

The first 1.5 years of INSTANT data reveal the complexities of the Indonesian Throughflow

A. Gordon<sup>1</sup>, I. Soesilo<sup>7</sup>, I. Brodjonegoro<sup>7</sup>, A. Field<sup>3</sup>, I. Jaya<sup>8</sup>, R. Molcard<sup>6</sup>, J. Sprintall<sup>2</sup>, R. D. Susanto<sup>1</sup>, H. van Aken<sup>4</sup>, S. Wijffels<sup>5</sup>, S. Wirasantosa<sup>7</sup>,

1. LDEO, Palisades, NY, USA
2. SIO, La Jolla, CA, USA
3. ESR, Seattle, WA, USA
4. NIOZ, Texel, the Netherlands
5. CSIRO, Hobart, Australia
6. LOCEAN, Paris, France
7. BRKP, Jakarta, Indonesia
8. IPB, Bogor, Indonesia

The major oceans basins are connected by passages of varied widths and depths. These passages allow for interocean exchange of water properties, which tend to reduce, though not remove, the thermohaline differences between the oceans. Such interocean exchange influences the heat and freshwater budgets of each ocean basin and in so doing represent an important part of the climate system. Most of the interocean exchange routes are at high latitudes, allowing for the establishment of the Antarctic Circumpolar Current and for low salinity surface water flow into the Arctic Sea by way of the Bering Strait. At mid-latitude there is leakage of subtropical Indian Ocean thermocline water into the South Atlantic around the southern rim of Africa. The Indonesian seas alone allow for an interocean exchange of *tropical* waters in what is referred to as the Indonesian Throughflow (ITF): a transfer of warm, relatively low salinity Pacific waters into the Indian Ocean. The ITF affects both oceans, though perhaps more so the thermohaline stratification of the smaller Indian Ocean. While the literature of the last 45 years offers a very wide range of annual mean transport values for the ITF, from near zero to  $25 \times 10^6 \text{ m}^3/\text{sec}$ , the more recent estimates narrow the range to  $10 \pm 5 \times 10^6 \text{ m}^3/\text{sec}$  with large seasonal and intraseasonal variability (Wijffels and Meyers, 2002; Gordon, 2005).

The ITF stream is fed from the North Pacific thermocline waters, though within the lower thermocline and deeper levels the waters are drawn directly from the South Pacific. The primary inflow passage is Makassar Strait, with the Lifamatola Passage east of Sulawesi the dominant deep-water route. During residence in the Indonesian seas the inflowing Pacific stratification is modified by mixing, with energy derived from dissipation of the powerful tidal currents within the rugged sea floor topography, and by buoyancy flux across the sea-air interface. This results in a unique Indonesian tropical stratification—one of a strong, though relatively isohaline, thermocline. The Indonesian water is exported into the Indian Ocean via the three major passages within the Sunda archipelago: Timor Passage, Ombai Strait and Lombok Strait. The waters of the ITF are apparent within the thermocline as a cool, low-salinity streak across the Indian Ocean near  $12^\circ\text{S}$  (Gordon, 2005) and at intermediate depths as a band of high silicate (Talley and Sprintall, 2005). These ITF waters have no choice but to exit the Indian Ocean within

the poleward-flowing western boundary Agulhas Current, though not before mixing and recirculating with ambient Indian Ocean thermocline water and interacting with the monsoonal atmosphere. The ITF acts to flush the Indian Ocean thermocline waters to the south by boosting transport of the Agulhas Current, increasing both the southward ocean heat flux across 20-30°S and the sea-air heat fluxes within the Agulhas Retroflexion, over the no-ITF condition (Gordon, 2005).

The ITF is a fundamental component of the climate system and affects the marine ecosystems of the Indonesian seas, yet it is poorly observed and simulated in ocean and climate models. The main throughflow passages have been monitored but over different years and for varied lengths of time, making it impossible to assemble a simultaneous picture of the multiple corridors of the ITF. The International Nusantara Stratification and Transport (INSTANT) program (Sprintall et al, 2004) will do much to develop a far more quantitative appreciation of the Throughflow phenomena. INSTANT is a multi-national (Indonesia, United States; Australia, The Netherlands, France) program to measure the velocity, temperature and salinity of the Indonesian Throughflow within all of the primary inflow and outflow passages simultaneously (figure 1), a feat never before accomplished.

The objectives of INSTANT are: 1. To determine the full depth velocity and property structure of the Throughflow and its associated heat and freshwater flux; 2. To resolve the annual, seasonal and intraseasonal characteristics of the ITF transport and properties; 3. To investigate the storage and modification of the ITF waters within the internal Indonesian seas, from their Pacific source characteristics to the Indonesian Throughflow water exported into the Indian Ocean; and 4. Contribute to the design of a cost-effective, long-term monitoring strategy for the ITF.

The initial deployment of ten INSTANT moorings was in December 2003 to January 2004 (the 11<sup>th</sup>, an Ombai mooring, was deployed in August 2003). Approximately 1.5 years later, in June/July 2005, the moorings were recovered and redeployed to acquire an additional 1.5 years of data. The final recovery is scheduled for November/December 2006. A glimpse of the first 1.5 years of INSTANT data is afforded with a composite view of the de-tided along channel speeds for a select mooring and depths within each passage (figure 2).

The along-channel flow within various depth intervals reveals much variability across a wide range of temporal scales, marked with month long periods of significant imbalance between the inflow and export implying substantial convergence and divergence within the interior seas. Makassar Strait along channel speeds are relatively large, with a velocity maximum near 140 m. The southward thermocline speeds are greater towards the latter half of the southeast and northwest monsoons. The estimated Makassar transport is 8 to 9 Sv, about the same or maybe a bit larger than that observed in 1997 during the Arlindo program (Susanto and Gordon, 2005). The highest speeds within the deep water, shown on the >700 m panel, are in Lifamatola Passage at a current meter ~300 m above the sill depth of ~1940-m. There speeds as high as 0.5 m/sec mark the overflow and descent of Pacific water into the depths of the Seram and Banda Seas.

Lombok and Ombai are particularly rich in intraseasonal fluctuations; Makassar and Timor are fairly steady in comparison. Flow into the Indonesian seas is observed within the Lombok and Ombai Straits in late May 2004: a likely cause is a downwelling coastally trapped Kelvin wave propagating eastward along the archipelago as a consequence of a Wyrтки Jet in the equatorial Indian Ocean as was also observed in December 1995 (Molcard et al, 2001) and in May 1997 (Sprintall, et al., 2000). There is a hint of its presence at Makassar Strait, with a similar 5 day delay as observed in Ombai after northward flows appear in Lombok. In the 350-450 m interval the Makassar flow exhibits the strongest Indian Ocean bound flow, but is matched by westward flow within Ombai within two periods, June-September 2004 and December 2004 to February 2005, coinciding with the peak times of the two monsoon phases.

The first 1.5 years of INSTANT measurements coincide with a weak El Niño, but since the redeployment a weak La Niña phase has ensued. As the ITF is thought to be reduced in El Niño and increased during La Niña, it will be interesting to compare the first 1.5 year record with the final 1.5 year record (though the swing in ENSO phase may not be sufficient to impact of the ITF transport).

Analysis of the INSTANT data in addressing the objectives listed above is a challenge we savor. Each time series is information rich and comparing and interpreting the phase differences between the passages and their varied spectra is an exciting prospect. In particular, comparison of these observations to model results will be a most challenging and interesting exercise. We all look forward to acquiring the full 3 year INSTANT record.

+++++

Figure 1. The array of INSTANT moorings. The black arrows show the ITF pathways. The dashed arrow in Lifamatola Passage represents the overflow across the 1940 m sill. The red "poles" mark the positions of the INSTANT moorings.

Figure 2. A composite view of the along-axis speeds [cm/sec; tides removed] from select moorings within each passage as measured during the first 1.5 years of INSTANT. Negative speeds are towards Indian Ocean. Color coding: Blue: Makassar; Green: Lifamatola; Orange: Lombok; Purple: Ombai; Red: Timor.

References:

Gordon, A.L., 2005. Oceanography of the Indonesian Seas and Their Throughflow. Oceanography 18(4): December 14-27

Molcard, R., M. Fieux and F. Syamsudin, 2001. The throughflow within Ombai Strait, *Deep Sea Research I* 48 1237-1253.

Sprintall, J., A.L. Gordon, R. Murtugudde, and R.D. Susanto, 2000. A semiannual Indian Ocean forced Kelvin wave observed in the Indonesian seas in May 1997, *Journal of Geophysical Research*, 105 (C7), 17217-17230.

Sprintall, J., S. Wijffels, A. L. Gordon, A. Field, R. Molcard, R. Dwi Susanto, I. Soesilo, J. Sopaheluwakan, Y. Surachman and H. Van Aken, 2004. INSTANT: A new international array to measure the Indonesian Throughflow. *Eos* 85(39):369.

Susanto, R.D. and A. L. Gordon. 2005. Velocity and transport of the Makassar Strait Throughflow. *Journal of Geophysical Research* 110, Jan C01005, doi:10.1029/2004JC002425.

Talley, L.D. and J. Sprintall, 2005. Deep expression of the Indonesian Throughflow: Indonesian Intermediate Water in the South Equatorial Current, *Journal of Geophysical Research*, 110 (C10), C10009, doi:10.1029/2004JC002826).

Wijffels, S. E. and G. Meyers, 2002. Interannual Transport Variability of the Indonesian Throughflow and the Role of Remote Wind Forcing. *Eos. Trans. AGU*, 83(22), West. Pac. Geophys. Meet. Suppl., Abstract OS41B-11, 2002. [http://www.agu.org/meetings/wp02/wp02-pdf/wp02\\_OS41B.pdf](http://www.agu.org/meetings/wp02/wp02-pdf/wp02_OS41B.pdf)

Figure 1

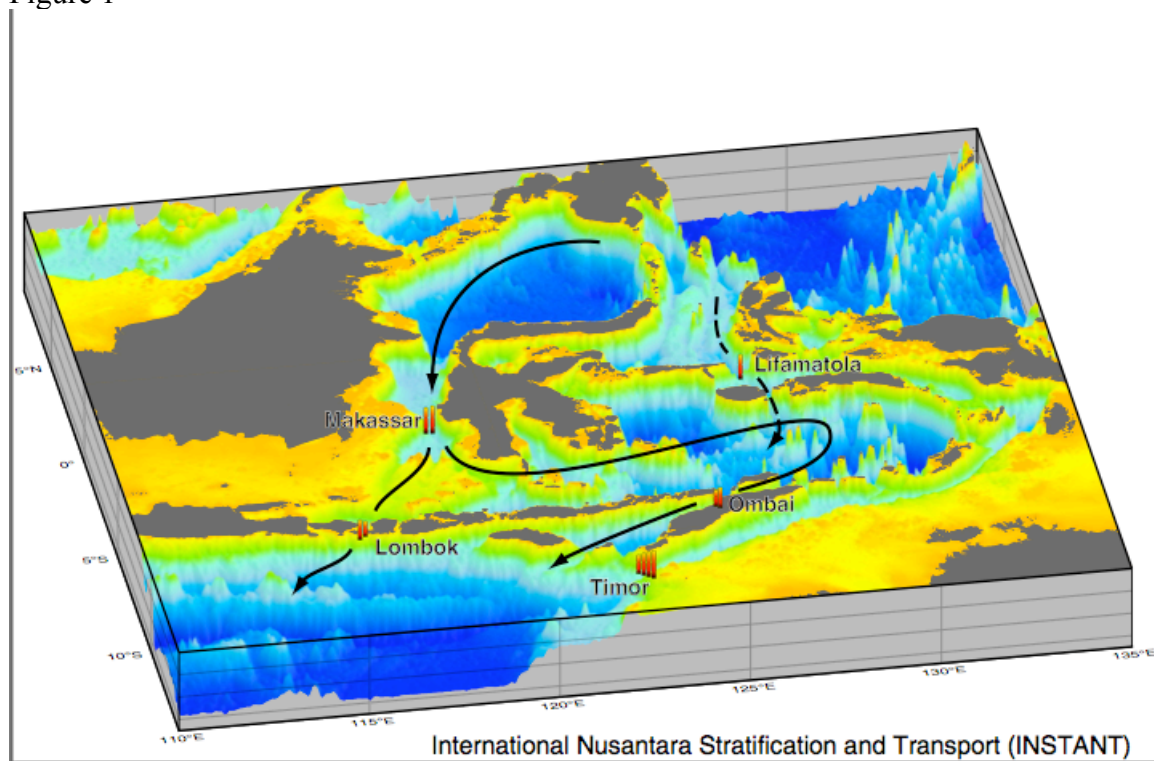


Figure 2a

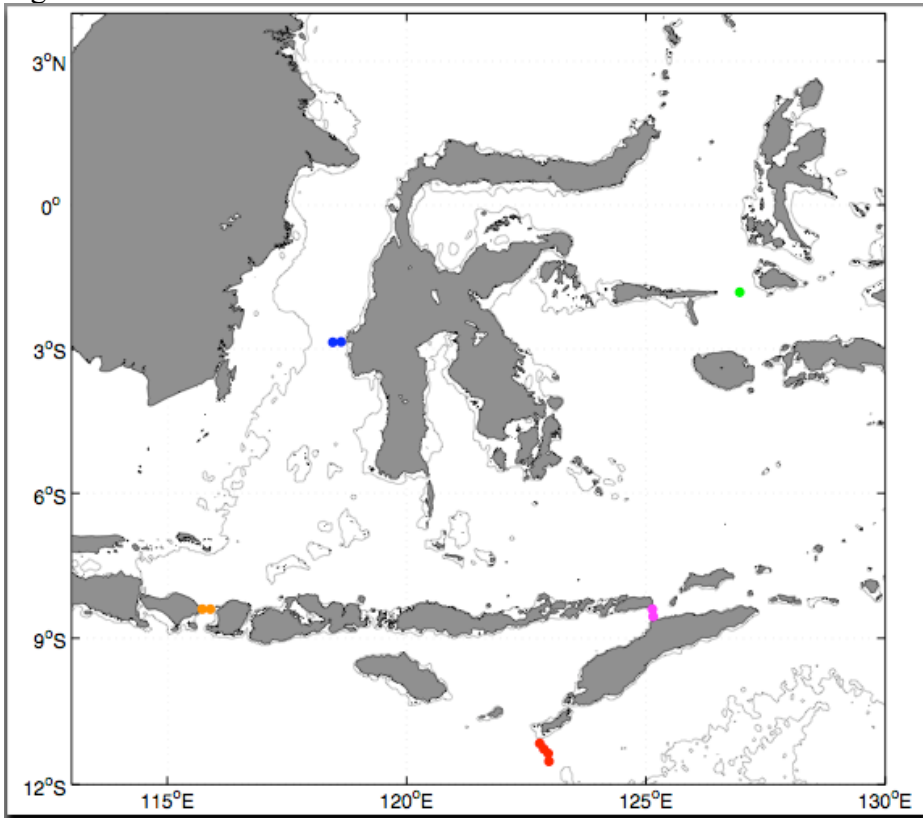


Figure 2b

Clivar Exchange, Indian Ocean Issue

