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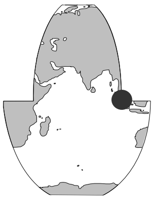
Makassar Strait Transport: Preliminary Arlindo Results from MAK-1 and MAK-2



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Makassar Strait is the primary pathway of the Pacific to Indian Ocean transport referred to as the Indonesian Throughflow. The transport through Makassar Strait was measured as part of the Indonesian-USA Arlindo programme, at two moorings deployed within the Labani Channel, a deep (2000 m) constriction (45 km) near 3°S (Fig. 1). Both moorings were operative from December 1996 to February 1998, a 1.4 year time series, when the MAK-2 mooring was released and recovered; the MAK-1 mooring was recovered in early July providing a 1.7 year record. The MAK moorings were deployed during a weak La Niña phase. An El Niño condition began in March 1997, becoming extreme during 1997 summer and fall, relaxing in early 1998. Arlindo data will be the subject of much study by the Arlindo research team†, but because of WOCE interest in Indonesian Throughflow we offer this preview of Makassar transport based on the Aanderaa current meters (current, temperature, pressure) and temperature-pressure pods of MAK-1 and MAK-2.

The Indonesian maritime continent with its complex network of passages and basins connecting the Pacific and Indian Oceans inhibits free communication between the Pacific and Indian Oceans. Schneider (1998) using a couple model, shows that the presence of the Pacific to Indian interocean transfer shifts the warmest SST and associated atmospheric convective region towards the west, relative to a no throughflow condition. Webster et al. (1998) state: the Indonesian Throughflow heat flux "…is comparable to the net surface flux over the northern Indian Ocean and a substantial fraction of the heat flux into the western Pacific warm pool…it would appear that the Throughflow is an integral part of the heat balances of both the Pacific and Indian Oceans."

Observations indicate that the Throughflow is composed mostly of North Pacific thermocline and intermediate water flowing through Makassar Strait (Gordon and Fine, 1996), which then passes into the Indian Ocean through the passages of Lesser Sunda Islands. East of Sulawesi South Pacific water infiltrates the lower thermocline and dominates the deeper layers, including the Lifamatola Passage overflow into the deep Banda Sea (Van Aken et al., 1988; Gordon and Fine, 1996; Hautala et al., 1996), but it is unlikely that the eastern channels carry total more than 3 Sv.

Indonesian Throughflow estimates based on observations, models and conjecture range from near zero to 30 Sv (Godfrey, 1996). Measurements in the Lombok Strait in 1985 (Murray and Arief, 1988; a near zero SOI value) indicate an average transport of 1.7 Sv. Molcard et al. (1996) as part of the French-Indonesian programme JADE, find a mean transport to the Indian Ocean of 4.3 Sv

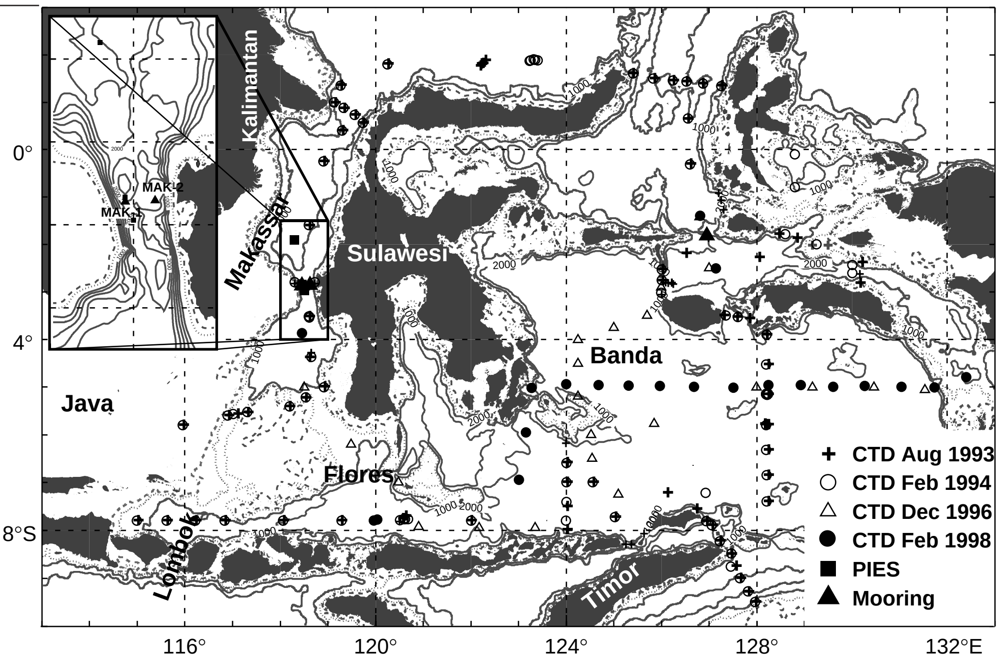

Figure 1. Distribution of CTD stations and time series moorings obtained by the Arlindo programme. The position of the current meter and temperature-pressure pod moorings in Makassar Strait, MAK-1 (2°52′ S, 118°27′ E) and MAK-2 (2°51′ S; 118°38′ E) the subject of this note, are shown in the insert, as are the Pressure, Inverted Echo Sounder sensors (PIES).

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† The US scientists involved in Arlindo Circulation are: Arnold L. Gordon (US chief scientist for Arlindo; CTD) and Amy Ffield (temperature-pressure pods), Lamont-Doherty Earth Observatory of Columbia University; Silvia Garzoli (PIES), NOAA Atlantic Oceanography and Meteorology Laboratory; Dale Pillsbury (current meters) Oregon State University; Rana Fine (CFC) University of Miami; Chester Koblinsky (satellite data), Goddard Space Flight Center. The Arlindo Indonesian Team include: R. Dwi Susanto (BPPT and LDEO); A. G. Ilahude (LIPI and LDEO); from BPPT: Muhamad Irfan, Handoko Manoto, Fadli Syamsudin, Djoko Hartoyo, Bambang Herunadi; and from LIPI: Muhamad Hasanudin.

between the sea surface and 1250 m in the Timor Passage from March 1992 to April 1993 (an El Niño period). With the Lombok values the JADE results suggest 6 Sv transport through the Lesser Sunda Islands. An annual mean Throughflow of 5 Sv is estimated from XBT data for the upper 400 m between Java and Australia for the period 1983 to 1989 (Meyers, 1996). T. H. Aung presented the results of the 1993–94 (El Niño period) ASEAN current meter array in the Makassar Strait at a June 1995 meeting in Lombok. The three ASEAN moorings were deployed in the wide northern entrance to Makassar Strait. Most of the current meters were below 400 m with one instrument at 275 m, thus missing the main thermocline, making estimation of transport difficult, but Aung states that the Makassar transport may be as large as 11 Sv. Potemra et al. (1997) model study and inspection of TOPEX/POSEIDON data find a summer maximum of 11 Sv, and a winter minimum of 4 Sv, with a 7.4 Sv 9-year mean. Gordon et al. (1997) find on average 9 Sv of Indonesian Throughflow water advected westward within the Indian Ocean.

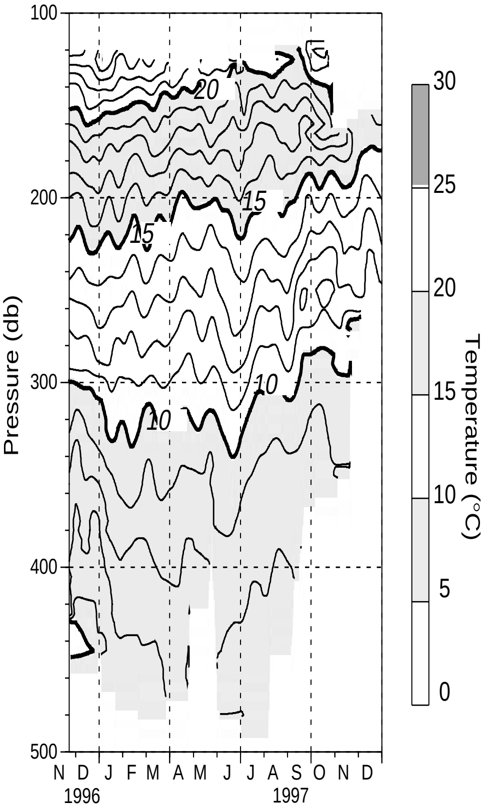

Figure 2. Temperature time series section constructed from 7 temperature-pressure pods on the MAK-1 mooring distributed between 110 m and 290 m. Due to a ~300 m mooring blowover by strong semi-diurnal tidal currents, a continuous pressure-time section was obtained. Each temperature-pressure pod effectively sampled 4 vertical profiles per day. Instrument failures reduce the time series to less than 1 year, rather than the full mooring deployment. The data have been time smoothed by a 35 day gaussian filter. The 15°C isotherm shallows 50 db between November 1997 and January 1998, with the 200 db temperature cooling 2°C over the same time interval.

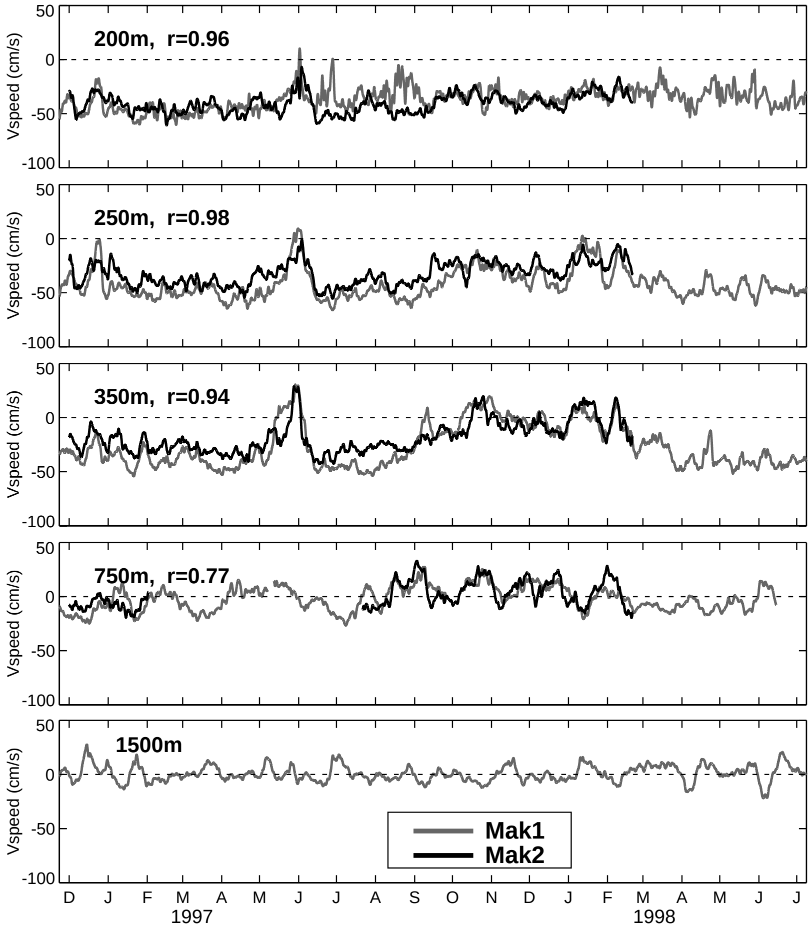

Figure 3. The low pass (2 day) filtered along channel (orientation of 170°) speed recorded at each Aanderaa current meter of MAK-1 and MAK-2. Negative values denote flow towards the south, the direction of the interocean Throughflow. The correlation (r) at similar depths between the two moorings is quite high for the shallower three levels. The lower r value at 750 m stems from the failure of the MAK-2 instrument at that level for nearly a 6 month period. Only MAK-1 had an instrument at 1500 m. The effects of the ENSO (see Fig. 4c for the SOI and El Niño indices) phasing may be seen in the Throughflow speeds: higher southward speeds occur from December 1996 to August 1997, with lower values in the September 1997 to February 1998 period, before increased speeds in the later part of the MAK-1 record. From mid-May to early June 1997 a marked relaxation in the Throughflow speeds is recorded; this event may reflect remote forcing from the Pacific or Indian Oceans. At the 750 m and 1500 m depths, which are below the 600 m sill depth separating the Makassar Strait from the Flores Sea to the south, reveal nearly zero mean flow, but display strong monthly oscillations.

The preliminary findings of the Arlindo Makassar MAK-1 and MAK-2 data are presented in Figs. 2 to 4, some key points each of which will be explored in detail by the Arlindo team, are:

1. The Makassar thermocline depth and transport reflect the phases of ENSO, with an ambiguous seasonal cycle: deeper thermocline, larger

throughflow during La Niña; shoal thermocline, with reduced transport during El Niño. Additionally, during the El Niño months December 1997 to February 1998 the transport average is 5 Sv, while during the La Niña months of December 1996 to February 1997 the average is 12 Sv, a 2.5 fold difference.

2. Along channel flow exhibits much activity at frequencies above seasonal. A special event occurs in May and June 1997 when a marked relaxation of the Throughflow transport is recorded. Candidates responsible are: Pacific Ocean Rossby waves, Indian Ocean coastal Kelvin waves, local atmosphere and dynamics internal to the Indonesian Seas.
3. The Makassar Strait 1997 twelve month average throughflow is 9.3 Sv. This assumes that the flow above the shallowest Aanderaa equals the flow at that current meter (case B, Fig. 4, page 23). Other models for the surface flow yield 1997 transport average of 6.7 Sv (zero surface flow, case C, Fig. 4) to 11.3 Sv (thermocline shear is extrapolated to the sea surface, case A, Fig. 4). How to handle the water flow above the shallowest Aanderaa current meter is an important issue, not just for the mass transport but also for the interocean heat and freshwater flux and for monitoring array design. We will have a firmer idea of the surface layer flow when the moored ADCP data are processed. The MAK-2 ADCP has a record from 1 December 1996 to 9 March 1997 before it flooded; the MAK-1 ADCP data record will be processed later this year. The preliminary MAK-2 ADCP data show a maximum of along channel flow at 110 m, with near zero surface flow. The hull ADCP of the Baruna Jaya IV, the Indonesian research vessel used in the November/December 1996 deployment and February 1998 recovery of the MAK moorings reveal similar reduction of along channel speed in the surface layer. The MAK-1 monthly along channel speeds displays higher southward values at the 250 m instrument relative to the 200 m instrument for 13 of the 20 month record (the months with higher transport). The data suggests shear reversal between 200 and 250 m in the western Labani channel, closer to 100 m in the east.
4. The Makassar transport (case B) determined from the Arlindo data is at the higher end of estimates derived from Timor Sea and Indian Ocean studies. While this would favour the case C Throughflow of 6.7 Sv, with zero mean along channel flow at the sea surface this may not be the only explanation. Perhaps we are seeing a Throughflow interannual (ENSO) signal (noting that the JADE Timor Passage values were obtained during an El Niño period)? Alternatively, might some of the Makassar transport pass back to the Pacific Ocean to the east of Sulawesi? Comparison of the MAK mooring results with: 1996–98 JADE mooring data near Timor (Molcard and Fieux); Lesser Sunda Island shallow pressure gauge array (Janet Sprintall); and data from the Arlindo mooring in Lifamatola Passage (Fig. 1) to be recovered in November 1998, may help resolve this issue.

Acknowledgement

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References

Godfrey, J. S., 1996: The effect of the Indonesian Throughflow on ocean circulation and heat exchange with the atmosphere: A review. J. Geophys. Res., 101(C5), 12217–12238.

Gordon, A. L., and R. Fine, 1996: Pathways of water between the Pacific and Indian Oceans in the Indonesian seas. Nature, 379(6561), 146–149.

Gordon, A. L., S. Ma, D. Olson, P. Hacker, A. Ffield, L. Talley, D. Wilson, and M. Baringer, 1997: Advection and diffusion of Indonesian Throughflow within the Indian Ocean South Equatorial Current. Geophys. Res. Lett., 24(21), 2573–2576.

Hautala, S., J. Reid, and N. Bray, 1996: The distribution and mixing of Pacific water masses in the Indonesian Seas. J. Geophys. Res., 101(C5), 12375–12389.

Meyers, G., 1996: Variation of Indonesian Throughflow and the El Niño Southern Oscillation. J. Geophys. Res., 101, 12255–12263.

Molcard, R., M. Fieux, and A. G. Ilahude, 1996: The Indo-Pacific Throughflow in the Timor Passage. J. Geophys. Res., 101(5), 12411–12420.

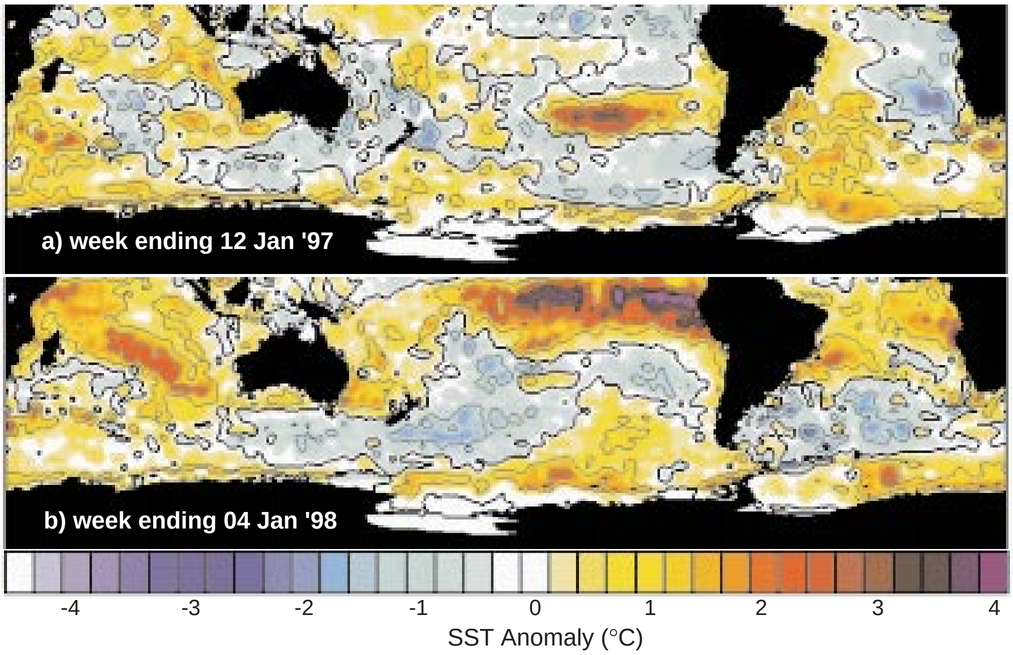
Murray, S. P., and Arief, D. 1988: Throughflow into the Indian Ocean through the Lombok Strait. January 1985–January 1986. Nature, 333, 444–447.

Potemra, J., R. Lukas, and G. Mitchum, 1997: Large-scale estimation of transport from the Pacific to the Indian Ocean. J. Geophys. Res., 102(C13), 27795–27812.

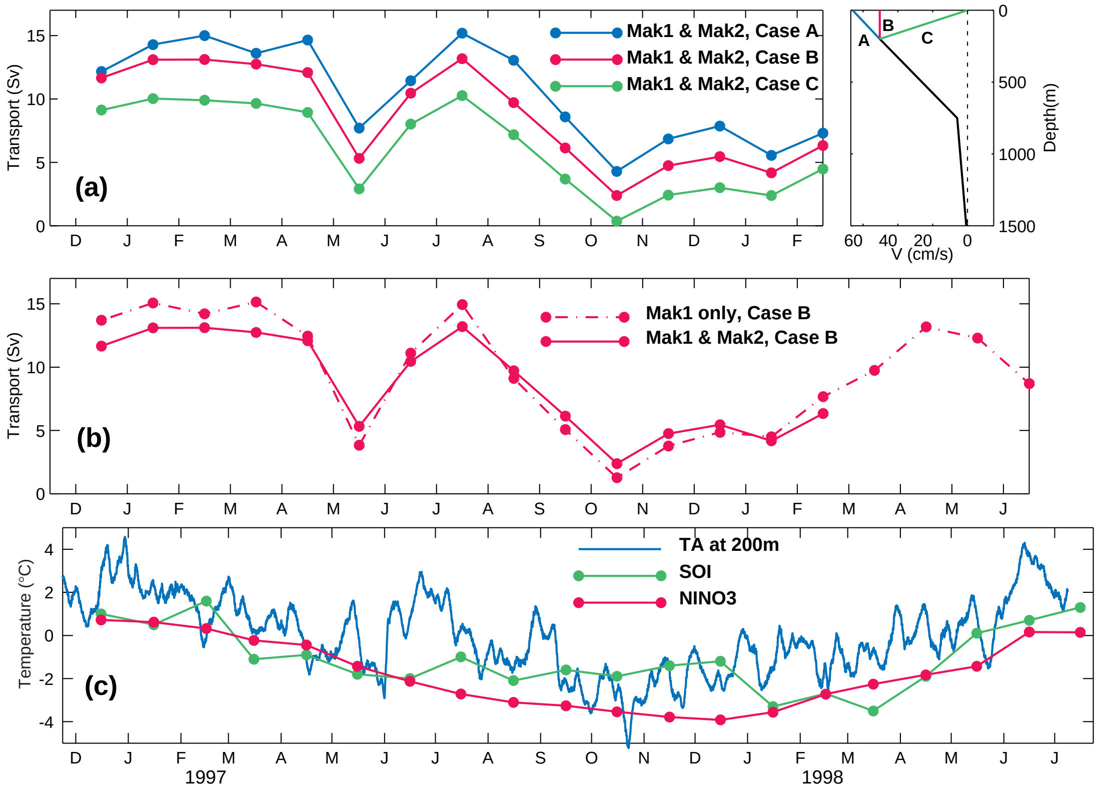
Schneider, N., 1998: The Indonesian Throughflow and the global climate system. J. Climate, 11(4), 676–689.

Van Aken, H. M., J. Punjanan, and S. Saimima, 1988: Physical aspects of the flushing of the East Indonesian basins. Neth. J. Sea Res., 22, 315–339.

Webster, P., V. Magaña, T. Palmer, J. Shukla, R. Tomas, M. Yanai, and T. Yasunari, 1998: Monsoon: processes, predictability, and the prospects for prediction. J. Geophys. Res., 103(C7), 14451–14510.



Baines, page 35, *Figure 1. SST anomalies for the Southern Hemisphere for the weeks ending (a) 12 January 1997 and (b) 4 January 1998, approximately 12 months apart. The ACW is evident in the Southern Ocean region, and the 12-months delay shows the eastward movement. Summer pictures are best because of the reduced cloud cover in the region. (Pictures by courtesy of the web page of Neville Smith, BMRC.)*



Gordon et al., page 30, *Figure 4. Total southward or throughflow transport within Makassar Strait (displayed as positive values) for each month (Fig. 4a,b). As the data from the moored ADCP (deployed at 150 m) is still being processed (see text) we use three models for carrying the Aanderaa along channel speeds to the sea surface (insert adjacent to 4a). As mentioned in the text, we favour case B, which on average differs from A and C results by 2.4 Sv, about 25% difference. Transport determined from use of both moorings for the period up to February 1998, agrees closely with the use of only MAK-1 (4b), suggesting that one mooring may be sufficient in monitoring Makassar transport. The temperature recorded by the 200 m instrument of MAK-1 was processed to remove the mean vertical temperature gradient, recorded during the strong semi-diurnal blowover movements. An anomaly of temperature was then calculated, the difference between the temperature change expected from the mean temperature profile from that actually recorded. The temperature anomaly (Fig. 4c) compares favourably to the ENSO indicators of SOI and the SST anomaly at El Niño-3. The thermocline is deeper during La Niña, shallower during El Niño, as also shown in Fig. 2; thermocline depth is correlated with transport magnitude.*

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We hope that colleagues will see this Newsletter as a means of reporting work in progress related to the Goals of WOCE as described in the Scientific Plan.

The editor will be pleased to send copies of the Newsletter to institutes and research scientists with an interest in WOCE or related research.

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