Shallow throughflow variability in the outflow straits of Indonesia

J.C. Chong*, J. Sprintall*, S. Hautala†, W.L. Morawitz†, N.A. Bray‡, and W. Pandoe§

Abstract. Since December 1995, the Indonesian throughflow has been monitored in five major passages as it flows from the Indonesian interior seas to the Indian Ocean. Pressure differences across the straits enable us to infer the geostrophic surface flow, and so provide the first simultaneous time-series measurements of surface geostrophic flow through these passages. Intraseasonal signals (30-90 day) are a ubiquitous feature in the surface flow, and are consistent with wind-forced Kelvin waves from both the eastern equatorial Indian Ocean and the south coast of Java. Using a relationship with surface velocity from three contemporaneous ADCP surveys, we approximate surface (0-100 m) volume transport fluctuations through four of the main exit passages. The amplitude of the total surface transport variation through these passages is fairly uniform, ranging from 10-15 Sv.

Introduction

Estimates of the water mass exchange between the Pacific and Indian Oceans through the Indonesian islands (known as the Indonesian throughflow, ITF) and its variability have been difficult to obtain because of the complex topography and the variable currents in the region. Yet, the ITF is believed to affect the global ocean thermohaline circulation and heat budget [Gordon, 1986]. Model studies have shown the throughflow not only impacts the current system and precipitation around Australasia but affects global weather patterns and sea surface temperature [Godfrey, 1996]. The extent of these changes depends on the magnitude and variability of the throughflow, that have yet to be thoroughly validated by observations.

In December 1995 an array of sub-surface pressure gauges was deployed to monitor the "outflow" straits, documenting the throughflow as it exits the interior Indonesian seas into the Indian Ocean. This array represents the first simultaneous measurements of surface flow through the Indonesian exit passages for a period of over two years (28 months). While at present we are unable to determine the "absolute" transport from these surface slope measurements (for reasons outlined below), we employ concurrent acoustic Doppler current profiler (ADCP) surveys of the straits to scale the surface flow to an anticipated order of transport magnitude through the straits. Our results confirm the current ideas of annual and semi-annual variability in the Indonesian throughflow. More interesting is the unexpected and pervasive intraseasonal (30-90 day) fluctuations measured in the throughflow pressure-gauge observations. This letter focuses on characterizing this intraseasonal energy.

The Shallow Pressure Gauge Array

As part of a joint Indonesian-American program, nine pressure gauges were deployed in five major outflow straits along the archipelago formed by the southern Indonesian islands: Lombok, Sumba, Savu, Ombai, and Timor (Figure 1). These five straits constitute the widest and deepest passages through which warm, fresh water from the Pacific leaks into the Indian Ocean. The gauges were recovered, refurbished, and redeployed twice (March 1997 and April 1998) using Indonesian research vessels. Underway measurements include repeat ADCP and conductivity-temperature-depth (CTD) surveys taken across the outflow straits during the deployment and turn-around cruises.

Pressure gauge pairs span the passages and provide an estimate of the average surface geostrophic velocity through the strait. At periods greater than inertial (about 3 days at this latitude) scaling of the momentum equations suggests that the flow along the strait is in geostrophic balance with the cross-strait pressure gradient:

\[ v(t) = \frac{1}{\rho f} \frac{\Delta p(t)}{\Delta x} \]

where the along-strait velocity \( v \) and pressure \( p \) vary with time, and \( x \) is the cross-strait direction, \( f \) is the local Coriolis parameter, and \( \rho \) is the density of seawater. There is a variety of evidence to support the geostrophic assumption relating cross-strait pressure difference to velocity through the straits. In Ombai Strait, the relationship was validated where pressure differences correlate favorably with direct measurements of surface velocity from a contemporaneous current meter at periods greater than 30 days (correlation coefficient of 0.7). For periods greater than 5 days, the correlation reduces to 0.6. Differences between the two

Figure 1. Location of the Shallow Pressure Gauge Array. The 200, 1000, and 2000 m isobaths are contoured.
velocity measurements are expected; pressure differences reflect the average geostrophic velocity, while current meters measure velocity at a single point and include ageostrophic components. Calculations of cross-strait Rossby number using current meter data in Ombai Strait are small, consistent with geostrophic dynamics. In all straits observed, changes between cruises in the average along-strait velocity from the 25m ADCP bin is in good agreement with changes in across-strait pressure difference recorded by the array (Figure 2).

The nine instruments in the array are deployed approximately 5-10 m below the water's surface. Pressure is measured every three minutes by a Paroscientific quartz sensor with an accuracy of 0.3 mb (~1% of the signal of interest). The largest error comes from instrument drift which results in a decrease in pressure by about 0.3 mb every year [Wearn and Larson, 1982]. Because the region is expected to have a large interannual signal, the linear trend was not removed from the records. For tractability, the data are averaged into hourly bins. The tides are removed from the pressure signal by fitting sinusoids of 15 tidal frequencies in a least-squares sense. Shifts in the data reference level occurred in two of the gauges (North Ombai and Ashmore Reef) because of anchor settling. These shifts were removed by comparing each record with predicted tides. The time-series were then low-pass filtered to remove signals with period shorter than 5 days.

**Observations of the ITF**

The pressure data are sufficient to infer shallow geostrophic velocity fluctuations relative to a temporal mean, since the exact vertical displacement of each gauge with respect to the geoid is unknown. Here we use the repeat ADCP surveys across each of the straits during the deployment and turn-around cruises to "level" the gauges and estimate the absolute surface geostrophic currents. Each strait was surveyed by constantly steaming between the two gauges within the strait. Where possible, each of the repeated transects lasted for at least 12 hours to capture one complete semidiurnal tidal cycle. The ADCP transects were then spatially bin-averaged to derive a mean velocity section across each strait at the time of the ADCP survey. In Lombok, Savu and Sumba Straits, the tidal velocities, though significant (0.1 m s⁻¹), are an order of magnitude less than the throughflow signal (1-2 m s⁻¹). Indeed, a tidal correction determined for Lombok Strait from current meter data [Murray and Arief, 1988] is typically less than 0.05 m s⁻¹. In Ombai Strait, preliminary estimates suggest the tidal signal is substantial enough not to be alleviated by simple temporal averaging. Future analyses will determine an appropriate tidal correction for Ombai ADCP data using available contemporaneous current meter data.

Figure 2 depicts the average surface velocity through the surveyed straits, based on a least-squares fit of the pressure gauge data to the ADCP 25-35 m velocity from the 3 surveys. Apart from Ombai Strait where, as noted, the tidal signal is not adequately resolved by the averaging of the ADCP survey data, the fit of the pressure gauge time series to the ADCP survey in each of the straits is generally very good. The spectra are also shown for the pressure-gauge estimate of surface velocity. We gain a sense of the magnitude of transport variability associated with the surface velocity measurements by examining the repeat ADCP sections. The 25 m velocity is linearly correlated with the total transport in the top 100 m to within ~0.5 Sv, which is close
to the formal error level of the ADCP sections. The 100-200 m layer contributes up to about 25% more transport, and appears to be consistently directed towards the Indian Ocean. This layer is often uncorrelated with the layer above. For example, in Lombok Strait during December 1995, flow in the upper 75 meters was directed towards the Java Sea, in an opposite sense to flow in the 75-150 m layer. Table 1 summarizes the correspondence between the surface velocity and (0-100 m) transport variations, where the total transport variation has been extrapolated from the linear correlation. Although the velocity amplitude varies widely between the straits, the magnitude of transport variations is more uniform. A more precise determination of the relationship between total transport and surface velocity will be the subject of a longer paper.

Spectra and time series of surface velocity (Figure 2) suggest that three time-scales dominate the variance of the outflow passages: annual, semi-annual and intraseasonal (30-90 days). Annual changes in the ITF arise from the directionally-varying winds over the Indonesian archipelago associated with the Australasian monsoon. The pressure gauge array indicates a predominant annual cycle in Lombok, Sumba and Savu Straits (Figure 2). The flow toward the Indian Ocean is strongest from July to September, during the more intense southeast monsoon, which is consonant with Wyrtki's [1987] suggestion as to the time when the warm, fresh water in the Banda Sea exits into the Indian Ocean as the ITF. Although, in Timor and Ombai Straits, where flow is essentially always towards the Indian Ocean, no clear annual or semi-annual cycle is discernible.

Semi-annual energy is apparent in Lombok and Sumba Straits, but does not penetrate across the Savu Sea into Ombai Strait, or south to Savu Strait and the Timor Passage. Remote forcing of coastal sea level is responsible for changes in flow and transport through the exit passages at this frequency. Strong westerly winds over the Indian Ocean during the two monsoon transition periods, nominally in May and November, establish an eastward Australasian monsoon. The pressure gauge array indicates a layer contributions up to about 25% more transport, and appears to be directed towards the Java Sea, in an opposite sense to flow in the Savu Sea. Concurrent CTD data (not shown) suggests this flow of warm, fresh surface water is consistent with advection from the near-equatorial Indian Ocean west of Sumatra [Sprintall et al., 1999], perhaps mixing with the outflow of fresh Java Sea water through Sunda Strait [Bray et al., 1997].

Intraseasonal fluctuations, changes on a 30-90 day timescale, are a ubiquitous feature in the pressure data. Furthermore, it is emerging as a pervasive characteristic of the observations in the region: signals at these frequencies have been found in historical datasets and numerical models in the region [Molcard et al., 1996; Arief and Murray, 1996; Qiu et al., 1999]. In the pressure gauge data the fluctuations of current on this time scale are over 30%, and comparable in magnitude to the annual cycle.

Historical current meter data in Lombok Strait show episodic northward surface flows that occur roughly every 20 to 60 days. These intraseasonal events are strongly correlated to rising sea level along the south coast of Java due to remotely-generated coastal Kelvin waves with a phase speed of 1.9 m s⁻¹ [Arief and Murray, 1996]. In spectra of surface velocity from the pressure gauge array (Figure 2) intraseasonal energy is strongest in Lombok Strait and decays in amplitude, over the entire 30-90 day frequency band, from west to east (note the different scales for the spectra of each strait). This is consistent with the declining importance of the equatorial Indian Ocean source moving east along the island chain [Qiu et al., 1999]. Lag correlation analysis of sea level from our pressure array suggests an eastward propagation of intraseasonal signals along the archipelago at a speed of 2.5 m s⁻¹, commensurate with the theoretical first baroclinic-mode Kelvin wave speed of 2.4 m s⁻¹ for this region.

In a high resolution, 1.5-layer shallow water model, Qiu et al. [1999] find a myriad of sources and pathways for the intraseasonal energy: resonance between the gravest Rossby mode in the Sulawesi Sea and periodic shedding of the Mindanao Current (50 days); remote wind forcing (50 and 85 days) in the Pacific and the Indian Ocean; and local wind forcing near Timor (30-35 days). In the model, the combination of these forcing agents creates differences in spectra at various places along the southern Indonesian boundary, similar to changes in surface velocity spectra at intraseasonal frequencies in Figure 2. Interestingly, spectra of both the Timor Passage and Ombai Strait pressure data show peaks at around 30 days, although the energy in this frequency band is significantly higher in Ombai Strait than in the Qiu et al. [1999] model. Perhaps this is a result of the 1.5 layer model geometry not adequately resolving Ombai Strait.

Although intraseasonal fluctuations occur throughout the year, they appear to be seasonally modulated, with larger changes occurring between December and March (Figure 2). This is particularly evident in the Lombok Strait velocity time series. To examine this seasonal preference further, and determine the

| Table 1. Velocity at 25 m (V25) and transport of the top 100 m (Q100) averaged from repeat ADCP surveys. The amplitude of the total variation in V25 and Q100 is obtained by extrapolation of the linear correlation that exists between the two values. |
|---|---|---|---|---|
| Ombai Strait | Savu Strait | Sumba Strait | Lombok Strait |
| width (km) | 35 | 244 | 71 | 37 |
| V25 (cm/s) | Q100 (Sv) | V25 (cm/s) | Q100 (Sv) | V25 (cm/s) | Q100 (Sv) | V25 (cm/s) | Q100 (Sv) |
| 1995 | - | -22.7 | -5.8 | 93.2 | 6.0 | 51.1 | 0.8 |
| 1997 | -50.6 | -2.9 | 15.7 | -3.8 | - | -66.8 | -2.5 |
| 1998 | -19.8 | -0.8 | -5.9 | 0.6 | -10.2 | -1.5 | -57.9 | -1.6 |
| Amplitude | 200 | 13 | 40 | 12 | 200 | 15 | 400 | 10 |
region where the intraseasonal Kelvin waves originate, we analyzed daily wind stress from the European Centre for Medium-Range Weather Forecasts (ECMWF) for the time period of our pressure measurements. Intense zonal intraseasonal wind activity was identified both along the equator in the eastern Indian Ocean between 80°E and 90°E (where events occur roughly 30-50 days apart), and along the south coast of the Indonesian archipelago (where events occur roughly 30-90 days apart). The magnitude of the intraseasonal wind bursts was found to vary with season: along the equator they were strongest during May to September, while along the archipelago they were strongest during December to May. If equatorial Kelvin waves are forcing coastal intraseasonal signals, then waves generated by equatorial wind bursts at 80°E should reach Lombok Strait in only 30 days. Therefore, intraseasonal changes at Lombok Strait quantitatively correlate best with local wind, although Qiu et al. [1999] suggest that intraseasonal signals in their model’s Lombok Strait are related to remote Indian Ocean forcing.

On a final note, the analyses of intraseasonal events described in this letter and in the cited literature focus on changes that occur along the coast of the Indonesian archipelago. However, recent altimetric measurements of sea surface height along with hydrographic data suggest the ITF may enter the Indian Ocean as a series of discrete eddies [Bray et al., 1997]. Similar to intraseasonal coastal sea level changes, the eddies are seasonally modulated with more activity during August-October when the ITF is maximum. It is not clear whether or how the two forms of intraseasonal energy are related. It could be that intra-seasonally wind-forced Kelvin waves travel down the archipelago [Arief and Murray, 1996], impact the coastal sealveal signal, and subsequently modify the flow through the straits to generate the intermittent eddies [Nof, 1995].

Conclusions

Pressure differences across the outflow straits of Indonesia are used to monitor the variations in shallow geostrophic velocity associated with the Indonesian throughflow. Over three cruises, repeat ADCP surveys of the straits were conducted to measure absolute velocities. A linear relationship connects the vertically-integrated (0-100m) transports from the synoptic ADCP measurements with surface (25 m) velocity fluctuations, suggesting that measuring surface geostrophic velocity variations via the pressure gauge array is an efficient method for measuring changes in the ITF. Continuing analyses aim at refining the preliminary relationship between surface velocity and transport presented here, by adding a fourth year of ADCP data, applying tidal corrections in each strait based on empirical relationships between direct shallow velocity measurements and tidal sea-level, and examining the vertical and cross-strait horizontal structure of the flow to assess the level of error.

Previous estimates of mean throughflow have been wide ranging (2-22 Sv) in part because the throughflow has energetic components over many time and space scales which have not generally been well-resolved. Typically, the volume transport has either been extrapolated spatially from year-long measurements in a single passage [Murray and Arief, 1988; Molcard et al., 1994; 1996] or temporally from synoptic and repeated hydrographic cruises [Meyers et al., 1995; Fieux et al., 1994; 1996]. Estimates of volume and property transports through the Indonesian outflow straits must be placed within the context of signals on annual, semi-annual, and especially intraseasonal timescales. The multi-year pressure gauge record provides a unique opportunity to identify the relative contributions to transport of the various frequencies. Once the throughflow mean is known, time series of in situ temperature and salinity at each gauge site make it possible to estimate the heat and freshwater transports. The ITF is the world’s only low-latitude interocean conduit and consequently plays a significant part in the global heat budget and freshwater balance.

Acknowledgments. The support of Indonesian research vessels and cooperation of BPPT Indonesia is gratefully acknowledged. Paul Harvey (SIO), Thomas Moore (SIO), and Phillip Adams (CSIRO) provided invaluable technical assistance both in and out of the field. The work was supported by the National Science Foundation (NSF-OGC 9529641) and the Office of Naval Research (ONR N00014-94-1-0617).

References


N.A. Bray, CSIRO Division of Marine Research, Casrtry Esplanade, Hobart, TAS 7001, Australia.
W.I.M. Morawitz and S. Hautala, School of Oceanography, University of Washington, Box 357940, Seattle, WA 98195-7490.
W. Pandoe, BPPT, Jl M.H. Thamrin 8, Jakarta 10340, Indonesia.
F. Sprintall and J.C. Chong, Physical Oceanography Research Division, Scripps Institution of Oceanography, 9500 Gilman Drive, La Jolla CA 92039-0230. (email: jsprintall@ucsd.edu)

(Received April 15, 1999; revised August 19, 1999; accepted November 04, 1999)