Direct evidence of the South Java Current system in Ombai Strait

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ABSTRACT

Direct velocity measurements from 2004 through 2006 confirm the eastward flowing surface South Java Current (SJC) and its deeper Undercurrent (SJUC) crosses the Savu Sea to reach Ombai Strait, a main outflow portal of the Indonesian Throughflow (ITF). The extension of the South Java Current system into Ombai Strait was hinted at by earlier measurement and modeling studies, but the 3-year velocity time series from two moorings in Ombai Strait clearly show separate distinct cores of flow in the SJC and SJUC. The deeper SJUC is driven by Kelvin waves forced by intraseasonal and semi-annual winds in the equatorial Indian Ocean and, when present, is observed across the entire strait. Eastward flow in the surface SJC is near year-round, although it appears that the mechanisms responsible for this flow differ throughout the year. Both the wind-driven Ekman flow during the northwest monsoon and the strongest semi-annual Kelvin waves that have surface signatures can result in eastward surface layer flow across the entire strait. In contrast, during the southeast monsoon the SJC has a subsurface maximum eastward flow at 50–100 m depth in the northern part of Ombai Strait, while the westward ITF is at an annual maximum at the surface in the southern part of the strait. Surface temperature maps suggest the presence of a front during the southeast monsoon that seems to trap the SJC to within ∼10–15 km of the northern boundary of Ombai Strait. The SJC and the frontal location are related to a complex interplay between local wind-driven Ekman dynamics, the strong ITF flow and topography. Significant

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1. Introduction

The South Java Current (SJC) and UnderCurrent (SJUC) form the eastern boundary current system that flows along the tropical Indian Ocean coasts of Sumatra and Java (Fig. 1), and plays an important role in distributing freshwater into and out of the southeast Indian Ocean. Historical surface ship-drift records compiled for the Indonesian region in 1949 (Quadfasel and Cresswell, 1992) first suggested that the surface flow in the SJC might be modulated semi-annually. The semi-annual strengthening of the SJC was later supported, at least for the region south of Java, through XBT measurements (Meyers et al., 1995) and direct observations from a year-long current meter mooring deployed on the shelf south of central Java (Sprintall et al., 1999). During the monsoon transitions that occur around April–May and October–November each year, the SJC is south-eastward and enhanced by the propagation of coastal Kelvin waves associated with the wind forcing of the Wyrtki Jet in the equatorial Indian Ocean (Wyrtki, 1973; Quadfasel and Cresswell, 1992). At these times, the narrow cores of relatively strong flow extend to ~100 m deep, and are trapped to the Sumatra-Java coastline transporting warm and fresh waters from the high rainfall, warm pool region of the eastern equatorial Indian Ocean (Fieux et al., 1994, 1996; Sprintall et al., 1999; Wijffels et al., 2002; Wijffels and Meyers, 2004). Eastward flow in the SJC is also observed during the northwest monsoon (NWM; December–March), although it is weaker than during the monsoon transitions (Quadfasel and Cresswell, 1992). During the southeast monsoon (SEM; June–September), the SJC is much more variable, although mostly in the same direction as the westward flowing Indonesian Throughflow (ITF) (Quadfasel and Cresswell, 1992; Wijffels and Meyers, 2004).

Below the shallow SJC at depths between 200 m and 1000 m, the SJUC transports a core of high salinity, low oxygen North Indian Intermediate Water (NIIW) eastward (Bray et al., 1997; Fieux et al., 1994, 2005; Wijffels et al., 2002). Although originally considered part of the surface SJC (Quadfasel and Cresswell, 1992), both the properties and the velocities within the SJC and the SJUC are consistently found to be distinct isolated cores, separated by a layer of much weaker flow (Bray et al., 1997; Fieux et al., 1994, 2005; Wijffels et al., 2002).
While the source of the SJC properties typically lies within the warm, freshwater pool of the equatorial eastern Indian Ocean, the saltier NIIW of the SJUC is formed north of the equator in the western Indian Ocean through mixing of the salty marginal sea outflows (Red Sea and Persian Gulf) and cross-equatorial intermediate water flow (You and Tomczak, 1993; Wijffels et al., 2002). Although the direct pathway of the NIIW to the southeast Indian Ocean is unknown, the hydrographic sections of salinity and other properties along Sumatra and Java suggest a relatively narrow width of the SJUC, similar to that of the SJC (Fieux et al., 1994).

While the long-term XBT time series, one-time hydrographic surveys and mooring deployments have contributed much to our knowledge of the property and flow characteristics of the SJC and SJUC along the coasts of Sumatra and Java, there is relatively little direct evidence to support the continuation of these currents along the coastal Nusa Tenggara wave-guide and into the Savu Sea and beyond (Fig. 1). The extension of the South Java Current system into the Savu Sea could have a significant influence on the distribution and exchange of freshwater within the region. For example, the period of eastward flow in both the SJC and the SJUC is against the direction of the main ITF and would act to decrease transport, and therefore could impact the heat and freshwater fluxes into the southeast Indian Ocean. Perhaps more importantly though, the continuation of the eastward flow, particularly of the SJUC, into the Savu Sea introduces different water mass characteristics of Indian Ocean origin into the internal seas. Here they can potentially mix with waters of Pacific origin to form the isohaline profile that characterizes the ITF. The contribution of these relatively salty Indian Ocean waters has largely been ignored in previous studies of the formation of the ITF water mass (e.g. Field and Gordon, 1992; Hautala et al., 1996, etc), and the saltier contribution has been solely assumed to be of South Pacific origin.

Some earlier observation programs suggest the possibility of the surface SJC extending into the Savu Sea and beyond. Eastward flows were observed along the very northern edges of both Sumba and Ombai Straits (Fig. 1) in snapshot ADCP surveys in March 1997 and March 1998 (Hautala et al., 2001). In contrast, an ADCP transect in December 1995 showed eastward flow across the entire width of Sumba Strait, extending from the surface to 150 m depth (Hautala et al., 2001), which subsequently flowed across the Savu Sea and past a mooring deployed just south of the main channel in Ombai Strait (Molcard et al., 2001). In fact, velocity from the year-long mooring showed eastward flow in the upper ~150 m for most of December 1995 with weak reversals also evident in May 1996, although the flow in the surface layer was predominantly westward (i.e. the ITF) during the rest of the year. Using a 4-year time series of shallow pressure measurements from either side of Ombai Strait, Potemra et al. (2002) suggested the importance of coastal Kelvin waves to sea level variability within the strait. The pressure signal in Ombai was strongly coherent with the pressure signal measured along the Nusa Tenggara wave-guide in Lombok and Sumba Straits. There have been no direct measurements of the extension of the deeper SJUC eastward flow crossing the Savu Sea into Ombai Strait and beyond, although recent property measurements suggest the presence of NIIW in the vicinity of Ombai Strait (Atmadipoera et al., 2009).

The extension of an eastward flowing South Java Current system into Ombai Strait hinted at by these earlier studies led us to deploy two moorings in the strait—one close to the northern boundary of Alor Island and another mooring in the south, at the same location as the Molcard et al. (2001) deployment. The goal was to detect any difference in the flow on either side of the channel as suggested by the snapshot ADCP sections of Hautala et al. (2001). In this paper, we present evidence from the directly measured 3-year velocity time series at the two moorings that confirms the presence of both the SJC and the SJUC in Ombai Strait. Furthermore, the northern mooring clearly shows that the eastward flow of the SJC is almost a year-round feature in Ombai Strait, and not just present on a semi-annual basis as suggested by the earlier measurement programs (Hautala et al., 2001; Molcard et al., 2001). The main core of the westward flowing ITF is primarily confined to southern Ombai Strait. The SJUC has a strong intraseasonal and semi-annual signal related to the passage of the Kelvin waves. The Kelvin waves are observed at depth by both moorings because the strait width is less than half the Rossby radius of deformation at this latitude (~100 km). These are the first direct observations of the SJUC extending along the Nusa Tenggara wave-guide into Ombai Strait, and imply a possible source of Indian Ocean water in the formation of the ITF profile.
2. Variability of velocity time series from the Ombai Strait moorings

As part of the International Nusantara Stratification and Transport (INSTANT) program (Sprintall et al., 2004), an array of 11 moorings were deployed simultaneously in the inflow and outflow straits to measure the ITF. Mean and variability of the transport estimates in the outflow passages of Lombok, Timor and Ombai Straits during INSTANT are described in Sprintall et al. (2009). Here, we focus specifically on the velocity time series observations from the two INSTANT moorings deployed in Ombai Strait, which were not fully described in Sprintall et al. (2009), highlighting the differences in the vertical flow structure on either side of the passage, and providing the first direct evidence of the SJC and SJUC in Ombai Strait.

The Ombai South (OMB-S) mooring was deployed in East Timorese waters at (125°3.8E; 8°32.0S) in August 2003 and the Ombai North (OMB-N) mooring was deployed in Indonesian waters at (125°0.2E; 8°24.1S) in January 2004 (Fig. 1). Both moorings were recovered and redeployed in June 2005, with a final recovery in December 2006. The moorings were deployed along a line between shallow pressure gauges (with temperature and conductivity sensors) on either side of the channel at Alor Island and East Timor (Fig. 1). Both moorings were instrumented with upward-looking ADCPs to resolve the surface to thermocline flow, with single-point current meters positioned at depth to resolve the sub-thermocline to intermediate depth flow. Complete details of the mooring instrumentation, deployment depths, data coverage and quality control can be found in Cowley et al. (2008) and Sprintall et al. (2009).

Ombai Strait is 40 km wide across the ~3250 m deep basin, with OMB-N being 6 km south from Alor Island and OMB-S being 20 km north from East Timor (Fig. 1). The two moorings are separated by ~14 km. As noted, the southern mooring site is at the same location as the 1996 deployment by Molcard et al. (2001), and the northern mooring was positioned in order to capture the flow reversals observed in the ADCP transects of Hautala et al. (2001). The flow through Ombai Strait is constrained upstream by the small strait between Alor and Atauro islands (sill depth ~1450 m) into the Banda Sea, and downstream across the Savu Sea by Sumba Strait (~900 m) and Savu/Dao Strait (~1150 m) that exit into the Indian Ocean (Fig. 1).

Even though the two moorings are separated by only 14 km, the full-depth time series of along-strait velocity at OMB-N is completely different to that of OMB-S (Fig. 2). Although the flow at OMB-N is weaker than that at OMB-S (note the different velocity scales in Fig. 2), it is primarily eastward in the upper 100–150 m. In contrast, at OMB-S the upper layer flow is largely surface trapped and primarily westward, except during the NWM when there are episodic reversals or relaxations in the upper layer flow. When these surface reversals occur at OMB-S, the westward flowing ITF is found in the subsurface. At OMB-N the main core of the ITF is always found beneath the eastward surface layer flow, although the ITF at OMB-N is considerably weaker than at OMB-S. The strong reversals from the surface to ~800 m depth observed at both OMB-N and OMB-S, for example in May/June 2004 and April 2006, are related to the passage of Kelvin waves (Drushka et al., submitted for publication). At the time of these deep-penetrating Kelvin wave events, strong eastward flows of ~50–60 cm s\(^{-1}\) are felt across the entire Ombai passage (Fig. 2). At intermediate depths (400–1000 m), the ITF at both OMB-N and OMB-S is punctuated by regular semi-annual reversals. As in the surface layer, the reversals at depth are of equal magnitude (10–15 cm s\(^{-1}\)) at both OMB-N and OMB-S. The strongest reversals at sub-thermocline depth at both mooring sites are found in May 2006 and September 2006 (Fig. 2).

The seasonal cycle at OMB-N and OMB-S, based on the annual and semi-annual harmonics from the 3-year INSTANT time series, displays a complex phasing across the passage (Fig. 3). The flow above 100–120 m depth at OMB-N is eastward throughout the year (Fig. 3a), whereas at OMB-S it is westward (i.e. in the direction of the ITF) throughout the year (Fig. 3b). Interestingly, OMB-N actually shows the weakest eastward surface flow occurs during the monsoon transition periods of March–April and September–October. Stronger shallow eastward flow is evident at OMB-N during the NWM when the westward surface flow at OMB-S is weakest. A subsurface maximum of ~15 cm s\(^{-1}\) eastward flow occurs from 40 m to 100 m depth during the SEM at OMB-N (Fig. 3a). Conversely, at OMB-S maximum westward ITF (90 cm s\(^{-1}\)) dominates the SEM and continues through October/November. Thus above 120 m, the flow through Ombai Strait varies horizontally across the passage, with the flow at OMB-N exhibiting more of a semi-annual cycle whereas the flow at OMB-S is characterized by more of
Fig. 2. Time series of along-strait currents (m s$^{-1}$) at (a) Ombai North and (b) Ombai South. Note the different vertical scales used for depth ranges 0–300 m and 300–1200 m. In panel (a) the currents scale from −0.5 m s$^{-1}$ to 0.5 m s$^{-1}$ and are contoured at 0.05 m s$^{-1}$ intervals. In panel (b) the currents scale from −2.0 m s$^{-1}$ to 2.0 m s$^{-1}$ and are contoured at 0.1 m s$^{-1}$ intervals. Negative flow is toward the Indian Ocean.

an annual cycle (Fig. 3). However, as suggested by Fig. 2, at both mooring sites the shorter period variability dominates the variance in the surface layer flow.

At depths below 120 m, the phasing and direction of the seasonal cycle become more similar at OMB-N and OMB-S, although differences remain in velocity magnitude. During the NWM, a subsurface maximum ITF is evident at both OMB-N and OMB-S (Fig. 3). At OMB-N the core extends from 100 m to 250 m depth with peak velocities of $\sim$ 10 cm s$^{-1}$, while at OMB-S the core extends from 100 m to 800 m depth with much stronger peak velocities of $\sim$ 75 cm s$^{-1}$ (Fig. 3). At OMB-N a weaker subsurface maximum ITF is found during the SEM beneath the eastward flow in the near-surface layer. Corresponding westward ITF is also observed at OMB-S during the SEM, only here the westward flow stretches all the way from the surface layer deep into the water column. Semi-annual reversals are evident at depth at both OMB-N and OMB-S around the monsoon transition seasons. The flow reversals start slightly earlier and last slightly longer at OMB-N, but similar peak velocities of $\sim$ 10 cm s$^{-1}$ are found at both mooring locations and in both spring and fall. The semi-annual signal explains 44% of the 400–800 m depth averaged flow variance at OMB-S and 18% at OMB-N, compared to only 1.4% explained by the annual signal at both moorings over the same depth range.

To investigate how the dominant velocity time scales may vary over the 3-year record at both OMB-N and OMB-S, we use a Morlet wavelet power spectrum analysis following Torrence and Compo (1998). The wavelets were computed separately for the 0–100 m average surface flow, and for the 400–800 m average flow that covers the core of the SJUC (Fig. 3).

In the surface layer, the spectogram of OMB-N flow (Fig. 4a) shows significant energy at short periods of 7–20 days that is broken up throughout the 3-year time series into short event-type bursts. The surface layer flow at OMB-S (Fig. 4b) also shows statistically significant energy at short periods,
Fig. 3. Seasonal cycle of along-strait current (m s\(^{-1}\)) at (a) Ombai North and (b) Ombai South. Note the different vertical scales used for depth ranges 0–300 m and 300–1200 m. In panel (a) the currents scale from \(-0.2\) m s\(^{-1}\) to 0.2 m s\(^{-1}\) and in panel (b) from \(-1.0\) m s\(^{-1}\) to 1.0 m s\(^{-1}\). Both panels are contoured at 0.05 m s\(^{-1}\) intervals. Negative flow is toward the Indian Ocean.

although at OMB-S the dominant period is 15–20 days and not so event-like as at OMB-N. The integral time scale for the 0–100 m average flow at OMB-S is 20 days, which is twice as long as the 10-day integral time scale found at OMB-N. Intraseasonal variability at \(\sim\)30–40 day periods at OMB-N coincides with the monsoon transitions, while at OMB-S it is present throughout much of the time series. Energy at longer intraseasonal periods of 60–90 days is found primarily at OMB-S, although the surface flow at this period is highly coherent across the passage throughout much of the first half year in both 2004 and 2006 (Fig. 5a). In 2004 the phase is such that OMB-N leads OMB-S by 1–2 days, whereas in 2006 the surface flow at both moorings is more in phase (Fig. 5a). There is a large spectral hole in the surface flow at longer intraseasonal time scales beginning late in 2004 and continuing throughout much of 2005 (Fig. 5a). During 2005 the energy at semi-annual period (180 days) is significant at OMB-S (Fig. 4b) and elevated at OMB-N (Fig. 4a) although the coherence between the two time series is not significant at this period (Fig. 5a).

Deeper in the water column in the core of the SJUC (400–800 m), significant energy is found in the 30–60 day intraseasonal band during the monsoon transitions at OMB-N (Fig. 4c) and throughout much of the 3-year record at OMB-S (Fig. 4d). This energy is significantly coherent between the two sites only during the monsoon transitions (Fig. 5b). The phase suggests that OMB-N leads OMB-S by
∼1–2 days. Although there is some significant energy at longer intraseasonal periods (60–90 days) at OMB-S, there is little coherence with the OMB-N flow at this period except from April 2006 until the end of the deployment period (Fig. 5b). The deeper flow is however, strongly coherent between OMB-N and OMB-S at semi-annual periods for much of the 3-year deployment period, and the phase suggests that OMB-N leads by a day.
3. Relationship of the Ombai Strait flow to regional wind forcing

To explore possible forcing mechanisms of the different flow regimes observed either side of Ombai Strait, we look for relationships of the flow patterns with the regional daily zonal wind stress observations from the QuikScat scatterometer (Figs. 6 and 7). The upper layer flow (0–100 m) at OMB-S shows a strong significant coherence with the zonal wind stress throughout Nusa Tenggara and even into the southern tropical Indian Ocean (Fig. 6c). Potemra and Schneider (2007) showed similar significant correlations of the upper ocean ITF transport from model output with zonal wind anomalies that extended into the southeast Indian Ocean. Potemra and Schneider (2007) attributed this significant correlation to a shift in the anticyclonic wind patterns of the southern Indian Ocean in response to the monsoon winds. Indeed, the positive sign of the correlation in Fig. 6c is consistent with the monsoonal wind-driven Ekman transport: the surface flows are to the east when the winds are to the east during the NWM, and vice-versa during the SEM. The lags of the maximum correlations are shortest and near-inertial (2–4 days) in the vicinity of the strait, and gradually increase moving west along the coastline of Java and Sumatra and into the Indian Ocean (Fig. 6d). The lag of the zonal winds in the equatorial Indian Ocean with the eastward flow at OMB-S is ~15–20 days, which is consistent with the expected arrival time of a Kelvin wave forced in this region (Drushka et al., submitted for publication). Similar lags are found for anomalously strong eastward flow observed in the surface layer of OMB-N with the...
equatorial Indian Ocean zonal winds (Fig. 6b), although in contrast to OMB-S, the strongest correlation is north of the equator between 80° and 90° E (Fig. 6a). Surface flow at OMB-N is also weakly correlated (although significantly within 95% confidence limits) with local regional winds at lags of 20–30 days. Since the mean flow at OMB-N is eastward, the sense of this correlation is that when winds are to the west during the SEM the eastward flow is stronger, and during the NWM the eastward flow is weaker.
or anomalously westward. Interestingly, there is also a weak correlation of anomalously westward OMB-N flow at lags of 10–15 days with westerly zonal winds in the Gulf of Papua between Australia and New Guinea (Fig. 6a and b). It has been suggested that off-equatorial Rossby waves in the western Pacific may excite coastally trapped signals that propagate along the north-coast of West Papua and through the Indonesian seas and/or directly along the northwest shelf of Australia (Wijffels and Meyers, 2004; McClean et al., 2005). This mechanism may be responsible for the relationship between
The average 400–800 m flow at both OMB-N and OMB-S is significantly correlated to the zonal wind stress in the equatorial Indian Ocean (Fig. 7a and c). For both velocity time series, the strongest correlation occurs with wind forcing at 80–90°E, although at OMB-N this is primarily just north of the equator, as found for the surface layer flow (Fig. 6a). At OMB-S the correlation with Indian Ocean zonal winds is significant in a narrow equatorial band both north and south of the equator (Fig. 7c). The strongest correlations at both moorings occur at lags of 25–30 days (Fig. 7b and d), slightly longer than that found for the relationship of the surface layer variability in Ombai Strait to equatorial Indian Ocean winds. Coherence of the average 400–800 m flow at both OMB-N and OMB-S with the equatorial zonal wind stress for the region (80–90°E, 3°S–3°N) is significant at semi-annual periods throughout the 3-year time series, and intraseasonal periods (30–60 days) in the monsoon transitions, particularly during the boreal fall (not shown). No significant correlation was found of the flow at either OMB-N or OMB-S with Pacific winds.

4. Frontal variability

The striking difference in the along-strait surface flow between OMB-N and OMB-S suggests the presence of a strong front somewhere in the 14 km that separates the two moorings. Sharp mid-strait surface frontal features within Ombai Strait have been observed and associated with enhanced phytoplankton blooms that impact the local productivity in the Savu Sea (Moore and Marra, 2002). There were no repeat ADCP transects across Ombai Strait during INSTANT to provide vertical information on the position or persistence of such a front. Here, we use AVHRR Pathfinder SST data at 4-km grid resolution to explore the surface expression of fronts within Ombai Strait. This is the highest spatial resolution, publicly available gridded data set that resolves the SST variability across the 40 km wide passage. Unfortunately however, this tropical region is frequently cloud covered, and the infrared SST data at temporal resolution higher than a month are frequently missing. Hence, we use a monthly climatology of SST within the Ombai Strait region from the 22-years (1986–2008) of available AVHRR data (Fig. 8). Near-surface temperature records (Fig. 9) from the coastal pressure gauge location either side of Ombai Strait (Fig. 1) confirm the significant differences and seasonal patterns observed in the AVHRR SST maps.

The monthly SST climatology shows the presence of a strong lateral front within Ombai Strait that extends into the Savu Sea (Fig. 8). The front appears sharpest during the monsoon transitions of May and October, when the surface waters in the northern part of the Savu Sea are more than a degree cooler than those to the south (Figs. 8 and 9). The warmer surface waters in the southern part of the strait have a similar temperature to that at the entrance to the Banda Sea. During the SEM, a plume of cold water is evident within much of the Savu Sea that narrows in extent as it approaches the eastern tip of Alor where OMB-N is located (Fig. 8). Consequently there is a strong SST gradient present in the Savu Sea throughout much of the SEM. During the NWM, the temperature gradient across Ombai Strait and within the Savu Sea is much reduced (Figs. 8 and 9). The seasonal pattern in the front is largely consistent with the velocity data (Fig. 3): largest differences between the surface flow at OMB-N and OMB-S occur during the SEM, and while the seasonal surface flow is still westward at OMB-S during the NWM (Fig. 3b), it is much reduced and episodic reversals to the flow are commonly observed at both moorings (Fig. 2).

The monthly time series of SST along 125°E between Timor and Alor islands is used to determine the latitude of the maximum SST gradient during the INSTANT time period (Fig. 10). Missing SST data along 125°E (~10% of the record) were filled by linear interpolation in time and space. While not perfect because of the relatively coarse monthly temporal resolution, we use the location of the maximum SST gradient as a proxy for the frontal position within Ombai Strait (Fig. 10b). During the INSTANT period, the correlation between the time series of maximum SST gradient and its latitude is −0.51 (significant at 95% confidence level) implying that a more negative SST gradient corresponds to a more northern front location. The seasonal migration of the front in Ombai Strait (Fig. 10) agrees well with the seasonal SST pattern in the Savu Sea (Fig. 9). During the SEM, the front is generally located between the two moorings, often at around 8°26′S, just 4 km south of OMB-N. Conversely, during the
NWM the front is usually located south of OMB-S. Again, the seasonal movement of the front in Ombai Strait is largely consistent with the surface velocity observations (Fig. 3), suggesting that the front probably indicates the southward boundary of the SJC in the passage during the SEM. Furthermore, during the Kelvin wave events of strong surface velocity reversals at both OMB-N and OMB-S, for
Fig. 10. Time series of (a) maximum SST gradient and (b) latitude of the maximum SST gradient at 125°E, near Ombai Strait. Asterisks indicate the monthly values during INSTANT. The location of the OMB-N and OMB-S moorings are shown by the dash-dotted lines in (b).

example in June 2004 and April 2006 (Fig. 2), the maximum SST gradient is near zero (Fig. 10a) and in these cases the “front” is located well south in the passage (Fig. 10b). Finally, it’s worth noting that the front remained north of OMB-S through most of 2005. This period corresponds to when there is little coherence on intraseasonal time scales between the surface layer flow at OMB-N and OMB-S (Fig. 5a).

5. Discussion and conclusions

Velocity data from moorings deployed in Ombai Strait reveal a semi-permanent eastward flowing SJC that frequently hugs the northern boundary of the Savu Sea. Throughout much of the 3-year record and in the seasonal cycle, the surface flow at OMB-N is eastward, whereas at OMB-S it is primarily westward. In contrast, the SJUC is observed across the entire Ombai Strait semi-annually, and intraseasonally during the monsoon transitions. The SJUC is clearly a separate deeper core of eastward flow distinct from the surface SJC. The extension of the South Java Current system across the Savu Sea into Ombai Strait was hinted at by earlier measurements, but the ADCP transects of Hautala et al. (2001) were discrete, one-time surveys and the moored measurements of Molcard et al. (2001) were located at the same site as OMB-S. Thus, while Molcard et al. (2001) noted flow reversals in the upper 140 m in December 1995 in response to a strong Kelvin wave (much like that in May 2004, Fig. 2), and also at depth during the monsoon transitions, the mooring was too far south to measure the coastally trapped SJC and the year-long deployment too short to conclusively resolve the semi-annual signal of the SJUC.

What causes the semi-permanent nature of the eastward SJC flow in northern Ombai Strait? We suspect interplay by a variety of mechanisms to do with remotely driven Kelvin waves, Ekman dynamics, the strong ITF and topographic effects force the surface flow eastward during the INSTANT deployment
period. Drushka et al. (submitted for publication) identified 40 Kelvin wave events during INSTANT that reversed the transport in both Lombok and Ombai Straits. Clearly only some of these events (e.g. May 2004, April 2006) reverse the flow in the surface layer (Fig. 2). This is in agreement with linear ray theory that suggests Kelvin wave energy propagates vertically, as a function of the stratification and frequency of the wind forcing. Wind forcing at shorter intraseasonal periods will generate Kelvin waves that penetrate deeper than those generated by semi-annual wind forcing. When the surface layer in Ombai Strait is reversed due to the Kelvin waves, typically during the monsoon transitions, the eastward flow is felt across the whole passage because its 40 km width is less than half the ∼100 km Rossby radius of deformation.

In coastal regions of changing water depths and spatially variable winds due to mountain topography and island gaps, such as found all along Nusa Tenggara, upwelling dynamics occur that can result in different flow regimes in the offshore zones. On the shelf, the bottom boundary layer upwell to replace the offshore Ekman transport. If upwelling is strong or continues for a sufficient length of time, the thermocline can rise to the surface and form a temperature front that can geostrophically support a coastal surface jet in the same direction as the wind. Such a front is observed in the Savu Sea during the SEM when the winds are upwelling favorable, although we do not observe the westward surface jet at our OMB-N mooring site probably because it is upstream. However, the historical ship-drift data show westward near-surface flow in the SJC during the SEM all along the southern Nusa Tenggara coastal region (Quadfasel and Cresswell, 1992). Further offshore, the water can rise from mid-depths through slow geostrophic onshore drift. This mid-depth drift is supported by an along-shore pressure gradient, which when balanced by friction along the shelf slope, may result in a coastal current down the direction of the pressure gradient and opposing the direction of the wind. During the SEM, such a coastal current would be directed eastward toward Ombai Strait. This coastal current occurs below the near-surface Ekman layer along the shelf slope and thus also provides a possible explanation for the subsurface (50–100 m) maximum in eastward flow observed at OMB-N found during this season (Fig. 3a). The current is trapped to the northern coastal shelf break and therefore would only impact the flow at OMB-N. In addition, the warm surface ITF is strongest at OMB-S during the SEM, opposing the flow in the northern part of the passage and probably strengthening the SST gradient that suggests the presence of a front just 5–10 km south of OMB-N during the SEM (Fig. 10). Whether a mid-thermocline current maximum exists in the SJC at other locations along the Nusa Tenggara is uncertain because we lack observations. However, using high-resolution model output, Iskandar et al. (2006) showed maximum eastward velocity occurs at 50 m depth in the SJC off Java. Interestingly, the mooring deployed for a year in 200 m water depth off the central coast of Java also showed persistent strong eastward flow at 55 m depth during the SEM (Sprintall et al., 1999). However, this was attributed to a series of Kelvin waves forced during prolonged anomalous wind anomalies during the concurrent strong Indian Ocean Dipole (IOD) and El Niño events in 1997–1998 (Yu and Reinecker, 1999). Similar coastal surface jets have been observed in the monsoon regimes near the coast of New Guinea (Ueki et al., 2003) and off the west coast of Somalia (McCreary and Kundu, 1985). Further subsurface velocity observations are needed along the Nusa Tenggara coast to determine whether the SJC has a subsurface maximum during the SEM. Certainly during the NWM, the eastward flow is at the surface in the SJC and is associated with Ekman flow in response to the westerly winds all along the Nusa Tenggara coast (Quadfasel and Cresswell, 1992). During this season, equally strong eastward flow is evident at both OMB-N and OMB-S, and there is little cross passage SST gradient.

The complex bathymetry within the vicinity of Ombai Strait may also contribute to the presence of a strong surface temperature gradient and differences in the flow across the passage. The southern wall is very steep, whereas the north wall has a shallower sloping shelf (Molcard et al., 2001). The main ITF jet entering through the passage east of Alor Island (Fig. 1) may be subject to cyclostrophic effects, as it has to bend westward around Alor Island to avoid Timor Island and enter into the narrow Ombai Strait. This acts to confines the main ITF to the southern part of the passage and allows the eastward intrusion of the SJC in the northern part of the passage. Furthermore, it has been suggested that strong mean flows such as the ITF can cause flow separation at the entrance to a strait resulting in topographically controlled fronts in their lee (Wolanski and Hamner, 1988; Franks, 1992). Vigorous vertical mixing along the front can enhance nutrient input to the surface layer, and Moore and Marra
The deeper flow of the SJUC is more clearly driven by Kelvin waves forced in the equatorial Indian Ocean that travel along the coastal waveguide through the Savu Sea to Ombai. Their presence is felt with equal magnitude across the entire Ombai Strait at depths of 400–800 m. The deeper flow at both moorings is highly coherent on semi-annual time scales throughout the entire record, and also at 30–50 day intraseasonal periods during the monsoon transitions. The intraseasonal fluctuations are related to jets excited by intraseasonal Madden–Julian Oscillation winds in the equatorial eastern Indian Ocean (Han et al., 2001; Han, 2005; Masumoto et al., 2005) that drive the deep-diving intraseasonal Kelvin waves along the coastal wave-guide into Ombai Strait (Drushka et al., submitted for publication; Schiller et al., this issue).

There is a distinct low-energy spectral “hole” at longer intraseasonal time scales in the Ombai Strait currents, from mid-2004 throughout most of 2005 in the surface layer (Fig. 5a), and throughout most of the record in the SJUC (Fig. 5b). Similar spectral energy holes were also found at these longer intraseasonal periods in the wavelets of the velocity records from two moorings deployed in Lombok Strait during INSTANT (not shown). Tide gauge sea level records along Sumatra and Java often show an SJC characterized by 60–90 day peaks (Iskandar et al., 2005), and high-resolution model output suggests that while the SJC is characterized by 90-day period variations, 60-day variations dominate the SJUC (Iskandar et al., 2006). It is unclear why there is an absence of longer period intraseasonal variations during INSTANT, particularly in the SJC, or even whether we should expect the longer intraseasonal periods to be characteristic of Ombai Strait velocity fluctuations. In the equatorial Indian Ocean, 20–60 day oscillations in ocean currents are more frequently directly observed than 90-day oscillations, and the equatorial wind amplitude is also stronger in the 10–60 day band (Han, 2005; Sengupta et al., 2007). It may also be that interannual variability due to Pacific Ocean or Indian Ocean climate modes during INSTANT modulated the 60–90 day energy. ENSO cycled through a relatively weak warming from the initial deployment in January 2004 until September 2005, followed by a weak cool phase. Relatively stronger El Niño conditions developed from April 2006 coinciding with a strong positive IOD until the mooring recovery. In fact, significantly coherent deep flow is found across the channel at slightly longer intraseasonal periods (50–75 days) during the 2006 IOD in response to anomalous equatorial Indian Ocean winds (Horii et al., 2008; Sprintall et al., 2009).

Models conflict as to whether the Kelvin waves propagate eastward through Ombai Strait into the Banda Sea. For example, while the 1/10° grid BRAN2.1 model shows clear evidence for penetration of the waves into the internal seas (Schiller et al., this issue), a preliminary run of the higher resolution 1/25° global HYCOM simulation suggests (at the model’s 100 m depth) the weak eastward mean flow retrofects to join the main ITF current flowing through Ombai Strait (Metzger et al., this issue). While the SST maps suggest that the eastward flowing SJC is probably impeded from entering the Banda Sea by its interaction with the strong ITF that flows through the strait at the eastern end of Alor Island (Fig. 1), there is no reason that the deeper eastward SJUC could not penetrate beyond Ombai Strait. The few CTD casts that exist in the southern Banda Sea certainly suggest the presence of North Indian Intermediate Water within the lower thermocline that could enter via the SJUC (Gordon et al., 1994; Atmadipoera et al., 2009). The SJUC provides an Indian Ocean water source that is saltier than the sub-thermocline North Pacific water masses but slightly fresher than the South Pacific water masses. In the past, the contribution of Indian Ocean water to the formation of the relatively isohaline ITF profile within the Banda Sea has been largely ignored (Field and Gordon, 1992; Hautala et al., 1996; Koch-Larrouy et al., 2008). More hydrographic data in the southern Banda Sea, especially during the monsoon transition seasons when the SJUC is strong, would help to determine whether or not this Indian Ocean water contributes to the water mass transformation of the ITF stratification within the Banda Sea.

The recent inauguration in May 2009 of the 3.5 million hectare Savu Sea Marine National Park is recognition of the unique biodiversity of the region, as well as providing a mechanism for the sustainable management of fisheries for the benefit of the local Indonesians. The incredibly productive nutrient rich waters of the persistent upwelling zones fuel an estimated 300 fish species, and provide critically important habitat for whale sharks, dugongs and sea turtles. The authors of this manuscript have often been awe-struck by enormous pods of spinner dolphins as well as deep-diving sperm.
whales observed during various cruises in the vicinity of Ombai Strait. The Sperm, Sei and Blue Whales all use the productive waters of the Savu Sea as feeding grounds along their migration routes. As noted above, the circulation in Ombai Strait and the Savu Sea is likely impacted by the large-scale interannual climate variability. Certainly, both Potemra et al. (2003) and Moore and Marra (2002) show remotely sensed ocean color (a measure of productivity) is enhanced in the Savu Sea during El Niño events and suppressed during La Niña. However, while Moore and Marra (2002) suggest that this pattern was due to upwelling of nutrients associated with shoaling thermocline depths, Potemra et al. (2003) found upwelling to be anomalously low during El Niño events whereas advective effects were enhanced. Given that pelagic fisheries sustain the livelihoods of nearly 4.5 million people living in the region, clearly further study is needed on the interaction of the circulation and upwelling in the Savu Sea on interannual and climatic time scales. In this way, strategies for a long-term management plan can be developed for the benefit of local communities as well as ensure the survival of the majestic marine life that inhabits the Savu Sea.

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References


