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The Indonesian throughflow during 2004–2006 as observed by the INSTANT program

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ABSTRACT

The Indonesian seas provide a sea link between the tropical Pacific and Indian Oceans. The connection is not simple, not a single gap in a 'wall', but rather composed of the intricate patterns of passages and seas of varied dimensions. The velocity and temperature/salinity profiles Indonesian throughflow (ITF) are altered en route from the Pacific into the Indian Ocean by sea–air buoyancy and momentum fluxes, as well as diapycnal mixing due to topographic boundary effects and dissipation of tidal energy. The INSTANT program measured the ITF in key channels from 2004 to 2006, providing the first simultaneous view of the main ITF pathways. The along-channel speeds vary markedly with passage; the Makassar and Timor flow is relatively steady in comparison to the seasonal and intraseasonal fluctuations observed in Lombok and Ombai Straits. The flow through Lifamatola Passage is strongly bottom intensified, defining the overflow into the deep Indonesian basins to the south. The 3-year mean ITF transport recorded by INSTANT into the Indian Ocean is 15×10^6 m^3/s, about 30% greater than the values of non-simultaneous measurements made prior to 2000. The INSTANT 3-year mean inflow transport is nearly 13×10^6 m^3/s. The 2×10^6 m^3/s difference between INSTANT measured inflow and outflow is attributed to unresolved surface

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layer transport in Lifamatola Passage and other channels, such as Karimata Strait. Introducing inflow within the upper 200 m to zero the water column net convergence still requires upwelling within the intervening seas, notably the Banda Sea. A layer of minimum upwelling near 600 m separates upwelling within the thermocline from a deep water upwelling pattern driven by the deep overflow in Lifamatola Passage. For a steady state condition upwelling thermocline water is off-set by a 3-year mean sea to air heat flux of 80 W/m^2 (after taking into account the shoaling of thermocline isotherms between the inflow and outflow portals), which agrees with the climatic value based on bulk formulae sea–air flux calculations, as well as transport weighted temperature of the inflow and outflow water. The INSTANT data reveals interannual fluctuations, with greater upwelling and sea to air heat flux in 2006.

1. Introduction to the Indonesian throughflow

The Indonesian seas represent a complex array of passages linking shallow and deep seas (Fig. 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/s). Estimates based on observations obtained from the mid-1980s and mid-1990s suggest a mean ITF of ~10 Sv (Gordon, 2005; Fig. 1) with interannual and seasonal fluctuations, as well as energetic intraseasonal (<90 days) variability and tides (Gordon,

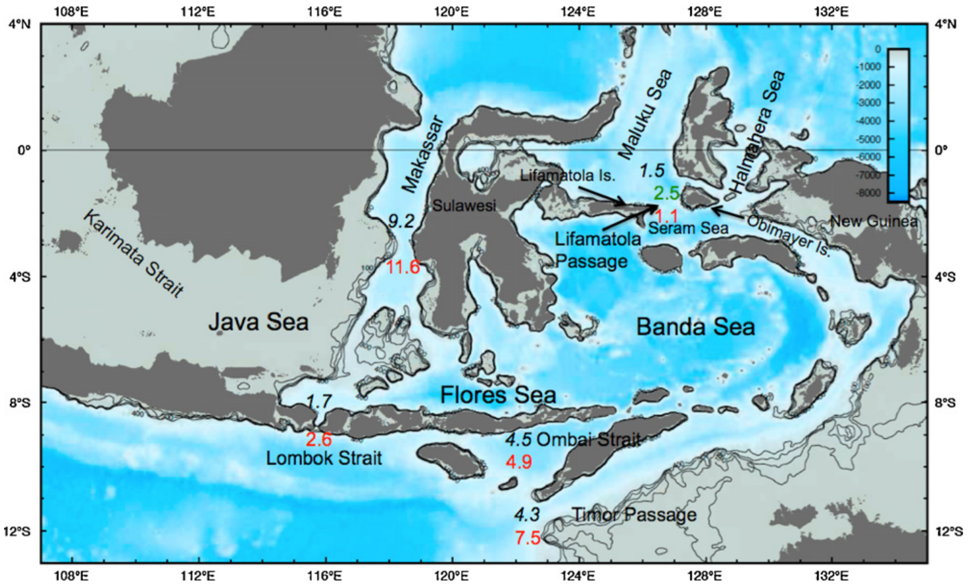

Fig. 1. Transport values in 10^6 m^3/s within the passages measured by the INSTANT program, 2004–2006. The italics numbers in black represent transport values based on pre-INSTANT data: Makassar Strait, 1997 (Gordon et al., 1999; Susanto and Gordon, 2005); Lombok Strait, 1985 (Murray and Arief, 1988; 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 pre-INSTANT value of 1.5 Sv for the Lifamatola Passage represents overflow of dense water at depths greater than 1500 m based on 3.5 months of current meter measurement in early 1985 (Van Aken et al., 1988). The red numbers are the 2004–2006 3-year mean transports measured by INSTANT. In Lifamatola Passage, the green number is the INSTANT overflow transport >1250 m, representing the overflow into the deep Seram and Banda Seas, and the red number is the total transport measured by INSTANT below 200 m. The positions of the INSTANT moorings are shown in Fig. 3. For details about the INSTANT moorings and transport values see Gordon et al. (2008); Sprintall et al. (2009); Van Aken et al. (2009).

2005; Qiu et al., 1999; Wijffels and Meyers, 2004; Susanto et al., 2000; Sprintall et al., 2000; Egbert and Ray, 2001; Ray et al., 2005; Pujiana et al., in press). The ITF is a response to ocean-scale wind stress as characterized by the "Island Rule" (Godfrey, 1989), and to the phase of El Niño-Southern Oscillation (ENSO; Meyers, 1996; England and Huang, 2005; Wijffels et al., 2008) and its Indian Ocean "cousin", the Indian Ocean Dipole, IOD (Saji et al., 1999; Wijffels et al., 2008; Potemra and Schneider, 2007) as well as the regional monsoonal wind pattern over southeast Asia (Gordon et al., 2003; Susanto et al., 2007).

Many model studies have investigated 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 characteristics of the 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 and Fine, 1996; Gordon, 2005). Lifamatola Passage east of Sulawesi, with a sill depth of ~2000 m, funnels spillover of deep 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). It is the goal of this paper to discuss the annual time scales of convergence/divergence within the Banda Sea.

The Indonesian water is exported into the Indian Ocean within the three major passages along the Nusa Tenggara archipelago: Timor Passage (1250 m eastern sill depth at Leti Strait, and ~1890 m western sill depth where the INSTANT moorings are located); Ombai Strait (upstream sill depth ~1450 m of Alor Strait, and downstream sill depth ~1150 m in Savu Strait); and Lombok Strait (sill depth ~300 m to south of INSTANT moorings) (Fig. 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 associated with the ITF do 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, the interocean heat and freshwater transports would change accordingly.

2. International Nusantara Stratification and Transport (INSTANT) program

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. The transports reported in the literature for the primary ITF passages and the time interval over which the transport is based is shown in Fig. 1. Historically, the transport through Makassar Strait is estimated as 9.2 Sv (Gordon et al., 1999; Susanto and Gordon, 2005), and the overflow in the Lifamatola Passage is 1.5 Sv (Van Aken et al., 1988). The sum of the export to the Indian Ocean as measured within Lombok Strait, Ombai Strait and Timor Passage over different time intervals is 11 Sv (Gordon, 2005). Are the pre-2000 ITF transport values as shown in Fig. 1 faithful to the climatic (long-term) mean or simply reflecting "noise" due to higher frequency variability?

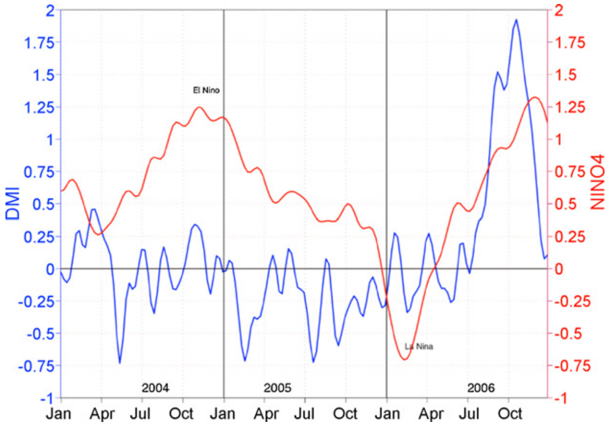

Fig. 2. The Nino4 index (see: http://www.esrl.noaa.gov/psd/forecasts/sstlim/timeseries/README.html) and Indian Ocean Dipole (Dipole Mode Index, DMI, Saji et al., 1999; see: http://www.jamstec.go.jp/frsgc/research/d1/iod/) during the INSTANT period. Neither index moved into an extreme phase relative to the prior 50 years during the INSTANT period. Nino4 was in a weak El Niño phase, except for a brief La Niña phase in early 2006. The DMI was slightly negative during most of the INSTANT period, with a large positive period in the latter half of 2006.

The International Nusantara Stratification and Transport program (Sprintall et al., 2004; see: http://www.marine.csiro.au/~cow074/index.htm) 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 (Sunda archipelago) 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 (Fig. 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.

The flow within the primary ITF passageways measured by INSTANT are reported in the literature: Gordon et al. (2008) for Makassar Strait; Van Aken et al. (2009) for Lifamatola Passage; Sprintall et al. (2009) for the export channels of the Sunda archipelago. The reader is referred to these papers for analysis of the flow within specific ITF passageways. Here we discuss comparative aspects of the inflow and outflow characteristics as observed by INSTANT, including an estimate of the convergence versus depth within the seas separating the inflow and outflow corridors.

Three years cannot capture the climatic 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 3-year INSTANT period was in a weak El Niño state, with a La Niña phase in late 2005 into early 2006 (Fig. 2), providing some confidence that the 3-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; Horii et al., 2008). The role of IOD in influencing the ITF transport independent of ENSO is not clearly established.

3. INSTANT along-channel speeds

A composite view of the along-channel velocity time series at various depths reveals much variability (Fig. 3). Detailed analysis of the along-channel flow is presented in the INSTANT publications mentioned above. Here we offer a qualitative comparison of the features revealed by simple inspection of the time series from the INSTANT passages.

At all levels Makassar and Timor throughflow are relatively steady, in comparison to Lombok and Ombai, which are rich in intraseasonal oscillations. The intraseasonal 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 Fig. 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 May 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. Atmadipoera et al. (2009) using the INSTANT time series within the three Sunda channels find that the passages act in a sequential way from April through September in the export of low salinity surface and upper thermocline water into the Indian Ocean, with the Lombok Strait leading export through Ombai and Timor by one and 5 months.

Within the thermocline (the 150 m panel of Fig. 3) the intraseasonal fluctuations are somewhat subdued relative to that in the surface layer, although Ombai continues to display the most vigorous variability with speeds occasionally comparable to that found in Makassar. 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 sustained thermocline intensification in the outflow indicates that the presence of net upwelling within the Banda Sea, as discussed below.

In the lower thermocline (the 350 m panel of Fig. 3) there is reduced along-channel flow. The weak flow in Lombok is to be expected as 350 m is below the sill depth, located south of the INSTANT Lombok moorings. 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 most variability with strong flows toward the Indian Ocean during the northwest monsoon when the surface flow is reversed. 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 0.7 m/s, at 1950 m, about 50 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.

4. INSTANT transports

The ITF transports within the passageways observed by INSTANT for 2004–2006 (Fig. 1; Table 1) are reported by Gordon et al. (2008) (Makassar Strait); Van Aken et al. (2009) (Lifamatola Passage) and Sprintall et al. (2009) (Lombok Strait, Ombai Strait and Timor Passage). The reader is referred to these papers for specifics on the data set and methods used in determining the velocity field and associated transport. In the above mentioned publications, the authors present what they consider are the most reasonable or "best" transport through each of the INSTANT measured passages (Table 1). Here we briefly discuss the mean, range and standard deviation of these "best" transport estimates that were reported in each passage over the INSTANT time period, along with an estimate of the errors associated with the inherent assumptions behind the transport calculations. These statistics and error estimates then provide some guidance for the temporal variability and uncertainty that can be expected in our calculation of the inflow–outflow convergences presented in Section 5.

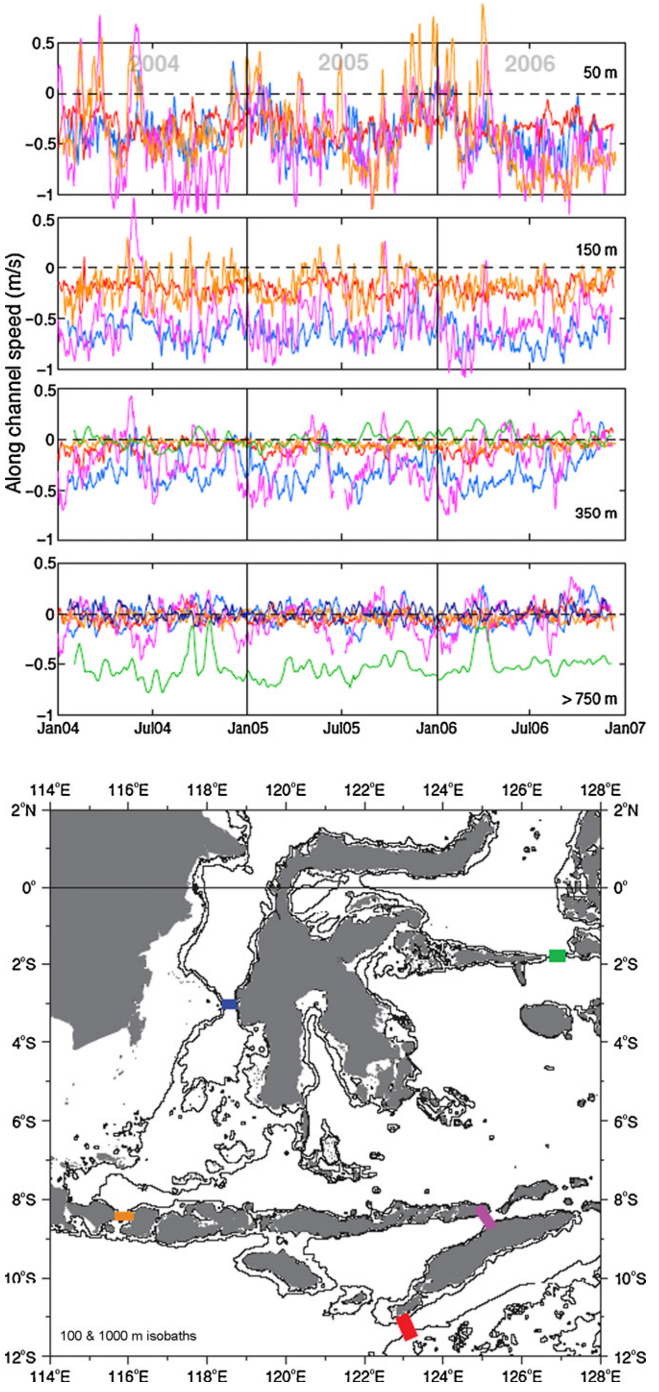

Fig. 3. Time series of along-channel currents in m/sec within the key passageways of the Indonesian Throughflow [upper panel] as measured by the INSTANT mooring array [lower panel]. The time series lines of the upper panel are color-coded to match the mooring color of the lower panel. Negative values 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

Table 1
Annual and 3-year net transport in 10^6 m^3/s for the passages measured by the INSTANT program. For Lifamatola the full depth transports is rounded to the nearest whole Sv value, as the water column above 1250 m is not well resolved. The outflow–inflow imbalance, rounded to the nearest whole Sv value to reflect the uncertainty, is compensated by unresolved transport within the surface layer of the Lifamatola Passage and/or other passages not observed by the INSTANT program (as discussed in the text). The sill depths of each passage [left column] are often less than the depth to which the transport values are summed [2nd column from the left], as the moorings were not necessarily at the passage sill depth. In all passages except Lombok the transport below the sill is <5% of the water column total (5% at Makassar; 2% at Ombai; 0% at Lifamatola and Timor); at Lombok it is nearly 15% of the water column total but this amounts to only 0.45 Sv.

Passage [sill depth]	Integration Range (m)	3-Year	2004	2005	2006
Makassar [700 m]	0–2000	11.6	11.3	11.6	11.8
Lifamatola [2050 m]	1250–2050	2.5	2.1	2.6	2.7
Lifamatola [2050 m]	0–2050	1	0	1	2
Total inflow		12.7	11.6	13.0	13.4
Lombok [300 m]	0–1000	2.6	2.0	2.3	3.4
Ombai [1150 m]	0–3000	4.9	4.7	5.8	4.3
Timor [1890 m]	0–2000	7.5	7.3	7.6	7.6
Total outflow		15.0	14.0	15.7	15.3
Outflow–inflow imbalance		2	2	3	2

The 3-year inflow transports are: 11.6 Sv for Makassar Strait, and 1 Sv for Lifamatola Passage, the latter represents the sum of the density driven deep overflow into the Seram and Banda Seas (2.5 Sv for depths >1250 m, which is well resolved by the single mooring within the narrow deep channel) and the upper layer transport (~1.4 Sv northward above 1250 m, which, as noted by Van Aken et al. (2009), is not well resolved by the Lifamatola mooring). The 3-year sum of the inflow transport is nearly 13 Sv. The outflow transport within the three primary passages of the Sunda archipelago is: 2.6 Sv for Lombok Strait, 4.9 Sv for Ombai Strait and 7.5 Sv for Timor Passage, yielding a net outflow of 15 Sv. As expected there are fluctuations of the annual transports (Table 1), but these are small, amounting to ~1.5 Sv, with 2004 being a year of relatively low net ITF, and 2005 and 2006 being about equal in magnitude.

The authors discuss the observed variability across a wide range of time scales (refer to the cited publications for details). The observed Makassar transport variability from the annual 3-year mean of 11.6 Sv varies from 6 to 16 Sv, with a standard deviation of 3 Sv (Gordon et al., 2008). The Sunda passages 3-year mean of 15 Sv export varies from a low of 4 Sv to a high of 24 Sv, with a standard deviation of 4 Sv (Sprintall et al., 2009). The Lifamatola mean transport below 1250 m representing the overflow into the deep basins to the south is 2.5 Sv with a standard deviation of 1.3 Sv (Van Aken et al., 2009). The transport above 1250 m is estimated as 0.9–1.3 Sv northward by Van Aken et al. (2009), with a suggested standard deviation of at least 1 Sv.

There are varied constructs for extrapolation of the observed flow fields to the surface, the sea floor and side-walls, which introduces a level of uncertainty in the transport calculations. Here we define the "uncertainty" as the range in transport using varied extrapolation methods, as discussed by the authors of the cited INSTANT papers. Using the range of values representing the different extrapolation methods as given by the authors, an uncertainty of ~15% is likely for Makassar Strait, and 27% for the sum of the Sunda export channels (the individual passages range from 30% for Ombai to 26% for Lombok). The Lifamatola transport below 1250 m is a fairly robust number, with an uncertainty of ~5%. However, above 1250 m the uncertainty due to a single mooring within a relatively wide channel is very large, probably in excess of 50%.

The INSTANT ITF mean outflow transport of 15 Sv is ~4 Sv or ~25–30% greater than export transport values based on pre-2000 observations (Fig. 1). While this may not be significant in view of the differ-

upper 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.

ent mooring design and general uncertainty of determining cross-channel transport, interannual ITF fluctuations are to be expected (Tillinger and Gordon, 2009). The pre-INSTANT measurements were made mainly in weak to strong El Niño phase when a reduced ITF transport is anticipated. The INSTANT measurements were made during weak El Niño conditions and La Niña phase in early 2006, with a substantial +IOD phase in much of 2006 (Fig. 2).

There is an inflow/outflow 3-year imbalance of ∼2 Sv (Table 1). Combining the extrapolation uncertainty of the five INSTANT passages leads to an inflow/outflow uncertainty of 3 Sv. Assuming a Gaussian distribution the standard deviation is 2 Sv. While the sign of the imbalance may not be robust, it appears likely that the INSTANT observed transport within the inflow passages is less than the INSTANT observed outflow. The inflow/outflow imbalance may be solely a product of the uncertainty in the side-wall extrapolations. However, difference may also be derived from incomplete monitoring of the inflow passages, including the numerous shallow passages not observed or poorly resolved by the INSTANT mooring array, such the upper ∼1000 m within the Lifamatola Passage.

The passages not measured by the INSTANT program include the inflow through passages such as Karimata Strait (separating the South China Sea from the Java Sea) and Torres Strait (separating the Indonesian seas from the western South Pacific between Australia and New Guinea). Karimata Strait with a sill depth of 50 m is considered to introduce South China Sea water into the Java Sea. Torres Strait is less than 10 m deep with the presence of numerous islands and reefs. From 5 months of current observations, Wolanski et al. (1988) found a strong tidal flow, but no evidence of a mean flow through Torres Strait. A more substantial 'missing passage' is the wide extent of shallow water near 2°S stretching from Sulawesi to the northwestern point of New Guinea (Fig. 1). Most of this gap is shallower than 100 m but parts, including the site of the single INSTANT Lifamatola mooring and the Halmahera Sea, are deeper than 400 m. The extrapolation of the Lifamatola mooring data to the full gap between Lifamatola Island and Obimayor is problematic (Van Aken et al., 2009). Additionally, there may be southward flow in the gap near 128°E between Obimayor and New Guinea, fed from the Maluku Sea or directly from the Halmahera Sea (sill depth of 580 m, Gordon et al., 2003). Analysis of the Arlindo CTD data indicates inflow of relatively saline South Pacific water through the Halmahera Sea (Gordon and Fine, 1996; Ilahude and Gordon, 1996).

5. Inflow–outflow convergence

The Pacific water entering the Indonesian seas is modified within the interior seas before export to the Indian Ocean. Using the most reasonable transport profile for the passages carefully derived by the INSTANT program investigators (Gordon et al., 2008; Van Aken et al., 2009; Sprintall et al., 2009), here we estimate the inflow–outflow convergence profile (Tables 2a and 2b), along with the resultant vertical velocity and downward heat fluxes within the interior seas as required for an annual and 3-year steady state condition. We do not extend this approach to the seasonal inflow/outflow values as we do not expect the net convergence to be zero; the Banda Sea thermocline shallows and sea level falls during the southeast monsoon with the reverse occurring during the northwest monsoon in response to seasonal Ekman upwelling (Gordon and Susanto, 2001).

We present the convergence profile only as a qualitative, conceptual guide of the likely vertical transports between the ITF inflow and outflow passages, and the associated vertical heat fluxes. As discussed above, there are substantial uncertainties in the inflow/outflow transport values and hence we caution against placing too much emphasis on the water column convergence values. Hopefully, future observational and modeling based investigations will help better quantify the water column convergence profile.

In order to introduce a reasonable 'additional' inflow profile, the 0–100 m layer is assigned to provide 2/3 of the required inflow to balance with the rest coming from the 100 to 200 m layer (Table 2b). Of course, other profiles of additional inflow are possible, such as a deeper contribution from the gap between Lifamatola Island and New Guinea. However, the expanse of the 0–200 m cross-sectional area and the missing upper 200 m coverage at Lifamatola Passage argues to place the bulk in the surface layers.

The convergence profile is balanced by vertical transport, which is converted to vertical velocity by dividing by the area of the seas between the inflow and outflow portals (approximately

Table 2a
Convergence within depth slabs between the INSTANT inflow and outflow profiles values in 10^6 m^3/s [Sv]; minus values represent divergence.

Depth range	3-Year	2004	2005	2006
0–100	−2.9	−2.3	−2.6	−3.8
100–200	−0.7	−0.6	−0.7	−0.9
200–300	0.1	0.0	0.0	0.3
300–400	0.3	0.3	0.2	0.6
400–500	0.3	0.2	0.1	0.4
500–600	0.1	0.2	−0.1	0.2
600–700	0.0	0.0	−0.2	0.0
700–800	−0.2	−0.3	−0.3	−0.1
800–900	−0.4	−0.4	−0.4	−0.3
900–1000	−0.4	−0.6	−0.5	−0.3
1000–1500	−0.5	−0.9	−0.6	−0.1
1500–2000	2.2	2.0	2.4	2.2
2000–2500	0.0	0.0	0.0	−0.1
2500–3000	0.0	0.0	0.0	0.0
3000 to bottom	0.0	0.0	0.0	0.0
Net convergence	−2.3	−2.4	−2.7	−1.9

Table 2b
Proposed unresolved inflow [Sv units] within the 0–100 and 100–200 m slabs within the INSTANT observed passages and/or in additional passages, as required to zero the net convergence.

	3-Year	2004	2005	2006
0–100	−1.5	−1.6	−1.8	−1.3
100–200	−0.8	−0.8	−0.9	−0.6

0.88 million km^2). The vertical velocity is upward throughout the water column of the interior seas (Tables 3a and 3b; Fig. 4). The upwelling drops below 10^{-6} m/s in the depth interval from 400 to 700 m. We refer to this as the null layer, which separates the stronger upwelling within the thermocline layer from the deeper layer upwelling cell coupled to the deep water overflow within Lifamatola Passage. The upwelling within the deep water of the Banda sea is reported as 2.4×10^{-6} m/s by Van Aken et al. (1991), and we find similar values using the INSTANT data (maximum upwelling of 2.4×10^{-6} m/s occurs in the 1000–1500 m layer, Tables 3a and 3b). The 3-year mean thermocline upwelling through the 100–200 m layer of 1.5×10^{-6} m/s combined with the mean (climatic) thermocline stratification of 0.083 °C/m yields a vertical mixing coefficient K_z/ρ of 2.7×10^{-4} m^2/s. Using the mean thermocline stratification with the yearly thermocline upwelling yields a K_z/ρ of 1.1, 1.1 and 5.8×10^{-4} m^2/s for

Table 3a
Upwelling in 10^{-6} m/s across the base of each depth layer as required to compensate for the inflow/outflow water column convergence profile. A minimum of vertical velocity is found near 600 m, separating a thermocline overturning cell from a deeper overturning cell associated with the Lifamatola sill overflow.

Depth range	Upwelling velocity, 10^{-6} m/s			
	3-Year	2004	2005	2006
0–100	1.6	0.8	0.9	2.9
100–200	1.5	0.6	0.6	3.2
200–300	1.4	0.6	0.6	2.8
300–400	1.0	0.3	0.4	2.1
400–500	0.7	0.0	0.3	1.7
500–600	0.6	−0.2	0.4	1.4
600–700	0.7	−0.2	0.5	1.4
700–800	0.9	0.1	0.9	1.5
800–900	1.3	0.6	1.3	1.8
900–1000	1.8	1.2	1.8	2.2
1000–1500	2.4	2.2	2.5	2.3

Table 3b
The downward flux of heat [W/m^2] across the top of each depth layer as required to maintain steady state temperature stratification.

Depth range	Heat flux (W/m^2)			
	3-Year	2004	2005	2006
0–100	34	17	19	63
100–200	29	11	11	59
200–300	12	5	5	24
300–400	4	1	2	7
400–500	2	0	1	5
500–600	1	0	1	3
600–700	1	0	0	1
700–800	1	0	1	2
800–900	2	1	2	3
900–1000	5	4	5	6
1000–1500	7	7	7	7

2004, 2005, 2006, respectively. This is more than an order of magnitude larger than the Atlantic thermocline value found by Ledwell et al. (1993), but only a factor of 2 greater than that deduced for the Banda Sea by Ffield and Gordon (1992) using historical data. The elevated upwelling and vertical mixing within the Banda Sea leads to a lower SST than would otherwise be expected, which then reduces the convection within the atmosphere and associated precipitation patterns (Jochum and Potemra, 2008).

Upwelling would lead to isotherm shoaling if not off-set, fully or partially, by downward heat flux. The shoaling of the isotherms within the upper 500 m is found to be on average about 15 m between the inflow and outflow (determined using the Levitus annual mean data). This accounts for 33% of the upwelling calculated from the inflow/outflow convergence. Therefore 67% of the upwelling requires heat from the atmosphere, so as to limit further isotherm shoaling. The downward heat flux is estimated using average temperatures over 100 m depth intervals (Tables 3a and 3b). During the 3-year period of the INSTANT observations, the total heat needed to warm the upwelled water down to 500 m is 80 W/m^2. However, there are substantial year-to-year variations: 35 W/m^2 in 2004; 38 W/m^2

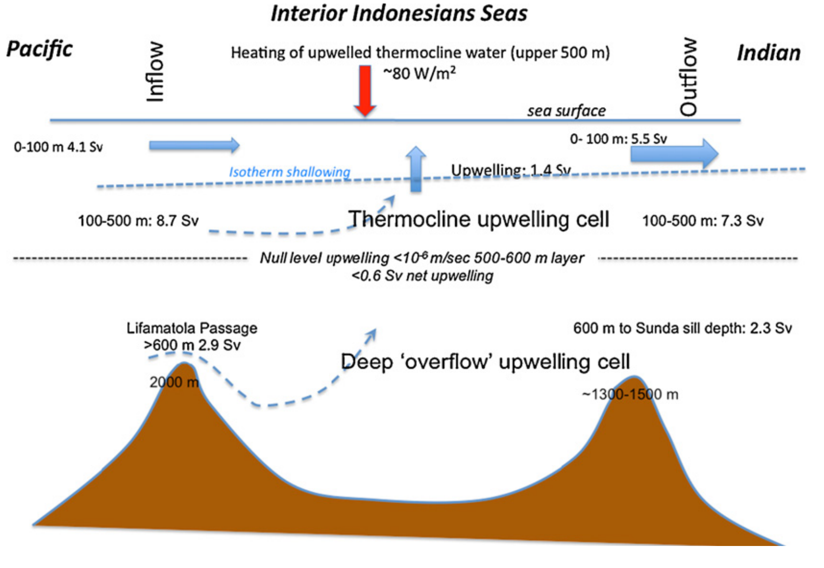

Fig. 4. Schematic of the Indonesian Throughflow inflow/outflow pattern within the interior Indonesian Seas and resulting upwelling inferred from the 2004–2006 INSTANT observations.

in 2005; and 159 W/m^2 in 2006. The climatic mean air to sea heat flux in the inflow/outflow area is 50–60 W/m^2 (Grist and Josey, 2003). Thus, while the INSTANT 3-year average is reasonably close to the climatic heat flux, the relatively low values of 2004 and 2005 are off-set by the very high air to sea heat flux of 2006.

Gordon et al. (2008) using the Makassar Strait INSTANT time series finds a 3-year mean transport weighted temperature of 15.6 °C. Sprintall et al. (2009) determined a 3-year mean transport weighted temperature for three export passages of 17.9 °C. The additional transport of ~2 Sv required to achieve inflow/outflow balance for the 3-year mean INSTANT transports, as described above, is assumed to be derived from the upper 200 m, with 2/3 (1.3 Sv) coming from the upper 100 m and the rest from the 100 to 200 m depth interval. Using Indonesian sea temperatures for the upper 200 m partitioned in the same proportion as the assumed additional transport, yields a transport weighted temperature for the additional transport of 24 °C. Combining this with the Makassar Strait inflow transport weighted temperature requires a 3-year mean air to sea heat flux of the INSTANT period 73 W/m^2 (again assuming the 0.9 million km^2 areas between inflow and outflow as used above). This more-or-less agrees with the 80 W/m^2 derived from the net convergence and associated upwelling of thermocline water (and is slightly closer to the Grist and Josey, 2003 value). Below 1250 m within the Lifamatola Passage the 2.5 Sv inflow (Table 1) has an estimated transport weighted temperature of 3.2 °C (Van Aken et al., 2009). However, the full water column southward transport is reduced by northward flow above 1250 m, to ~1 Sv (Table 1). As the water above 1250 m is warmer than that deeper than 1250 m, it would lower the transport weighted temperature of the deep overflow. In view of the uncertainty of the net transport above 1250 m within Lifamatola Passage, we do not include the Lifamatola Passage 3-year mean transport weighted temperature in the estimation of air to sea heat flux, but it is likely that it slightly elevates the air to sea heat flux above the 73 W/m^2 discussed above.

The 2006 convergence, and the associated vertical velocity and downward heat flux, represent a marked deviation from the 2004 and 2005 values. This comes about by surface layer intensification of the 2006 outflow, mainly in the upper 100 m but extending into the 100–200 m interval. The 2006 divergence in the upper 200 m was relatively large, being off-set by large convergence in the 200–500 m depth layer. This imposes a stronger upwelling within the thermocline in 2006, by a factor of 2 over the 3-year mean, which then requires a greater downward heat flux to maintain steady state isotherm depths. Part of the large heat flux may be a consequence of using the climatic mean to determine the upward shift of the thermocline isotherms between the inflow and outflow, as described above. If the upward shift were larger, as might be expected from the change in the convergence profile in 2006, then the need for the large downward heat flux is reduced and closer to the climatic mean.

We suspect the underlying cause of the anomalous convergences in 2006 is the La Nina and +IOD condition that existed in 2006. During the 2006 IOD, the interannual transport anomalies in all three outflow passages were remarkably similar. Coinciding with the 2006 IOD, anomalously strong outflow into the Indian Ocean was observed above ~150 m depth, with strong reversals below 150 m, extending to ~800–1000 m depth in both Ombai and Timor (Sprintall et al., 2009). It is thought that the enhanced ITF in the upper layer is related to prolonged easterly wind anomalies along the south of Java (Potemra and Schneider, 2007). These winds lower the sealevel along the Nusa Tenggara coast, and increase the surface layer divergence out of the Banda Sea as they draw the Ekman transport offshore. The reversals in the lower layers are due to Kelvin waves forced in the equatorial Indian Ocean in response to wind anomalies associated with the 2006 IOD (Horii et al., 2008).

6. Conclusions

The 3-year mean ITF transport recorded during INSTANT via the primary deep outflow passages of the Sunda archipelago (Lombok Strait, Ombai Strait and Timor Passage) into the Indian Ocean is 15×10^6 m^3/s. This is about 25–30% greater than the values from non-simultaneous measurements made prior to 2000, a period dominated by El Niño conditions.

The form of the along-channel time series within each of the INSTANT observed passages differ. The Makassar and Timor throughflow are relatively steady, in comparison to Lombok and Ombai, which are rich in intraseasonal oscillations and are likely related to Kelvin waves that propagate from the Indian Ocean along the southern coast of Sumatra and Java. The inflow and outflow pattern of the along-channel speeds at seasonal and at higher frequencies do not rise and fall in tandem, suggesting an imbalance at these time scales related to internal storage of water within the stratum of the interior seas of Indonesia, most likely within the Banda Sea.

The INSTANT 3-year mean ITF inflow transport (Makassar Strait and Lifamatola Passage) is $13 \times 10^6\,m^3/s$. The $2 \times 10^6\,m^3/s$ difference between INSTANT measured inflow and outflow is attributed to uncertainty of the extrapolation to the side-walls within each of the INSTANT passages and/or unresolved surface layer transport in Lifamatola Passage and other channels, such as Karimata Strait. Differencing inflow/outflow profiles suggest the presence of net upwelling of water in the intervening seas, notably the Banda Sea (Fig. 4). The upwelling is segmented into a thermocline cell and a deep water cell, separated by a null area of very weak upwelling near 600 m. The thermocline upwelled water requires a 3-year mean sea to air heat flux of $80\,W/m^2$ (after taking into account the swallowing of thermocline isotherms between the inflow and outflow portals), which agrees well with independent estimates based on bulk formulae sea-air flux calculations (Grist and Josey, 2003).

The INSTANT data reveal interannual fluctuations, with greater upwelling in 2006, which assuming steady state isotherm depth requires relatively large sea to air heat flux. This response is likely a consequence of the strong positive phase of the IOD during 2006, which suggests that the IOD impact on the transport through the outflow passages noted by Sprintall et al. (2009), also strongly influences the velocity and property profiles of the interior seas.

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References

Arief, D., Murray, S.P., 1996. Low-frequency fluctuations in the Indonesian throughflow through Lombok Strait. J. Geophys. Res. 101, 12455–12464.

Atmadipoera, A., Molcard, R., Madec, G., Wijffels, S., Sprintall, J., Koch-Larrouy, A., Jaya, I., Supangat, A., 2009. Characteristics and variability of the Indonesian throughflow water at the outflow straits. Deep Sea Res., Part I 56 (11), 1942–1954.

Egbert, G.D., Ray, R.D., 2001. Estimates of M_2 tidal energy dissipation from TOPEX/Poseidon altimeter data. J. Geophys. Res. 106, 22475–22502.

England, M., Huang, F., 2005. On the interannual variability of the Indonesian throughflow and its linkage with ENSO. J. Climate 18, 1435–1444.

Ffield, A., Gordon, A.L., 1992. Vertical mixing in the Indonesian thermocline. J. Phys. Oceanogr. 22 (2), 184–195.

Ffield, A., Gordon, A., 1996. Tidal mixing signatures in the Indonesian seas. J. Phys. Oceanogr. 26, 1924–1937.

Godfrey, J.S., 1989. A Sverdrup model of the depth-integrated flow for the world ocean allowing for island circulations. Geophys. Astrophys. Fluid Dyn. 45, 89–112.

Gordon, A.L., Fine, R.A., 1996. Pathways of water between the Pacific and Indian Oceans in the Indonesian Seas. Nature 379, 146–149.

Gordon, A.L., Susanto, R.D., Ffield, A., 1999. Throughflow within Makassar Strait. Geophys. Res. Lett. 26, 3325–3328.

Gordon, A.L., 2005. Oceanography of the Indonesian seas and their throughflow. Oceanography 18 (4), 14–27.

Gordon, A.L., Susanto, R.D., 2001. Banda sea surface layer divergence. Ocean Dyn. 52, 2–10.

Gordon, A.L., Susanto, R.D., Vranes, K., 2003a. Cool Indonesian throughflow as a consequence of restricted surface layer flow. Nature 425, 824–828.

Gordon, A.L., Giulivi, C.F., Ilahude, A.G., 2003b. Deep topographic barriers within the Indonesian seas. In: Schott, F. (Ed.), Physical Oceanography of the Indian Ocean during the WOCE Period, 50. Deep-Sea Research II, pp. 2205–2228.

Gordon, A.L., Susanto, R.D., Ffield, A., Huber, B.A., Pranowo, W., Wirasantosa, S., 2008. Makassar Strait throughflow, 2004 to 2006. Geophys. Res. Lett. 35, L24605, doi:10.1029/2008GL036372.

Grist, J.P., Josey, S.A., 2003. Inverse analysis adjustment of the SOC air–sea flux climatology using ocean heat transport constraints. J. Climate 16, 3274–3295.

Hirst, A.C., Godfrey, J.S., 1993. The role of Indonesian throughflow in a global ocean GCM. J. Phys. Oceanogr. 23, 1057–1086.

Horii, T., Hase, H., Ueki, I., Masumoto, Y., 2008. Oceanic precondition and evolution of the 2006 Indian Ocean dipole. Geophys. Res. Lett. 35, L03607, doi:10.1029/2007GL032464.
Ilahude, A., Gordon, A., 1996. Thermocline stratification within the Indonesian Seas. J. Geophys. Res. 101 (C5), 12401–12409.
Jochum, M., Potemra, J.T., 2008. Sensitivity of tropical rainfall to Banda sea diffusivity in the community climate system model. J. Climate 21, 6445–6454.
Koch-Larrouy, A., Madec, G., Bouruet-Aubertot, P., Gerkema, T., Bessieres, L., Molcard, R., 2007. On the transformation of Pacific water into Indonesian throughflow water by internal tidal mixing. Geophys. Res. Lett. 34, L04604, doi:10.1029/2006GL028405.
Ledwell, J.R., Watson, A.J., Law, C., 1993. Evidence for slow mixing across the Pycnocline from an open-ocean tracer-release experiment. Nature 364 (6439), 701–706.
Lee, T., Fukumori, I., Menemenlis, D., Xing, Z., Fu, L.-L., 2002. Effects of the Indonesian throughflow on the Pacific and Indian Oceans. J. Phys. Oceanogr. 32, 1404–1429.
MacDonald, A.M., 1993. Property fluxes at 30°S and their implications for the Pacific-Indian throughflow and the global heat budget. J. Geophys. Res. 98, 6851–6868.
Maes, C., 1998. Estimating the influence of salinity on sea level anomaly in the ocean. Geophys. Res. Lett. 25, 3551–3554.
McCreary, J., Lu, P., 2001. Influence of the Indonesian throughflow on the circulation of the Pacific intermediate water. J. Phys. Oceanogr. 31, 932–942.
Meyers, G., 1996. Variation of Indonesian throughflow and the El Niño—southern oscillation. J. Geophys. Res. 101, 12255–12263.
Molcard, R., Fieux, M., Ilahude, A.G., 1996. The Indo-Pacific throughflow in the Timor Passage. J. Geophys. Res. 101 (C5), 12,411–12,420.
Molcard, R., Fieux, M., Syamsudin, F., 2001. The throughflow within Ombai Strait. Deep Sea Res., Part I 48, 1237–1253.
Murray, S.P., Arief, D., 1988. Throughflow into the Indian Ocean through the Lombok Strait, January 1985–January 1986. Nature 333, 444–447.
Murtugudde, R., Busalacchi, A.J., Beauchamp, J., 1998. Seasonal-to-interannual effects of the Indonesian throughflow on the tropical Indo-Pacific basin. J. Geophys. Res. 103, 21425–21441.
Potemra, J.T., Schneider, N., 2007. Interannual variations of the Indonesian throughflow. J. Geophys. Res. 112, C05035, doi:10.1029/2006JC003808.
Potemra, J.T., Hautala, S.L., Sprintall, J., 2003. Vertical structure of Indonesian throughflow in a large-scale model. Deep Sea Res., Part II: Topical Stud. Oceanogr. 50, 2143–2161.
Pujiana, K., Gordon, A.L., Sprintall, J., Susanto, D., in press. Intraseasonal variability in the Makassar Strait thermocline. J. Marine Res.
Qiu, B., Mao, M., Kashino, Y., 1999. Intraseasonal variability in the Indo-Pacific throughflow and the regions surrounding the Indonesian Seas. J. Phys. Oceanogr. 29, 1599–1618.
Qu, T., Du, Y., McCreary, J.P., Meyers, J.R.G., Yamagata, T., 2008. Buffering effect and its related ocean dynamics in the Indonesian throughflow region. J. Phys. Oceanogr. 38, 503–516.
Ray, R., Egbert, G., Erofeeva, S., 2005. A brief overview of tides in the Indonesian seas oceanography 18 (4), 74–79.
Saji, N.H., Goswami, B.N., Vinayachandran, P.N., Yamagata, T., 1999. A dipole mode in the tropical Indian Ocean. Nature 401, 360–363.
Schott, F., McCreary, J., 2001. The monsoon circulation of the Indian Ocean. Prog. Oceanogr. 51, 1–123.
Song, Q., Gordon, A., 2004. Significance of the vertical profile of Indonesian throughflow transport on the Indian Ocean. Geophys. Res. Lett. 31, L16307, doi:10.1029/2004GL020360.
Sprintall, J., Gordon, A.L., Murtugudde, R., Susanto, R.D., 2000. A semiannual Indian Ocean forced Kelvin wave observed in the Indonesian seas in May 1997. J. Geophys. Res. 105 (C7), 17217–17230.
Sprintall, J., Wijffels, S., Gordon, A.L., Ffield, A., Molcard, R., Dwi Susanto, R., Soesilo, I., Sopaheluwakan, J., Surachman, Y., Van Aken, H., 2004. INSTANT: a new international array to measure the Indonesian throughflow. EOS 85 (39), 369.
Sprintall, J., Wijffels, S.E., Molcard, R., Jaya, I., 2009. Direct estimates of the Indonesian throughflow entering the Indian Ocean: 2004–2006. J. Geophys. Res. 114, C07001, doi:10.1029/2008JC005257.
Susanto, R.D., Gordon, A.L., 2005. Velocity and transport of the Makassar Strait throughflow. J. Geophys. Res. 110, doi:10.1029/2004JC002425, January, C01005.
Susanto, R.D., Gordon, A., Sprintall, J., 2007. Observations and proxies of the surface layer throughflow in Lombok Strait. J. Geophys. Res. 112 (C3), C03S92, doi:10.1029/2006JC003790.
Susanto, R.W., Gordon, A.L., Sprintall, J., Herunadi, B., 2000. Intraseasonal variability and tides in Makassar Strait. Geophys. Res. Lett. 27 (10), 1499–1502.
Talley, L.D., Sprintall, J., 2005. Deep expression of the Indonesian throughflow: Indonesian intermediate water in the South Equatorial current. J. Geophys. Res. 110, C10009, doi:10.1029/2004JC002826.
Tillinger, D., Gordon, A.L., 2009. Fifty years of the Indonesian throughflow. J. Climate 22 (23), 6342–6355, doi:10.1175/2009JCLI2981.1.
Van Aken, H.M., Punjanan, J., Saimima, S., 1988. Physical aspects of the flushing of the East Indonesian basins. Neth. J. Sea Res. 22, 315–339.
Van Aken, H.M., Van Bennekom, A.J., Mook, W.G., Postma, H., 1991. Application of Munk's abyssal recipes to tracer distributions in the deep waters of the southern Banda basin. Oceanologic a Acta 14 (2), 151–162.
Van Aken, H.M., Brodjonegoro, I.S., IndraJaya, 2009. The deep-water motion through the Lifamatola passage and its contribution to the Indonesian throughflow. Deep Sea Res., Part I 56, 1203–1216.
Vinayachandran, P.N., Kurian, J., Neema, C.P., 2007. Indian Ocean response to anomalous conditions in 2006. Geophys. Res. Lett. 34, L15602, doi:10.1029/2007GL030194.
Wajsowicz, R.C., 2002. Air–sea interaction over the Indian Ocean due to variations in the Indonesian throughflow. Climate Dyn. 18, 437–453.
Wajsowicz, R.C., Schneider, E.K., 2001. The Indonesian throughflow's effect on global climate determined from the COLA coupled climate system. J. Climate 14, 3029–3042.

Webster, P., Magana, V., Palmer, T., Shukla, J., Tomas, R., Yanai, M., Yasunari, T., 1998. Monsoons: processes, predictability, and the prospects for prediction. J. Geophys. Res. 103, 14451–14510.
Wijffels, S., Meyers, G., 2004. An intersection of oceanic wave guides: variability in the Indonesian throughflow region. J. Phys. Oceanogr. 34 (5), 1232–1253.
Wijffels, S., Meyers, G., Godfrey, J.S., 2008. A twenty year average of the regional currents and interbasin exchange in the Indonesian region. J. Phys. Oceanogr. 38 (9), 1965–1978.
Wolanski, E., Ridd, P., Inoue, M., 1988. Currents through Torres Strait. J. Phys. Oceanogr. 18 (11), 1535–1545.
Wyrtki, K., 1961. Physical Oceanography of the Southeast Asian Waters, NAGA Rep. 2 Scripps Inst. Oceanography.