF to the oceanography of the Indonesian seas and to the large scale of Pacific and Indian Oceans and climate system. The quantitative comparison to models output will lead to improved simulation of the ITF in regional and global ocean and climate.

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Figures

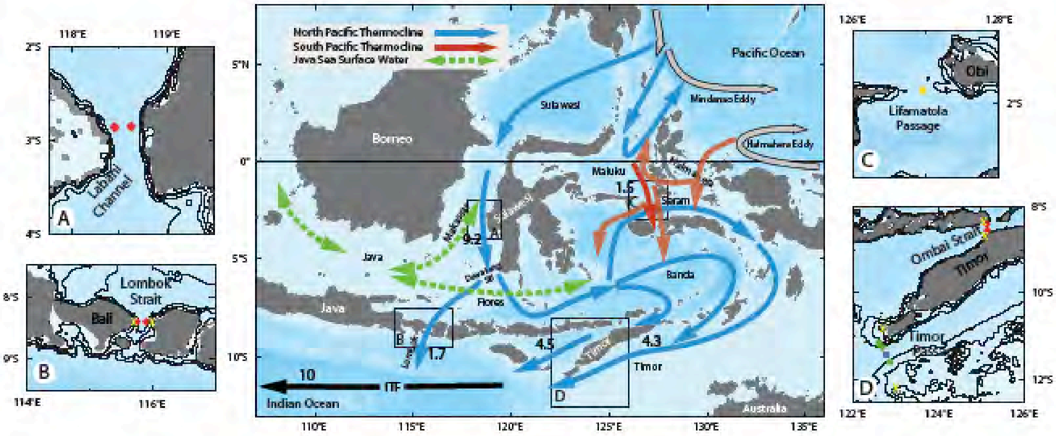


Figure 1 Schematic of ITF (modified from Gordon, 2005). The blue arrows represent the flow pattern of North Pacific thermocline water; the solid orange arrows represent South Pacific flow entering the Indonesia Halmahera Sea within the lower thermocline; the red arrow represent overflow of Pacific water across the 2000 m sill of the Lifamatola Passage into the deep Banda Sea. The dashed green arrows represent the monsoonal reversing flow of surface water between the Java Sea. Transport values in 10^6 m^3/sec are given in black, representing different observational periods: Makassar Strait in 1997 (Gordon et al. 1999; Susanto and Gordon, 2005); Lombok Strait in 1985 (Murray and Arief, 1988; Arief and Murray, 1996); Timor Passage (south of Timor) from March 1992 to April 1993 (Molcard et al. 1996); Ombai Strait (north of Timor) for 1996 (Molcard et al., 2001). The transport values for the passage between Java and Australia are derived from a variety of sources (Meyers et al., 1995; Meyers, 1996; Quadfasel and Godfrey, 1992). The overflow at the Lifamatola Passage sill was estimated as 1.5 Sv (Van Aken et al., 1988). Inserts A-D the position of which are shown by the boxes in the central frame, with 100, 500, and 1000 m isobaths, show positions of INSTANT moorings and positions of the shallow pressure gauges (yellow X's).

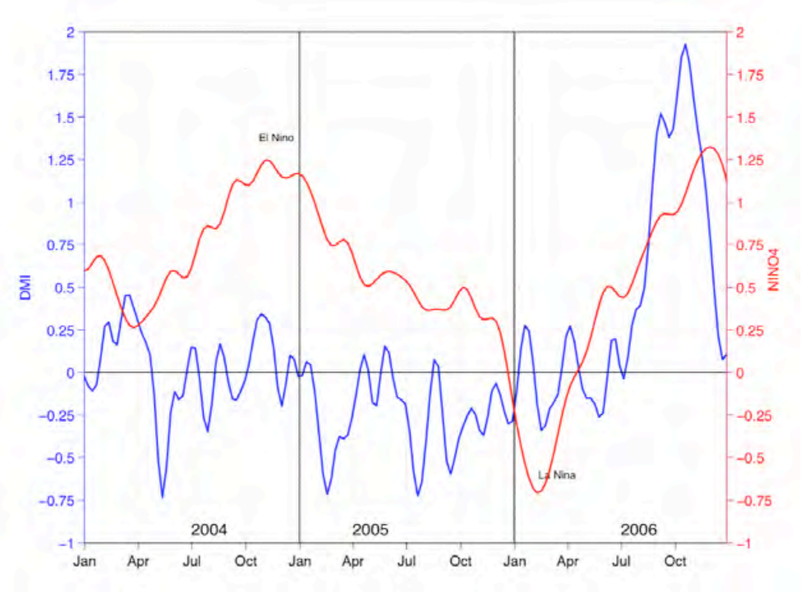
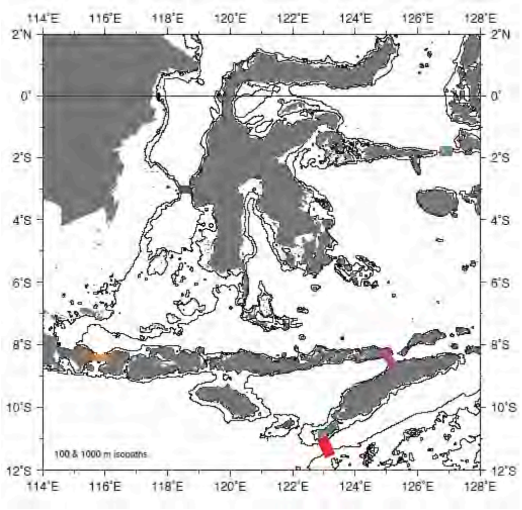


Figure 2 The Nino4 index and IOD index during the INSTANT period.



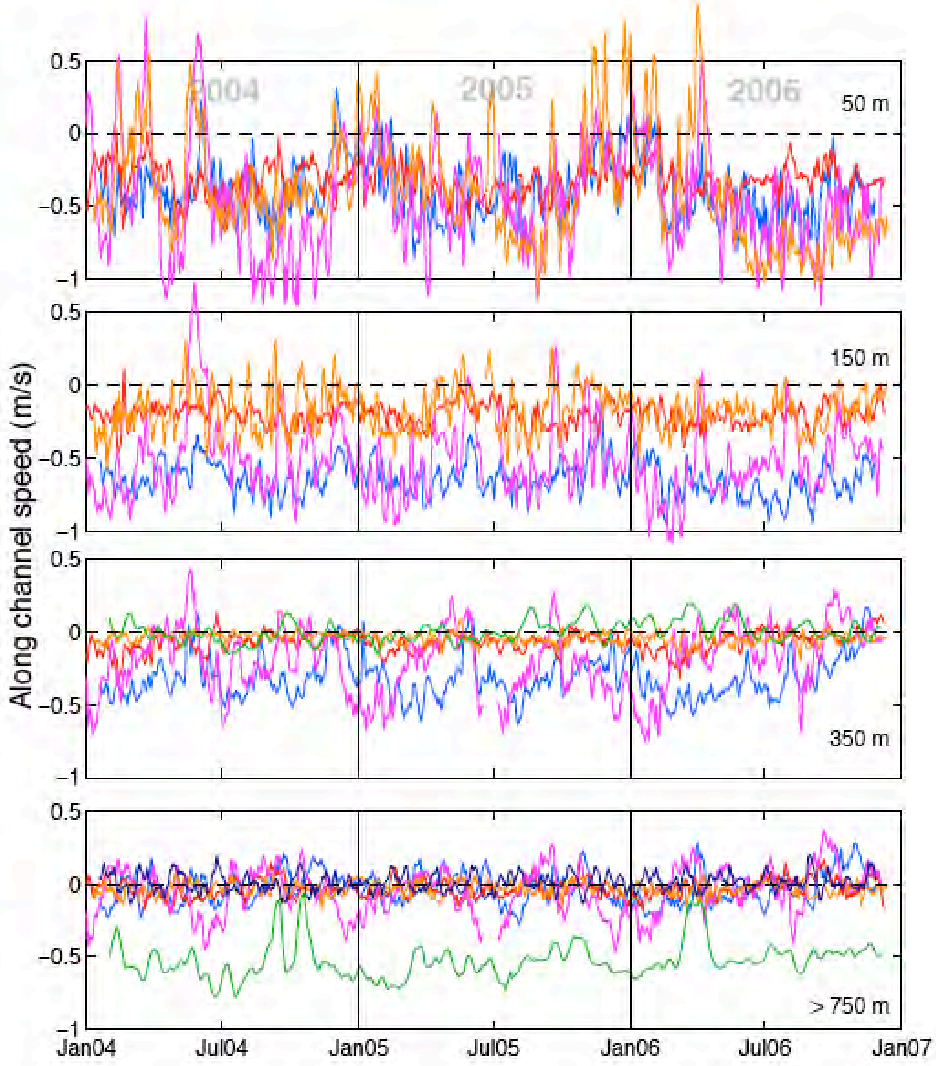


Figure 3 Time series of along-channel currents in m/sec within the key passageways of the Indonesian Throughflow [lower panel] as measured by the INSTANT mooring array [upper panel]. Negative values denote flow to the south or west (towards the Indian Ocean, depending on the orientation of the passage). The severe blow-over of the Lifamatola mooring prohibited measurements in the surface and thermocline layers. The Lifamatola time series in the >750 m panel is from ~1750 m. The Makassar Strait is represented by two lines in the >750 m panel, the lighter blue is from a current meter set at 750 m depth, the darker blue line is from a 1500 m current meter.