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Makassar Strait throughflow, 2004 to 2006

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[1] The transfer of Pacific water into the Indian Ocean through the Indonesian seas affects the heat and freshwater budgets of both oceans. The observed transport in the Makassar Strait, the primary Indonesian throughflow pathway, from January 2004 through November 2006 is 11.6 ± 3.3 Sv (Sv = 10^6 m^3/s). This transport is 27% larger than observed during 1997 when a strong El Niño suppressed the flow. The 2004-06 Makassar transport displays clear seasonal behavior, with associated heat and freshwater variability, in contrast to the El Niño dominated 1997 transport. The 2004-06 transport reached maximum values towards the end of the northwest and southeast monsoons, with minimum transport are in October-December. A sustained high transport is observed in early 2006, perhaps in response to an La Niña condition. The maximum throughflow occurs within the thermocline, as in 1997, though the longer 2004-06 measurements also reveal a shallowing of transport as speeds increase. The transport-weighted temperature is 15.6°C in 2004-06, nearly 1°C warmer than that observed in 1997, presumably a consequence of El Niño. **Citation:** Gordon, A. L., R. D. Susanto, A. Ffield, B. A. Huber, W. Pranowo, and S. Wirasantosa (2008), Makassar Strait throughflow, 2004 to 2006, *Geophys. Res. Lett.*, *35*, L24605, doi:10.1029/2008GL036372.

1. Introduction

[2] The Indonesian seas allow for transfer of tropical waters from the Pacific to the Indian Ocean in what is referred to as the Indonesian throughflow [ITF], with significant impact on the oceanic heat and freshwater budgets and on the climate system [*Gordon*, 2005]. Estimates based on measurements obtained from 1985 to 1996 suggest an ITF slightly greater than 10 Sv (Sv = 10^6 m^3/s) [*Gordon*, 2005]. Seasonal and intraseasonal fluctuations are apparent amidst the strong tidal currents [*Ffield and Gordon*, 1996; *Susanto et al.*, 2000]. Interannual variability has been linked to the El Niño-Southern Oscillation (ENSO) [*Meyers*, 1996; *England and Huang*, 2005].

[3] Prior to 2004 the major corridors of the ITF (Figure 1) were measured, though at different times (see *Gordon 2005* for a review). Because the ITF varies with time, these measurements are not synoptic. The International Nusantara Stratification and Transport (INSTANT) program [*Sprintall et al.*, 2004] was established to overcome this deficiency by simultaneously measuring the ITF from the Pacific inflow at Makassar Strait and Lifamatola Passage to the Indian Ocean export channels of Timor, Ombai and Lombok, over a 3-year period. The INSTANT fieldwork began in December/January 2003/04 and was completed in November/December 2006.

[4] To prompt comparison with other data sets and with model output we offer a descriptive overview of the along-channel speed and transport and of the thermocline variability as observed by the two INSTANT Makassar moorings deployed within the narrow Labani Channel constriction near 3°S (Figure 1). These moorings were placed at the same sites as the Arlindo 1996-1998 moorings [*Gordon et al.*, 1999].

[5] Water properties indicate that Makassar Strait is the primary inflow passage for Pacific water above the Makassar sill depth of 680 m (Figure 1), carrying ~80% of the total ITF transport [*Gordon*, 2005]. East of Sulawesi the Lifamatola Passage with a sill depth of ~2000 m represents the dominant inflow path for deeper Pacific water. During residence in the Indonesian seas the inflowing Pacific stratification is modified by tidal induced mixing and buoyancy flux across the sea-air interface, creating a relatively isohaline thermocline, which is then exported to the Indian Ocean.

2. Makassar Moorings

[6] Moorings were deployed on 18 January 2004 at 2°51.9′ S, 118°27.3′ E (MAK-west) and 2°51.5′ S, 118°37.7′ E (MAK-east), a separation of 19.4 km within the 45 km wide Labani Channel, as measured at the 50 m isobath [*Smith and Sandwell*, 1997] (see also http://topex.ucsd.edu/marine_topo/). The moorings were recovered and redeployed in July 2005, with the final recovery on 27 November 2006.

[7] Both moorings were instrumented with upward-looking *RD Instruments* Long Ranger 75 kHz Acoustic Doppler Current Profilers (ADCP), at a nominal depth of 300 m. These were configured to measure all 3 velocity components in 10 m bins at 30 minute intervals. Downward-looking 300 kHz ADCPs were mounted on both moorings, but data return from these instruments was poor, with a usable record only from the second deployment of MAK-east. Single point current meters were positioned on both moorings at 400 and 750 m. Additional current meters were positioned at 200 and 1500 m on MAK-west. The current meters and ADCPs included temperature sensors. MAK-west was instrumented with 15 additional temperature/pressure (TP) and two conductivity-temperature-pressure (CTD) recorders over the nominal depth range of 45 to 468 m. The mooring wire parted at 80 m near the end of the first deployment of MAK-west resulting in the loss of 3 TP recorders. The remainder of the mooring was largely unaffected. MAK-east was equipped with one additional TP and two CTD recorders, in the nominal depth range of 115 to 400 m. Vertical excursions (mooring blowover) of more than 100 m were common at MAK-west. Blowover was less

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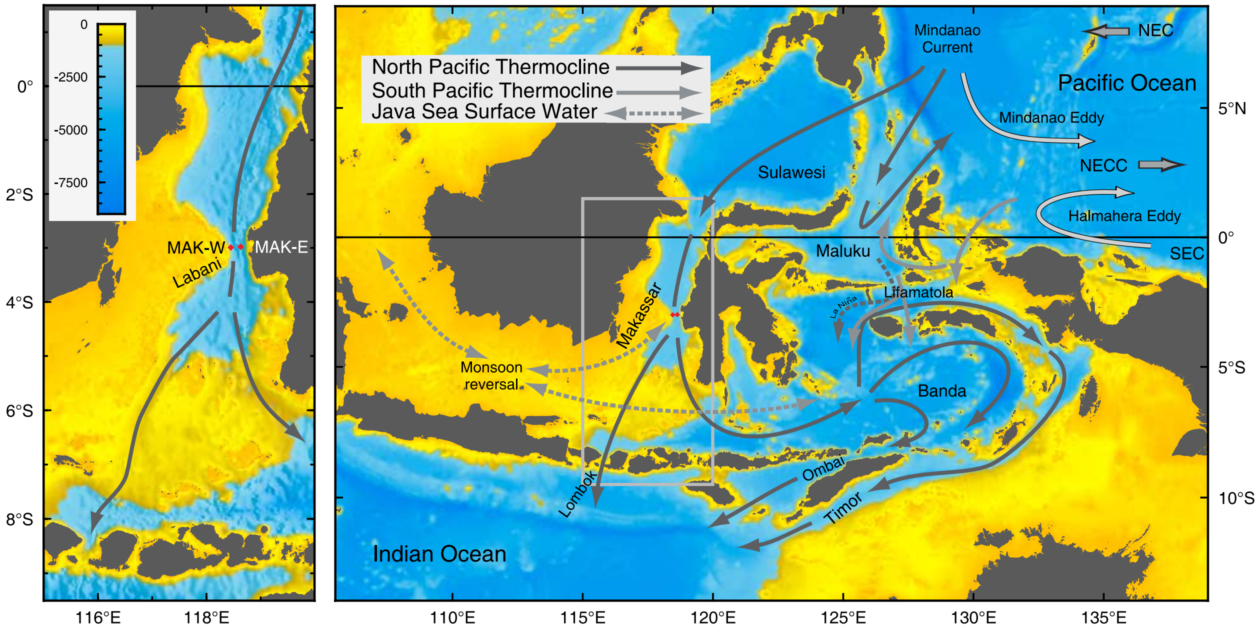

Figure 1. (left) Expanded view of the Makassar Strait region. The solid grey lines mark the approximate pathway of the Makassar throughflow. (right) Schematic of the Indonesian throughflow pattern. The grey box delineates the expanded view shown on the left.

at MAK-east, in part owing to the shorter length of mooring wire above the Long Ranger ADCP.

3. Along-Channel Speed

[8] The record length speeds at select depths at the INSTANT Makassar Strait moorings (Table 1) reveal a maximum speed within the thermocline (140 m in Table 1). The average ratio of the MAK-east to MAK-west speeds is 0.95 (surface layer), 0.84 (mid-thermocline) and 0.76 (lower thermocline), respectively. The thermocline speed maximum and the western intensification of the Labani throughflow are consistent with the Arlindo data [*Gordon et al.*, 1999; *Susanto and Gordon*, 2005].

[9] The average direction of the flow at MAK-east is towards 165°. At MAK-west there is a stronger eastward component, with an average direction of 155°. The along-axis trend of Labani Channel is oriented along ~170°, so the average direction of the two moorings is directed slightly to the east of along-axis direction. The Naval Research Laboratory (NRL) 1/32° global Layered Ocean Model [*Shriver et al.*, 2007] (see also http://www7320.nrlssc.navy.mil/global_nlom/) shows the maximum southward currents in the Makassar Strait north of Labani Channel along the western side of the Makassar Strait. The flow along the western side of the northern Makassar Strait must then shift eastward, around the shallow bathymetry, to transit Labani Channel. The slight eastward flow relative to the along-axis orientation of the Channel may be due to inertia. That the relative eastward component increases as the meridional component exceeds 1 knot is consistent with this speculation.

[10] Following the convention used for the Arlindo data, the combined MAK-west and MAK-east along-axis speed (Figure 2) is defined as the flow paralleling the axis of Labani Channel, with negative values directed towards 170° (towards the Indian Ocean). This value would be 1.6% less than the mean direction of the two INSTANT moorings.

[11] The velocity profile (Figure 2, left) displays a distinct thermocline maximum (v-max) between 110 to 140 m. The profile varies with season: greater v-max during July/August/September (JAS, southeast monsoon), relative to the January/February/March (JFM, northwest monsoon) profile.

Table 1. Record Average Speed and Compass Directions at Various Depths at MAK-West and MAK-East

Mooring	Depth	Speed	Direction
MAK-west	40 m	0.43 m/s	161°
	140 m	0.67 m/s	157°
	280 m	0.45 m/s	154°
	400 m	0.22 m/s	151°
Below sill depth	750 m	0.02 m/s	173°
	1500 m	0.01 m/s	−6°
MAK-east	40 m	0.40 m/s	164°
	140 m	0.55 m/s	166°
	280 m	0.32 m/s	165°
	400 m	0.16 m/s	164°
Below sill depth	750 m	0.03 m/s	179°

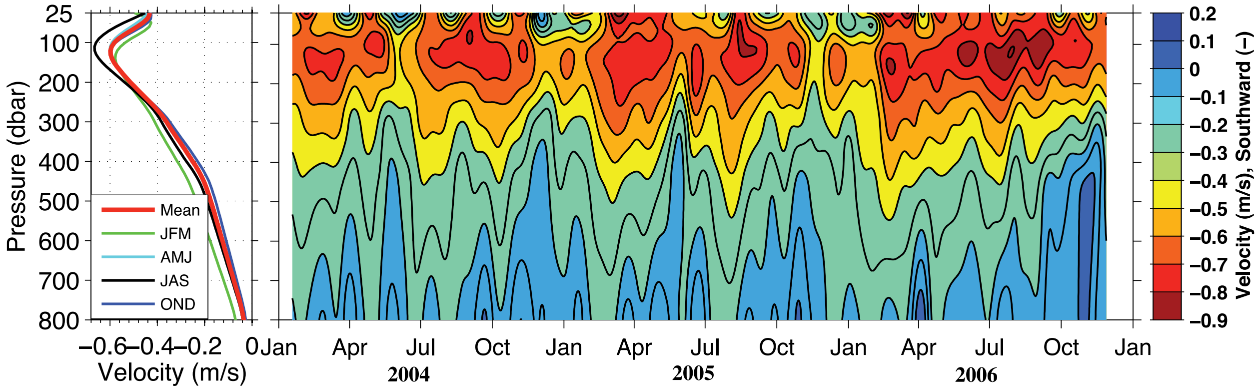

Figure 2. (left) The seasonal profiles and (right) along-channel velocity section. The velocities represent an average of MAK-west and MAK-east values. The vertical coordinates are given in decibar (dbar), which is approximately a meter (m).

The JAS and JFM profiles reverse their relative position at depths below 220 db, indicating a deeper reaching Makassar throughflow during the northwest monsoon. The time series section of the along-axis current (Figure 2, right) further displays the depth dependence of the v-max, with a tendency for the higher speeds as the v-max shallows. The v-max deepens during the northwest monsoon, February-March 2004, March-April 2005 and February-April 2006; with the shallowest v-max during the southeast monsoon, July-September 2004, 2005 and 2006. The thermocline v-max displays a semi-annual fluctuation, with highest values within the middle to latter stage of each monsoon: February-April 2004, July-September 2004, March-April 2005, August-September 2005, February-March 2006, June-September 2006. The strong southward speeds in 2006 stand out as an anomaly, lacking the May/June throughflow relaxation as observed in the two prior years. The period of sustained throughflow begins rather abruptly in early February 2006, spanning a wide swath of depths, from the sea surface to well below the thermocline.

[12] Reduced throughflow in May 2004 and May 2005 may represent the impact of Kelvin Waves generated during the monsoon transitions in the Indian Ocean that propagate eastward to Sumatra, and then continue as coastal-trapped Kelvin Waves [*Sprintall et al.*, 2000] to the ITF export portals. This feature was absent in May 2006. The La Niña condition of January to April 2006 (negative ninõ4; Figure 3) with commensurate higher Makassar throughflow transport (Figure 3) may have suppressed the propagation of the Kelvin Wave into Labani Channel. A secondary weakening of the southward speeds occur in November 2004, 2005 and 2006, may also represent an Indian Ocean Kelvin Wave monsoon transition event. Surface layer reversals of 1 to 2 months duration are observed during the northwest monsoon (primarily in December-January) of 2005 and 2006, consistent with the Arlindo time series [*Gordon et al.*,

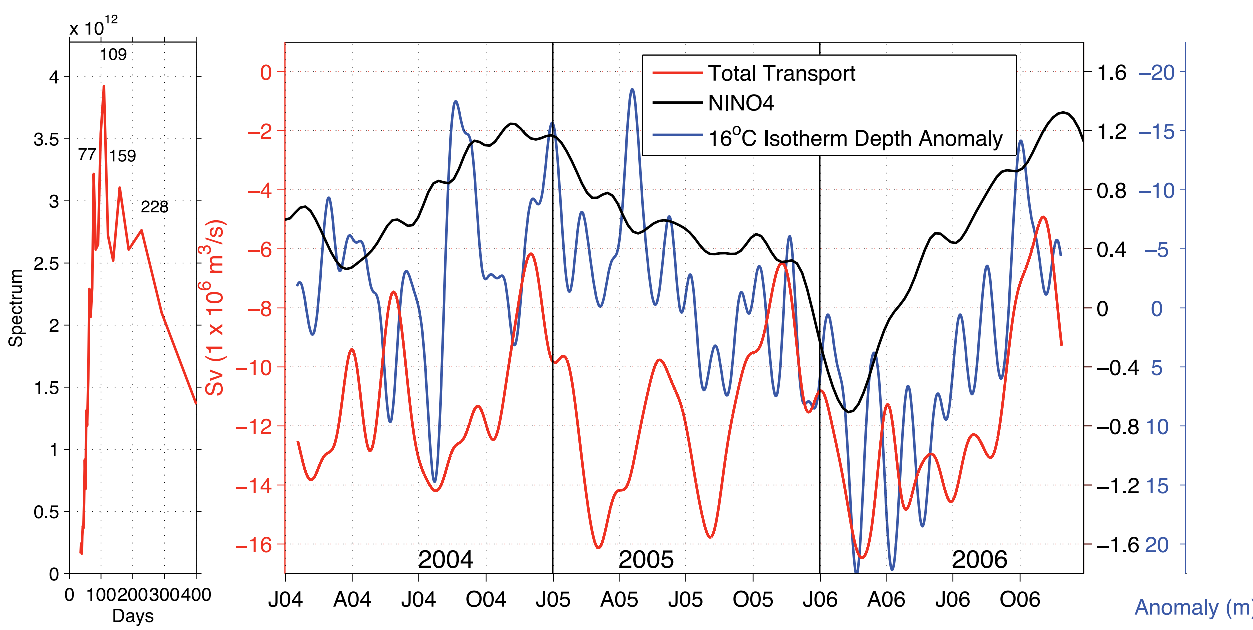

Figure 3. (left) The spectrum (power spectral energy, Sv^2/day) of the total Makassar Strait volume transport with the peaks (in days) of the periods labeled. (right) The total Makassar Strait volume transport (Sv, red line, red left axis) and depth anomaly of the 16°C isotherm (m, blue line, blue right-most axis) after a 30-day low pass filter has been applied, as well as the Niño4 time series (area-averaged SST anomaly within 5°N to 5°S, 160°E to 150°W; black line, inner right black axis).

Table 2. Makassar Strait Transport, Transport Weighted-Temperature and Depth of the 16°C Isotherm by Season and Year During the INSTANT Observational Period[a]

Seasonal	JFM	AMJ	JAS	OND
Transport	−13.1 ± 2.8 Sv	−11.7 ± 3.1 Sv	−12.6 ± 2.5 Sv	−8.8 ± 3.0 Sv
Transport-Weighted Temperature	16.6° ± 3.7°C	16.0° ± 3.9°C	16.9° ± 2.6°C	12.7° ± 3.0°C
16°C Isotherm Depth	181 ± 10 m	182 ± 11 m	180 ± 10 m	178 ± 8 m
Annual	2004	2005	2006	3−Year
Transport	−11.2 ± 3.0 Sv	−11.7 ± 3.2 Sv	−11.8 ± 3.7 Sv	−11.6 ± 3.3 Sv
Transport-Weighted Temperature	14.4° ± 3.6°C	15.6° ± 3.6°C	16.7° ± 3.7°C	15.6° ± 3.7°C
16°C Isotherm Depth	177 ± 9 m	179 ± 9 m	185 ± 10 m	180 ± 10 m

[a]Northwest Monsoon is JFM, January-March; AMJ, April-June. Southeast Monsoon is JAS, July-September; OND, October-December. Sv = 10^6 m^3/s.

2003], though in 2004 a series of surface flow reversals occur throughout the year.

4. Along-Channel Transport and Transport-Weighted Temperature

[13] The Makassar Strait transport (Figure 3 and Table 2) is derived by multiplying the average velocity profile of MAK-west and MAK-east and the depth-dependent cross-section area of Labani channel. Above 800 m, an average velocity of MAK-west and MAK-east is used, and below 800 m, only MAK-west velocity is used. The Labani Channel cross section area is divided into 10 m depth bins. The velocity profile of MAK-west and MAK-east is gridded into 10 m depths and 2 hour intervals, then combined to produce an average velocity. While mathematically southward transport is denoted as a negative value (Figure 3), below we discuss the Makassar transport without sign.

[14] *Susanto and Gordon* [2005] determined the calendar 1997 transport from the Arlindo data using two methods of extrapolation to the Labani side-walls. A transport of 9.1 Sv is calculated based on linear interpolation of the observed along channel zonal shear dv/dx, to the side-walls (this is equivalent to the method used by *Gordon et al.* [1999], which yielded similar transport, 9.2 Sv); a lower transport of 6.8 Sv assumes a linear drop-off to zero flow at the side-walls from each mooring. The average of the two methods is 7.9 ± 1.2 Sv. The INSTANT Makassar transport estimate is determined by extending the average MAK-west and MAK-east along-axis speeds within 10 m bins to the side-walls. This is effectively the same as used by *Gordon et al.* [1999] and for the larger transport estimate of *Susanto and Gordon* [2005] for the Arlindo data, of 9.2 Sv.

[15] The Makassar Strait transport record length average is 11.6 Sv with a standard deviation of 3.0 Sv (Table 2). The most striking feature is the consistency in the average annual values: 11.2, 11.7 and 11.8 Sv, for 2004, 2005 and 2006, respectively. The INSTANT three year Makassar transport is about 27% (2.5 Sv) larger than the Arlindo 1997 transport. That 1997 was dominated by a strong El Niño, whereas the ENSO average for the three year INSTANT period was in a relative neutral state, with a La Niña period in late 2005 into early 2006 (Figure 3; the niño4 remained near +0.5 during the INSTANT period), provides a sense of the ENSO influence on the ITF. This dramatic increase in the transfer of Pacific water into the Indian Ocean is expected to have major impact on the mass and thermohaline budgets of the Indian Ocean (a topic to be explored in future studies).

[16] The INSTANT Makassar transport displays considerable seasonal fluctuations (Figure 3 and Table 2). The minimum transport occurs in the monsoon transition months of April to June (AMJ; 11.7 Sv) and October to December (OND; 8.8 Sv), the latter representing the absolute seasonal minimum, signifying the presence of an annual signal. The maximum transport occurs towards the end of each monsoon, reaching 13.1 Sv in the northwest monsoon and 12.6 Sv in the southeast monsoon. The energy peak of the seasonal fluctuations is further brought out by the power spectrum (Figure 3, left). The spectrum representing the accumulated energy (Sv^2/day) over the entire time series as a function of frequency is produced by Hilbert-Huang Transform, which is appropriate for nonlinear and nonstationary time series [*Huang and Wu*, 2008] (previously applied to the 1997 Makassar data by *Susanto et al.* [2000]). The seasonal fluctuations are also observed within the Mindanao Current, where they are induced by local Ekman pumping combined with westward propagation of Rossby waves originating in the central tropical Pacific [*Qu et al.*, 2008]. As the Mindanao Current is the primary source of the Makassar throughflow, a Pacific origin of the Makassar seasonality is suggested.

[17] The Makassar Strait transport time series (Figure 3) attains maximum values of ~16 Sv in February-March 2005 and 2006, and in August 2005, with secondary maximums of ~14 Sv in February and August 2004. From late February to September 2006 the transport exhibits a sustained high value of >14 Sv, except for a brief relaxation to 11 Sv in early April. The transport dips to 6-7 Sv in November-December 2004 and again in November 2005, with the absolute minimum of 4 Sv in November 2006.

[18] The depth anomaly of the 30 day low pass 16°C isotherm (180 m mean depth; Table 2) reveals strong intra-seasonal (<90 days) fluctuations that do not correlate with transport, varying from +20 m (deeper than the mean) in early 2006 during a 9-month extended period of sustained deepening, to −15 m (shallower than the mean) most notably at three times between August 2004 and April 2005 (Figure 3). During the periods of sustained high transport in early 2006 to September 2006, the 16°C isotherm is deep, following the La Niña trend revealed by the niño4 index. A ENSO correlation of the thermocline depth to transport was observed during the Arlindo time series [*Ffield et al.*, 2000].

[19] The 3-year transport-weighted temperature (TWT) is 15.6° ± 3.7°C (Table 2), increasing in each of the three years from 14.4°C to 16.7°C from 2004 to 2006. *Vranes et al.* [2002] find a TWT of 14.7°C for the Arlindo record length. The TWT is a function of the vertical distribution of along-axis speed and the depth of the 16°C isotherm. The season of coolest TWT occurs in the October-December months,

the time of minimum speeds. The year of warmest TWT (16.7°C) is in 2006, corresponding to the combined effect of the averaged highest transports and deepest thermocline.

[20] Although there are energetic intraseasonal fluctuations of transport and thermocline depth, at lower frequency both exhibit a response to the phase of ENSO, with a tendency of greater transport and deeper thermocline as the El Niño condition [+niño4] is weak or absent. This is best seen in early 2006 after the La Niña [-niño4] peak of February 2006. The maximum correlation coefficient of the 30-day low pass transport to 30-day low pass ninõ4 is 0.42 (weaker Makassar throughflow scales to positive niño4) with a one-week lag of transport relative to niño4. The maximum correlation of the 16°C isotherm depth to niño4 is −0.70 with a five-week lag.

5. Conclusions

[21] From January 2004 through November 2006 the Makassar Strait throughflow was measured at two moorings as part of the INSTANT program. Makassar Strait is the main conduit for the inflow of Pacific water into the Indonesian seas, carrying ∼80% or more of the Indonesian throughflow. The INSTANT Makassar moorings were placed at the same sites as the December 1996 through June 1998 Arlindo moorings, thus allowing for comparison of these two time periods.

[22] The INSTANT time series displays similar vertical profiles of along channel speed as the Arlindo time series, with a distinct velocity maximum, about 50% greater than the surface layer flow, within the thermocline. The thermocline speed maximum tends to shallow as its speed increases. The more extended INSTANT observational period reveals seasonality to the along-axis speed profile, which during the Arlindo period may have been masked by a strong El Niño. The thermocline along-axis speeds observed during INSTANT are highest in the southeast monsoon, though the along-axis speed below 220 m is higher during the northwest monsoon. During the northwest monsoon while the transport is reduced, a larger percentage is drawn from the cooler subthermocline stratum.

[23] The strong and sustained southward along-axis speeds in 2006 stand out as an anomaly, lacking the slackening in May/June 2006 as observed in those months for the two prior years. The period of sustained throughflow begins rather abruptly in early February 2006 spanning a wide swath of depth.

[24] The mean Makassar Strait transport during the INSTANT period is 11.6 Sv, about 27% greater than the 9.2 Sv transport found during the Arlindo period using comparable methods of side-wall extrapolation. The INSTANT period was not dominated by a strong ENSO condition as was the Arlindo period, which occurred during a strong El Niño from April 1997 to May 1998, which is expected to suppress the ITF. Indeed the INSTANT transport maximum occurred in early 2006, at a week lag to the peak of a La Niña episode, during which time the depth anomaly of the 16°C isotherm was 20 m deeper than the mean. A similar correlation of the thermocline to transport for greater than intraseasonal time scales was observed during the Arlindo time series. The INSTANT Makassar transport reveals seasonal signal with the minimum transport during the monsoon transition months of April to June and October to December, the latter having the absolute seasonal minimum.

[25] The INSTANT Makassar time series offers an intriguing view of the major inflow pathway of the ITF during 2004-06 and of its contrast to an earlier El Niño dominated condition. We offer this concise descriptive account of the Makassar Strait throughflow to prompt comparison with other data sets and with model output. A more detailed investigation of the INSTANT Makassar time series spatial/temporal features, as well as its comparison to the other passages measured by the INSTANT program is planned.

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