Throughflow within Makassar Strait

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Abstract. From late November 1996 to early July 1998 velocity measurements were made at two moorings within a constriction in Makassar Strait near 3°S. The 1997 average throughflow is 9.3 Sv, with an uncertainty of about ± 2.5 Sv depending on how the surface flow is taken into account. The results show that throughflow within Makassar Strait can account for all of the Pacific to Indian interocean transport. The correlation of transport to ENSO may be as high as 0.73, though the time series is too short to say this with assurance. Most of the remaining variance is explained by the annual cycle, with a June maximum and December minimum. A strong intra-seasonal event occurs from late May to July, 1997.

Introduction

Velocity and temperature were measured at various depths within Makassar Strait as part of the Indonesian-US Arlindo program [*Gordon et al.,* 1998]. This was accomplished at two moorings, MAK-1 (23 November 1996 to 8 July 1998) and MAK-2 (1 December 1996 to 21 February 1998), deployed near 3°S within the Labani Channel, a 2000 m deep, 45 km wide constriction in Makassar Strait (Figure 1). West of the Labani channel is a <10 m deep coral reef rimming a broad promontory of generally <30 m deep, confining the throughflow to the Labani channel. This paper presents the along channel currents and transport estimates for Makassar Strait based on the time series records from Aanderaa current meters on each mooring, set at depths of 200, 250, 350, 750 and 1500 db (for zero wire angle; the 1500 db instrument was only on MAK-1). Each mooring had an upward looking ADCP at 150 m, but only a partial record at MAK-2 was recovered. Temperature and pressure sensors were attached to the mooring line [*Ffield, A., K. Vranes, A. Gordon, R. Susanto, S. Garzoli, Temperature variability within Makassar Strait, submitted to Geophys. Res. Lett.*]. Blowover of the moorings, primarily a result of strong semi-diurnal tides, was substantial. For example, 90% of the MAK-1 200 m instrument values varied from 204 db to 336 db depth, with a mean depth of 248 db.

Background

Model research reveals dependence of Pacific and Indian Ocean heat and freshwater budgets on the Indonesian Sea throughflow [*Toole and Raymer,* 1985; *Wijffels et al.,* 1992; *Hirst and Godfrey,* 1993; *Gordon and McClean,* 1999]. Heat and freshwater flux into the Indian Ocean at the expense of the Pacific may affect tropical SST patterns and atmosphere-ocean coupling with potential impacts on the ENSO and monsoon phenomena [*Schneider,* 1998; *Webster et al.,* 1998]. Observations indicate that the throughflow is composed mostly of North Pacific thermocline and intermediate water flowing through Makassar Strait [*Gordon and Fine,* 1996]. In the deep channels east of Sulawesi, South Pacific water infiltrates into the lower thermocline

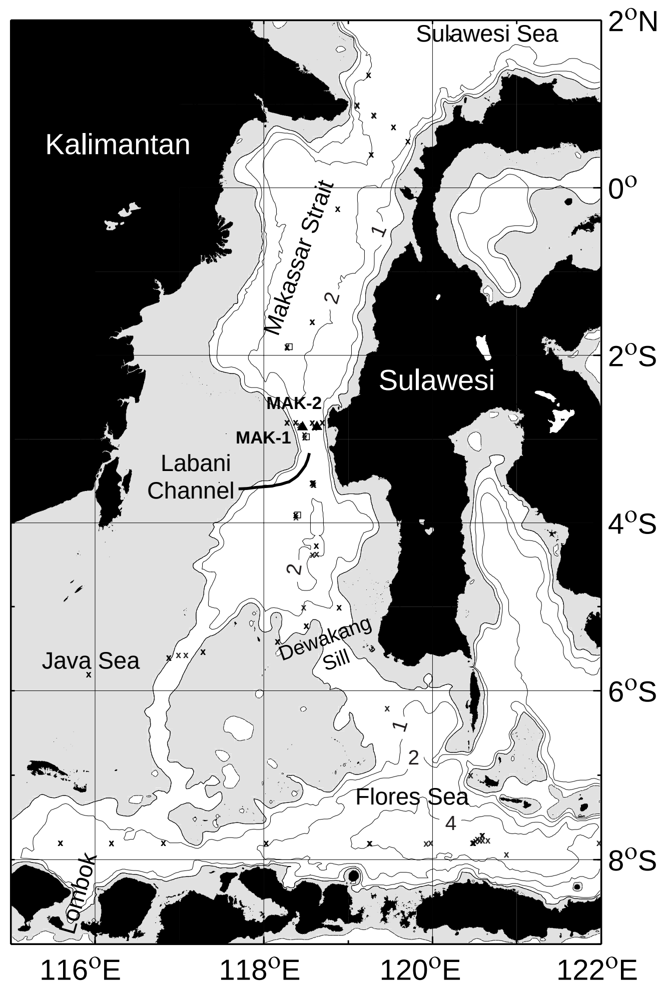

Figure 1. The position (triangles) of the 1996-98 moorings in Makassar Strait, MAK-1 (2° 52' S, 118°27' E) and MAK-2 (2°51'S; 118°38'E). Position of bottom pressure and inverted echo sounders sensors (PIES) are shown by the solid box symbols. Arlindo CTD stations obtained from 1993 to 1998 are shown by solid circles The shaded area is less than 500 m depth. The isobaths are labeled in km.

of the Banda Sea and dominates the deeper layers, through density driven overflow [*Ilahude and Gordon,* 1996; *Hautala et al.,* 1996]. *Wajsowicz* [1996] model throughflow is carried by the western most (friction-determined) channel; Makassar Strait is the westernmost deep channel.

Indonesian throughflow transport estimates based on observations and models range from near zero to 30 Sv [*Lukas et al.,* 1996; *Godfrey,* 1996]. Measurements in the Lombok Strait [*Murray and

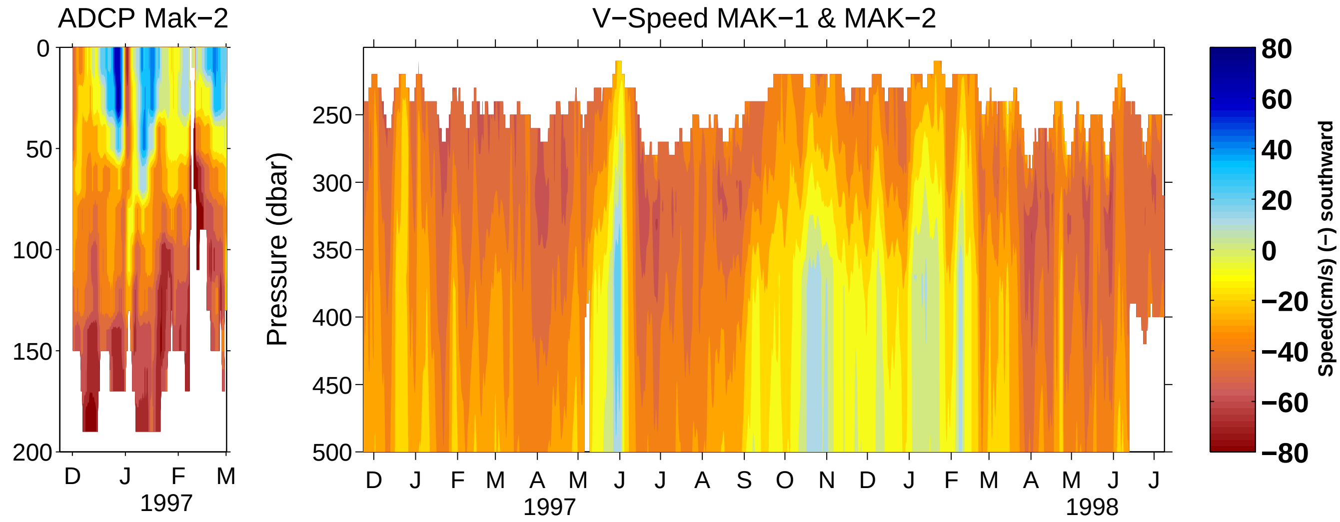

Figure 2. The 2 day low pass filtered along channel (orientation of 170°) speed at MAK 1 and MAK 2 Aanderaa current meters and for the three month record of the MAK-2 upwards looking ADCP.

Arief, 1988] from January 1985 to January 1986 show an average transport of 1.7 Sv. The mean transport between the sea surface and 1250 m in the Timor Passage from March 1992 to April 1993 is 4.3 Sv [*Molcard et al.*, 1996]. The throughflow within the upper 400 meters passing westward between Java and Australia is estimated from 1983 to 1989 XBT data [*Meyers*, 1996] to be 5 Sv, with a 12 Sv August-September maximum, and essentially zero transport in May-June and again in October-November. *Potemra et al.* [1997] model study finds a northern 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 9 Sv of Indonesian throughflow water embedded within the Indian Ocean South Equatorial Current.

Makassar Currents and Transport

The semi-diurnal and diurnal tides, with strong fortnightly modulation, are the most dominant feature of the current meter time series. Removal of the tidal signal with a 2 day filter better exposes the along channel southward flow [*Gordon and Susanto*, 1999]. The correlation between the two moorings of speeds at similar depths is 0.94 [*Gordon et al.*, 1998]. The combined MAK-1 and MAK-2 data are shown in Figure 2.

The observations indicate that the throughflow decreases significantly below a depth of approximately 400 db. The 750 and 1500 db instruments, which are set at depths greater than the 550-650 m deep Dewakang Sill in the southern Makassar Strait, record zero mean flow, but with significant 1 to 2 month oscillations, which are 180° out of phase with each other. The data (Figure 2) indicate frequent occurrence of maximum southward speeds near 300 db (a product of the MAK-1 time series), the depth of the North Pacific Intermediate Water salinity minimum core [*Ilahude and Gordon*, 1996]. The subsurface maximum occurs in 13 months of the 20 month record, most common from April to September 1997 and again in April 1998 to the end of the record in June 1998. The MAK-2 Aanderaas and ADCP (see below) data indicate maximum southward flow at a shallower depth, probably between 150 and 200 db.

The Makassar Strait transport (Figure 3) is calculated as follows: 20 minute values of the along channel speed and depths of each of Aanderaa current meter are determined; linear interpolation between these levels provide a transport profile within the depth range of the Aanderaas. The transport above the shallowest Aanderaa is estimated using three model profiles: Profile A, the mean thermocline shear is extrapolated to the sea surface; Profile B, assumes that the flow above the shallowest Aanderaa equals the flow at that current meter; and Profile C, the along channel speed decreases linearly from the shallowest Aanderaa to zero at the sea surface. The 1997 12 month average throughflow using MAK 1 and MAK 2 data (assigning half of the Labani Channel cross-section area to each) is 11.3 Sv; 9.4 Sv and 6.7 Sv for Profile A, B and C, respectively.

A mixed Profile model for the upper layer flow is used that may better represent the seasonal variability of the surface flow (discussed below): Profile C during the northern winter monsoon December to February; Profile B during the monsoon transition months of March to May and from September to November and Profile A for the northern summer monsoon, June to August. The 1997 12 month average for this Mixed Profile model is 9.2 Sv, essentially the same as Profile B. The transport varies from zero during the late May 1997 to over 20 Sv in July 1997. Using only the MAK-1 time series for the full Labani Channel leads to a Profile B and Mixed Profile transport for 1997 of 9.5 Sv for both, effectively the same as using both moorings, indicating that a single mooring in Labani Channel would accurately monitor the Makassar throughflow. Interocean heat flux is particular sensitive to the Profile model used: the product of °C and transport varies by a factor of 2 between Profiles A and C.

An ASEAN three mooring current meter array [Aung, 1999] was deployed in the northern entrance to Makassar Strait, which is about twice the width of Labani Channel. Most of the current meters were below 400-m depth (zero wire angle), with one instrument at 275-m in the eastern end of the array. The ASEAN array misses the thermocline, but on extrapolation to the sea surface Aung states that the Makassar transport may be as large as 11 Sv, agreeing with the Arlindo Profile A value for 1997.

The MAK-2 ADCP time series record from 1 December 1996 to 1 March 1997 (Figure 2) shows increasing southward speeds with depth, with surface flow varying from near zero to northward. This was not a local wind effect as the NSCAT measured winds during this period were directed towards the south. Surface current charts [*Wyrtki*,

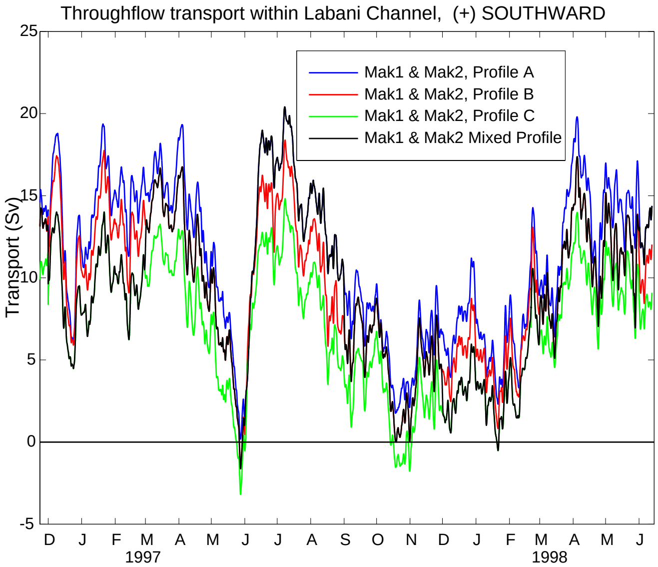

Figure 3. Throughflow transport based on 1 week low pass filter values within Makassar Strait, for the four speed versus depth model profiles described in the text. Data from both moorings are used to the end of the MAK-2 record in February 1998, after which only the MAK-1 data is used. The throughflow transport towards the Indian Ocean, towards the south, is displayed as positive values.

1961; *Defense Mapping Agency,* 1993] show weak flow to the south in the northern winter monsoon, with strong flow to the south in the summer monsoon. Five satellite tracked drifters launched in the Pacific passed into Makassar Strait, before disappearing at the southern limits of the Strait [p.c., *Don Olson,* January 1999]. Observations suggest that the surface flow is weak in the winter, strong to the south in the summer. Model results suggest similar temporal dependence. *Potemra et al.* [1997] using the POCM model driven by ECMWF winds, find that Ekman transport in the Indonesian Seas is near zero or directed towards the Pacific in the winter months, with strong Indian Ocean bound Ekman transport in summer. The POP model results display a surface (upper 100 m) flow towards the north in Makassar Strait during the winter, and towards the south in the summer months [p.c. *McClean,* February 1999]. Surface flow reversal may be due to the strong monsoonal zonal wind across the southern boundary of Makassar Strait [Java and Flores Seas; *Wyrtki,* 1961] relative to the weak monsoonal winds in the northern boundary of Makassar Strait (Sulawesi Sea).

The MAK moorings were deployed during a La Niña phase. An El Niño condition began in March 1997, becoming extreme during 1997 summer and fall, relaxing in early 1998. Observational and model studies suggest the throughflow is modulated by ENSO, with larger transports during La Niña and smaller transports during El Niño [*Meyers,* 1996; *Fieux et al.,* 1996; *Potemra et al.,* 1997; *Gordon and McClean,* 1999]. The monthly transport determined from MAK-1 reveals some correspondence to the Nino3 SST anomaly (Figure 4a). During the El Niño months December 1997 to February 1998 the Profile B transport average is 5.1 Sv, while during the La Niña months of December 1996 to February 1997 the average is 12.5 Sv, a 2.5 fold difference. The correlation of throughflow transport to ENSO (expressed as the negative of its Nino3 proxy, Figure 4b) for Profile B is 0.73, and 0.53 for the Mixed Profile model, though the time series is far too short to say this with assurance. In Figure 4b, a zero Nino3 anomaly value corresponds to a mean transport of approximately 12

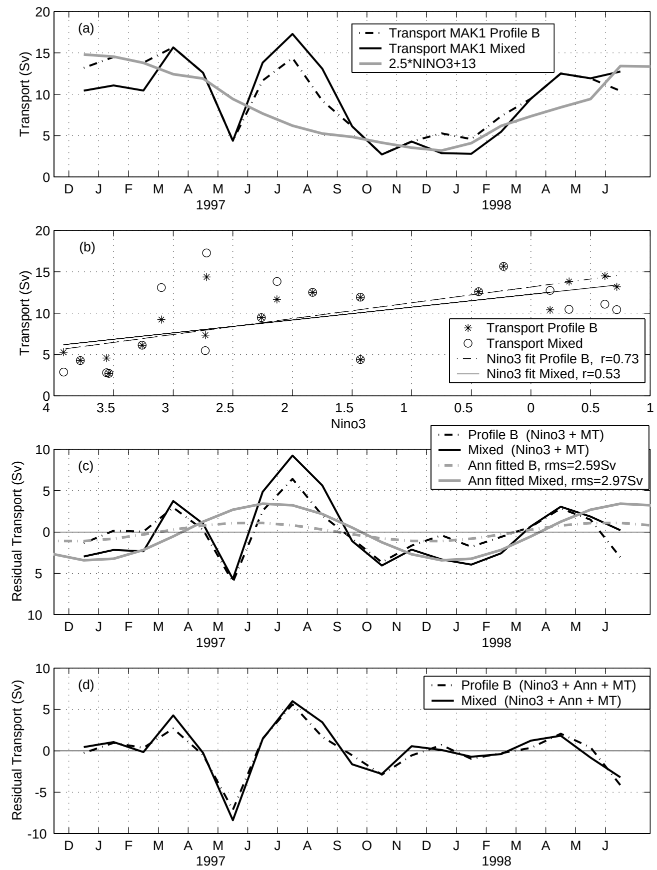

Figure 4. a) Monthly volume transport (Profile B and Mixed Profile models) based on MAK-1 time series and its relation to Nino3 SST anomaly. As a positive Nino3 SST anomaly (El Niño) corresponds to low throughflow transport the Nino3 value is adjusted and expressed as a negative to allow its representation on the transport versus time plot. b) Linear fit of monthly transport to Nino3 SST anomaly for Profile B and for the Mixed Profile models. c) Residual transport after the mean throughflow (MT) and the Nino3 dependence are removed. An annual curve (Ann) is fit to the residual for both Profiles. d) Residual monthly transport with the mean throughflow, the Nino3 dependence and annual curve removed.

Sv. Fitting an annual curve to the transport residual after the mean transport and the ENSO dependence are removed (Figure 4c) suggests a maximum transport in June, minimum in December. Others [*Meyers*, 1996; *Potemra et al.*, 1997] have found a summer maximum, winter minimum in the throughflow. Removing the mean transport, the ENSO dependence and the annual influence (Figure 4d) leaves a near zero residual except for a large negative anomaly (minimum throughflow) in May 1997 and positive anomaly in July 1997. From early June to mid-June the throughflow transport increases (Mixed Profile) from near zero to 18 Sv. It is suggested that these two higher frequency features are linked. Averaging the negative and positive anomaly transports leads to a zero anomaly for May to July. This feature may be driven by Indian Ocean Kelvin Waves [*Murtugudde et al.,* 1998]. The slight reduction of the residual transport (Figure 4d) in May to June 1998 and that *Meyers* [1996] finds minimum throughflow in May-June and again in October-November, suggests that a spring relaxation of the throughflow may be an annual event.

Conclusions

Along channel currents and transport measured by the MAK-1 and MAK-2 current meters indicate the presence of large southward transport within Makassar Strait including variability over a wide range of scales. A throughflow maximum often occurs within the thermocline, mostly during the times of high throughflow. Our results indicate that the Indonesian throughflow for 1997 within Makassar Strait is about 9 to 10 Sv, which can account for all of the interocean transport as estimated from (albeit scant) observations and models.

Many questions remain: How typical are the 1996-98 Makassar Strait results of the longer term climatic condition? And how does the flow within the upper 200 m vary relative to the thermocline flow? To quantify the climatic importance of the throughflow both the magnitude and source and their variability must be measured over ENSO time scales. The data indicate that within Labani channel a single mooring may be used to capture the Makassar throughflow and its thermal field.

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