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Temperature variability within Makassar Strait

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Abstract. Recent mooring observations of ocean temperature provide the first high resolution, long term record of temperature variability in the Makassar Strait of the Indonesian Seas. The mooring observations span the entire cycle of the strong 1997/1998 El Niño. A high correlation (r = 0.67) is found between variability in the average thermocline temperature, to variability in the southward Makassar volume transport: during high (low) volume transport, the average temperature of the thermocline is also high (low). In addition, from nearly 15 years of XBT data, the Makassar thermocline temperature is shown to be highly correlated (r = 0.77) to SOI. This reveals that the Makassar temperature field - when coupled with the throughflow - transmits the equatorial Pacific El Niño and La Niña temperature fluctuations into the Indian Ocean. The ENSO variability in the internal energy transport is calculated: 0.63 PW during the La Niña months of December 1996 through February 1997, and 0.39 PW during the El Niño months of December 1997 through February 1998.

Introduction

The Indonesian throughflow impacts the global climate system by carrying warm Pacific water from about 5°N, through the Indonesian Seas, into the Indian Ocean at 12°S. Models predict a throughflow internal energy transport between 0.63 and 1.15 PW (1 PW = 1 x 10^{15} W; *Murtugudde et al.*, 1998; *Schiller et al.*, 1998; *Schneider and Barnett*, 1997; *Hirst and Godfrey*, 1993). Heretofore, model calculations of internal energy transport have not been compared to observations.

To measure temperature, velocity, and pressure at various ocean depths in the Indonesian throughflow, two moorings were deployed in the Makassar Strait of the Indonesian Seas (Figure 1). The moorings were part of the ARLINDO program, a joint US/Indonesian effort directed at studying the Indonesian throughflow. The mooring records start at the end of an La Niña event, and encompass the strong 1997-1998 El Niño event. In this paper, the Makassar Strait temperature variability at periods longer than local tides is presented, and the internal energy transport is estimated.

Temperature Data

On November 23, 1996 the "MAK-1" mooring was deployed at 2°52'S, 118°27'E in the 2000 m deep, 45 km wide, Labani Channel of the Makassar Strait. The mooring was recovered on July 16, 1998, and 11 temperature and temperature-pressure time series records were obtained from the instruments with up to 1.64 years of data. Seven of the temperature and pressure sensors were distributed between 110 and 290 db providing measurements either every 2 or 4 minutes. Four of the temperature sensors were distributed at 140, 200, 250, and 350 db as part of the ADCP and current meter array, and they provide measurements every 20 minutes. (Two near-surface and 2 deep temperature-pressure time series records were lost due to instrument malfunctions.) The "MAK-2" mooring was located just east of MAK-1 at 2°51'S, 118°38'E; however, MAK-2 did not include a full suite of temperature and pressure sensors.

Fortuitously, during the entire mooring deployment strong semi-diurnal tidal currents caused significant mooring blowover each tidal cycle, with a displacement of up to 200 db. Consequently, every temperature and pressure sensor profiled the thermocline 4 times daily, and a nearly continuous temperature time-section was obtained between 150 and 400 db from the MAK-1 mooring (Figure 2). The strong semi-diurnal currents at

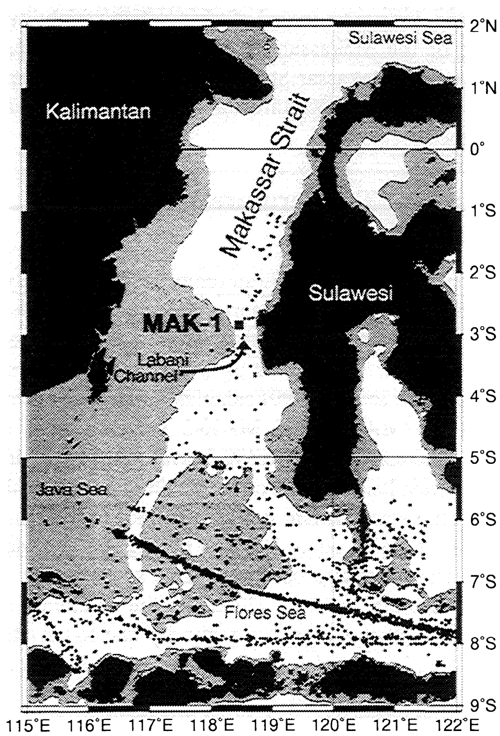

Figure 1. Map of the Makassar Strait. The location of the MAK-1 mooring is marked by a solid square, and the locations of the XBT stations are marked by solid circles. The 500 m bathymetry is shaded in gray.

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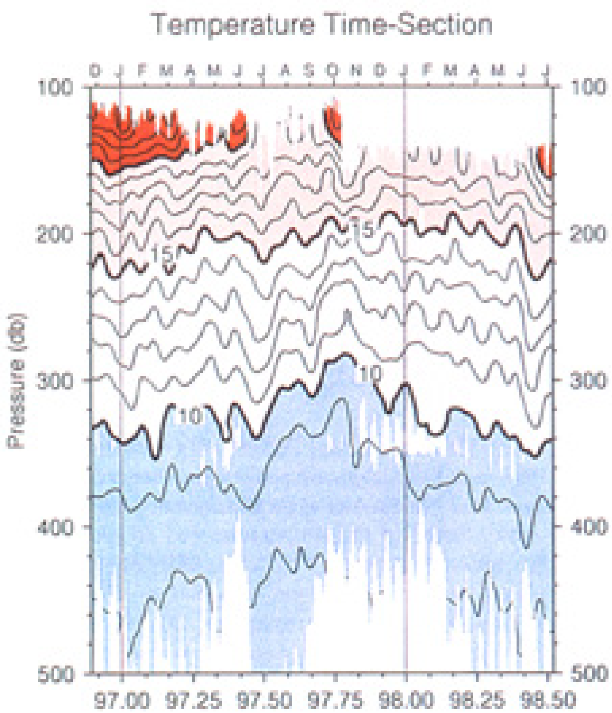

Figure 2. Temperature time-section constructed from temperature and pressure sensors distributed in the thermocline of the Makassar Strait. The data are smoothed by a 35 day running gaussian filter. The contour interval is 1˚C.

the mooring sites are modulated fortnightly, and the corresponding spring and neap tides are revealed in the smoothed temperature time-section as fortnightly data gaps corresponding to periods when the mooring experienced more or less blowover than usual. The MAK-1 temperature record provides the first high resolution, long term record of temperature variability in the thermocline of the Makassar Strait. The section reveals the complexity of the Makassar Strait thermocline with significant short and long period temperature variations as a function of both depth and time.

Relationship of Temperature Variability to Volume Transport

To compare the Makassar Strait temperature variability to the Makassar Strait volume transport, the temperature data was averaged between 150 and 400 db. For comparison, "Profile B" from *Gordon et al.* (1999) was used for the volume transport estimate. *Gordon et al.* (1999) calculated the volume transport using both the MAK-1 and MAK-2 current meter arrays, although the inclusion of the MAK-2 array did not significantly change their results. For "Profile B", they assumed that the transport profile was constant from the surface to the shallowest current meter record at about 200 db. In addition, the Makassar net volume transport was observed to be small below 400 db (*Gordon and Susanto*, 1999). Therefore, the variability in their "Profile B" transport estimate is primarily due to variations in nearly the same layer as the 150 to 400 db average temperature, and the two time series can be directly compared.

A key result of the new data is the clear correspondence between the long period trends in the average 150 to 400 db temperature, to the long period trends in the volume transport (Figure 3): during high (low) volume transport, the average temperature of the thermocline is also high (low). The correlation coefficient (r) is 0.67. (If volume transport lags by 29 days, the correlation coefficient increases to 0.83.) In contrast, at shorter periods the temperature variations do not follow the volume transport variations, and annual and semi-annual cycles are not immediately obvious. However, throughout the record striking phase reversals occur on time scales ranging from 1 to 5 months. These reversals occur at roughly similar times between 200 db and 430 db, but are most pronounced below 340 db. An example of these reversals is shown in Figure 4, in this case, the 265 db temperature and speed.

Relationship of Temperature Variability to ENSO

Many observational and model studies suggest that the Indonesian throughflow is modulated by El Niño - Southern Oscillation (ENSO): larger volume transport during La Niña, smaller volume transport during El Niño (*Kindle et al.*, 1989; *Meyers*, 1996; *Bray et al.*, 1996; *Fieux et al.*, 1996; *Gordon and Fine*, 1996; *Potemra et al.*, 1997; *Gordon and McClean*, 1999). The Makassar Strait volume transport measured by the MAK-1 and MAK-2 moorings are the first direct measurements within the Indonesian Seas of the ENSO variability: 12.5 Sv during the La Niña months of December 1996 through February 1997, and 5.1 Sv during the El Niño months of December 1997 through February 1998 (*Gordon et al.*, 1999).

The long period trends of the MAK-1 thermocline temperatures also seem to follow the interannual trends associated with ENSO; for example, the Makassar Strait 15˚C isotherm rises about 35 db during the onset of El Niño in 1997, reaches its shallowest depth in December 1997 during the extreme of El Niño, and then falls back about 35 db when La Niña returns in July 1998 (Figure 2). This agrees with the temperature analysis of expendable bathythermograph (XBT) and tide gauge data from 1980 to 1994 by *Bray et al.* (1996). Despite data gaps, they clearly show that during El Niño sea level drops and the thermocline rises in the "Flores-Makassar" region (actually included the western Banda Sea as well); for example, during the 1987 El Niño, the "Flores-Makassar" 20˚C isotherm was more than 20 m shallower than the mean depth (their Figure 18). Using XBT data, *Meyers* (1996) also finds a shallower 20˚C isotherm during El Niño in the outflow region of the throughflow between northwestern Australia and Java.

Here, to further quantify the ENSO variability in the thermocline of the Makassar Strait, all "good" XBT data within the Makassar Strait - Flores Sea region were obtained from the Global Temperature and Salinity Subsurface Data Centre, Centre IFREMER de BREST (Figure 1). The data were averaged together to form a nearly 15 year data set that begins in 1985, with a 5 m vertical resolution. Between 150 and 400 m and during the MAK-1 observation period, the correlation between the XBT and the MAK-1 temperature time series is 0.86. This high correlation suggests that the XBT data is probably a sufficient proxy for the Makassar Strait thermocline at longer time scales, despite the large spatial (heavily weighted to the Flores Sea) and uneven temporal (sometimes larger than tidal) distribution of the data. Temperature correlations of the nearly 15 years of XBT data to frequently cited ENSO indices - as well as visual inspection of the time series (Figure 5) - reveal the large ENSO variability in the Makassar thermocline, especially at 100 m: 0.77 for the Southern Oscillation Index (SOI, atmospheric pressure difference between Darwin, Australia and Tahiti), -0.80 for NINO3 (sea surface temperature [SST] anomaly in the region bounded by 5˚N, 5˚S, 150˚W, and 90˚W), and -0.82 for NINO4 (SST anomaly in the region bounded by 5˚N, 5˚S, 160˚E, and 150˚W). The correlations are somewhat lower for the averaged 150 to 400 m layer: 0.59 for the SOI, -0.48 for NINO3, and -0.65 for NINO4; however, all the correlations increase when the ENSO time series are lagged a month or so.

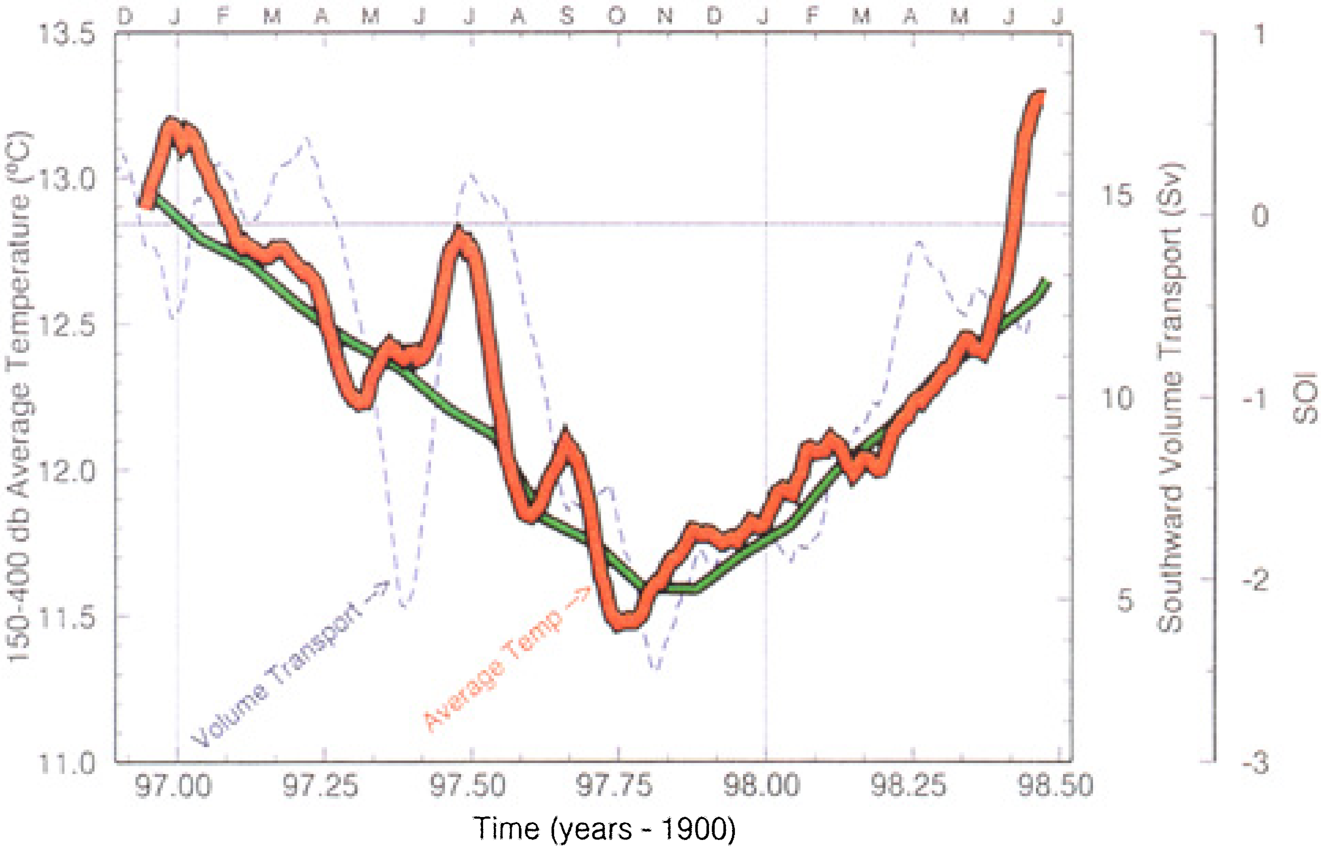

Figure 3. Time series of the average temperature between 150 and 400 db in the Makassar Strait (thick red line, 30 day running mean). The SOI (thick green line, 1 year running mean) and the Makassar Strait volume transport (thin blue dashed line; 30 day running mean; "Profile B", *Gordon et al.*, 1999) are also shown. One Sverdrup (Sv) equals 1 x 10^6 m^3/s.

Full Depth Temperature Variability

Also as part of the ARLINDO program, an Inverted Echo Sounder (IES) was deployed near the MAK-1 mooring at 2°50'S, 118°27'E. The IES measures the travel time of a sound source from its start at the sea floor to the ocean surface and back. Its travel time is proportional to the average temperature of the full depth water column, but variations in travel time are dominated by the larger temperature variations in the surface and thermocline. The correlation between the Makassar Strait travel time and the average 150 to 400 db temperature time series is 0.86. As the temperature data included in the average time series only begins at 150 db, it is most likely that the differences in the time series reflect the temperature variations in the upper 150 db captured by the IES, but not by the mooring sensors.

Internal Energy Transport

Quantifying the internal energy transport (*Warren*, 1999) of the Indonesian throughflow is critical to understanding global energy balances. An estimate for the Makassar Strait is made by integrating the product of temperature, transport, density and specific heat in the upper 400 db. The 0 to 150 db temperature is obtained by subtracting the depth weighted 150 to 400 db temperature time series from the full depth temperature time series estimated from IES travel time; the calculation assumes that there are no significant temperature variations or transport below 400 db.

The 1997 Makassar Strait internal energy transport is 0.50 PW. If the Makassar temperatures are referenced to 3.72°C, as in *Schiller et al.* (1998), then the 1997 internal energy transport is 0.39 PW. This observation is probably low relative to other years, because 1997 was a strong El Niño year; during La Niña the internal energy transport is likely to be higher, due to both higher throughflow and higher thermocline temperatures. Therefore, as with the volume transport estimate, the ENSO variability in the internal energy transport is calculated: 0.63 PW during the La Niña months of December 1996 through February 1997, and 0.39 PW during the El Niño months of December 1997 through February 1998. During a more extreme phase of La Niña, the internal energy transport is expected to be even higher.

Model estimates of the internal energy transport are generally higher for the Indonesian throughflow, with *Schiller et al.* (1998) reporting 1.15 PW and summarizing other model estimates as ranging from 0.63 PW to 1.08 PW. However, as the throughflow continues through the Indonesian Seas enroute to the Indian Ocean, it will continue to warm through ocean-atmosphere interaction. In addition, any throughflow below 400 db in the

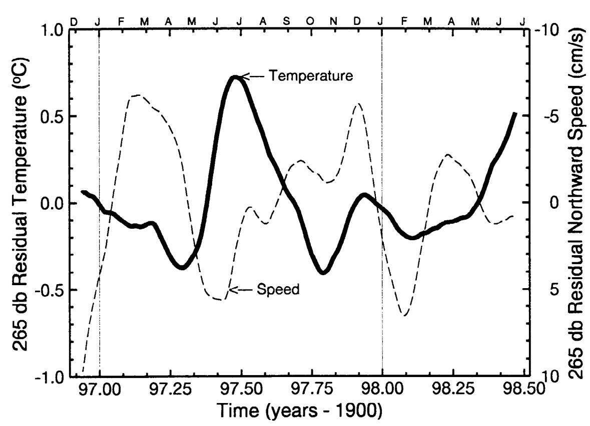

Figure 4. The residual 265 db temperature and speed time series. The NINO3 dependency was removed from each timeseries, and the remaining signal filtered by a 60 day running mean.

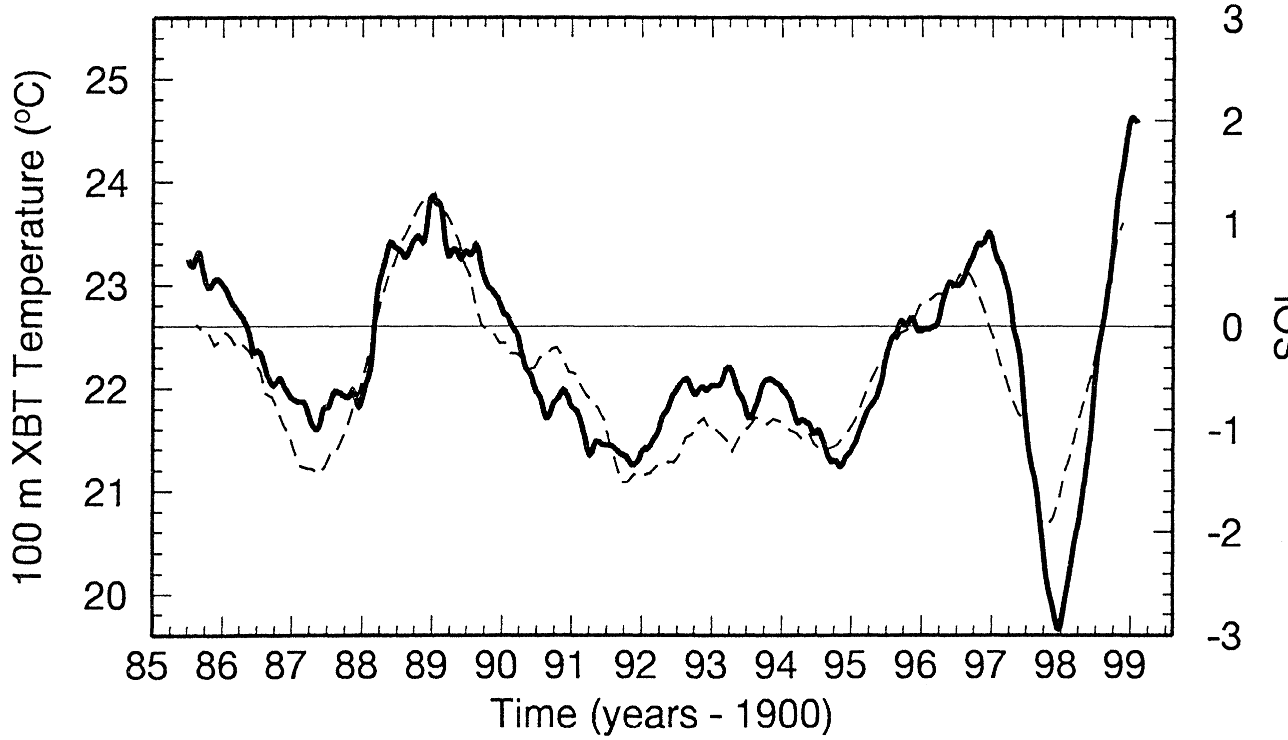

Figure 5. Time series of the 100 m XBT temperature and the SOI. The data are smoothed by a 1 year running mean filter.

Makassar Strait will increase the internal energy transport estimate, as will any contribution to the throughflow from the channels east of Sulawesi (thought to be of secondary importance [*Gordon et al.*, 1999]). If approximations are made to enable a full depth estimate of the internal energy transport in the Makassar Strait, then our estimates increase by 0.09 PW or less (*K. Vranes*, Ph.D. thesis, in preparation).

Conclusions

The Makassar Strait volume transport is integrally linked to the thermocline temperature field, a relationship which, if confirmed by a longer time series, may offer an efficient long term monitoring strategy of the volume transport and internal energy transport of the Makassar Strait; for example, by using regional XBT data. As a start to verifying the importance of the Indonesian throughflow to the global energy balance, the ENSO dependence in the Makassar Strait internal energy transport was estimated from the observations to be 0.63 PW during La Niña and 0.39 PW during El Niño.

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