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Dynamics of the South Java Current in the Indo-Australian Basin

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Abstract. A year-long deployment of a mooring in the South Java Current (SJC) of Indonesia provides a fascinating insight into this poorly understood, semi-annually reversing boundary current. A striking three-week period of south-eastward flow begins in mid-May 1997. An analytical model directly account for changes in velocity at this time due to the passage of a westerly wind-forced, downwelling Kelvin wave from the equatorial western Indian Ocean. The entire water column is warmed, with a fresh cap overlying salty water, consistent with the Indian Ocean source. Following the wave passage, the SJC is north-westward, and the prevailing south-easterly monsoon winds lead to upwelling of cold, salty water. In early August, the SJC abruptly returns to south-eastward flow, and remains so until November 1997 in the face of steady south-easterly local winds. The anomalous flow direction and cooler water are related to an upwelling Kelvin wave, forced by unseasonal prolonged easterly wind anomalies in the equatorial Indian Ocean. After a small reversal of flow in November 1997, the SJC is south-eastward, as expected during the north-east monsoon. A trend toward increasing salinities in the record is attributed to the increased input of salty Indian Ocean water, enhanced evaporation, and a lack of freshwater advection due to the regionally reduced precipitation during the 1997-98 El Niño.

Introduction

Dynamics in the Indo-Australian Basin (IAB; Figure 1) appear to be a complex interplay between remote forcing from both the equatorial Indian and Pacific Oceans, as well as strong local fluxes. The Indonesian throughflow enters from the northern and eastern boundaries of the IAB through several passages. Mass and property exchange occur via the large-scale currents in the region - the South Equatorial Current (SEC) / Eastern Gyral Current system [*Wijffels et al.*, 1996], and the seasonally reversing South Java Current (SJC). The SJC is particularly interesting as it is closely related to the sea-level along the south coast of the Java - Nusa Tenggara island chain (the northern boundary of the IAB), and thus affects the overall pressure difference from the western Pacific that is widely thought to govern the mean throughflow and its low frequency variations [*Wyrtki,* 1987].

The Dutch colonialists compiled monthly ship-drift surface current, temperature and salinity data for the Indonesian region in 1949 [*KNMI*, 1949], that were highlighted more recently in *Quadfasel and Cresswell* [1992]. The SJC reverses to south-eastward flow semi-annually around May and November, probably through the propagation of coastal and equatorial Kelvin waves forced by westerly wind bursts during the monsoon transitions in the equatorial Indian Ocean. At these times, the SJC has been found to consist of narrow cores of accelerated flow extending to depths of ~ 150-250 m, and 90 nm south of Java to ~10°S and the boundary with the westward flowing SEC [*Fieux et al.*, 1994; *Meyers et al.*, 1995]. South of Java, the *KNMI* [1949] historical data reveal the occurrence of a very warm, fresh surface layer (salinities ~33.8), too fresh to be the throughflow Banda Sea Water (BSW; ~34.4) [*Fieux et al.*, 1994]. Below this freshcap, in the thermocline and at depth, relatively saline (~34.65) North Indian Intermediate Water (NIIW; *Bray et al.*, 1997) is often found. The relationship between these water types and the phases (east or west) of the SJC is not clear. During the south-east monsoon period (June-October) the SJC is north-westward, slower and in the same direction as the SEC and throughflow [*KNMI,* 1949]. Lower surface temperatures at the coast suggest wind-induced upwelling might also occur.

Considering the impact of the South Java coastal region on the throughflow as it exits the Indonesian passages, and the benefit of upwelling to enrich local fisheries, relatively few observational programs have been undertaken here since the Dutch colonial period in Indonesia. Indonesia denied clearance to sample across the SJC during three WOCE cruises in 1995. However with the recent improved political process, a mooring was deployed off the south coast of Java as a joint venture between scientists in the United States, Indonesia and Australia to study the SJC characteristics. This letter discusses the property variability from that year-long deployment in the light of regional and remotely forced winds, and provides a context for future studies of this poorly understood current.

The South Java Current Mooring: March 1997 - March 1998.

The primary data used in this study are moored time series measurements of currents, temperature and salinity collected in 200 m of water off the south coast of Java at (8°11.5'S, 109°32'E) for the period March 1997 to March 1998 (Figure 2). Current velocity was measured using Vector Measuring Current Meters (VMCMs) at depths of 55 m, 115 m and 175 m. Post-recovery flow calibration revealed one of the 55 m VMCM hubs had failed, thus the magnitude of the velocity data from the 55 m VMCM must be viewed with caution, although the direction was unaffected. The VMCMs at 115 m and 175 m passed both flow and compass post-recovery calibrations. A high correlation exists between flow measured at all levels. A temperature logger and a Seabird SEACAT measuring

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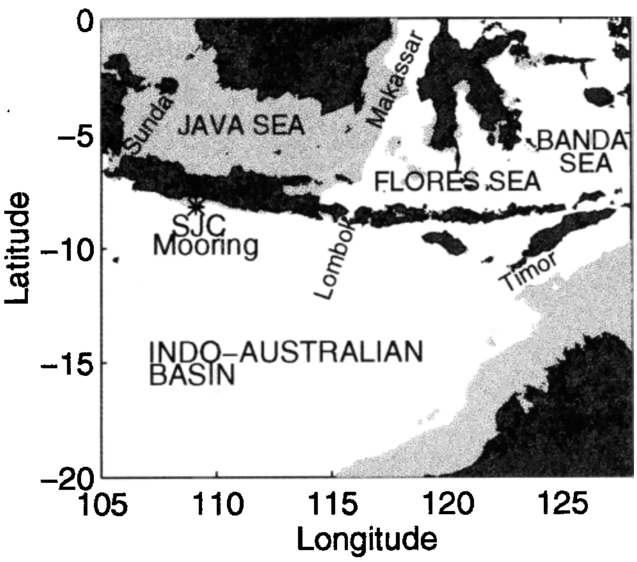

Figure 1. The Indo-Australian Basin and regional seas, showing the location of the South Java Current mooring (*), and the major straits. The 200 m bathymetry is shaded grey.

conductivity were instrumented at each of the VMCM depths. Seven temperature loggers were interspersed between the VMCMs at depths indicated in Figure 2.

The deployment of the mooring in the South Java Current in mid-March 1997 coincided with the beginning of the south-east monsoon period which occurred earlier than normal that year. The daily-averaged wind data from the nearby coastal town of Cilacap (Figure 1), shows that by mid-May relatively persistent south-easterlies are already established (Figure 2). Following the wind, the daily averaged surface currents at 55 m and 115 m are toward the north-west, although the currents at 175 m are south-eastward. There is a fresh cap in the westward flow at 55 m, overlying deeper saltier water .

In late April/early May the wind speed decreased slightly (Figure 2). The near-surface currents reversed direction toward the south-east and, after some minor episodic reversals, gradually strengthened and remained south-eastward until early June. Near the end of May, the currents at 55 m and 115 m had attained maximum record speeds of 1 m/s and 0.8 m/s, respectively. In the first two weeks of May, salinity at 55 m increases to the same salinity found at depth (~34.8), probably as a result of upwelling. From mid-May, the salinity at 55 m dramatically dropped to reach 33.9, coincident with the time of maximum eastward flow, while the deeper instruments recorded a salinity increase to ~35. These salinities are consistent with advection from the near-equatorial Indian Ocean west of Sumatra, where a fresh cap overlies pure NIIW at depth. Along with the salinity changes, rapid warming occurred throughout the water column, with the 20° isotherm plunging from the surface in early May to 155 m by the end of May. This period of eastward flow of warm, Indian Ocean source water heralds the arrival of the semi-annual downwelling Kelvin wave, forced by westerly wind bursts in the equatorial Indian Ocean, as we will show below.

By mid-June the south-east monsoon strengthened. Associated with this return to steady and intensified wind forcing, there was mean north-westward flow in the mooring record at all depths, consistent with the seasonally-averaged ship-drift data [*KNMI*, 1949]. The entire water column quickly became much colder (e.g. the 20° isotherm was at the surface again by the end of June), probably as a result of wind-induced upwelling. Coinciding with the cooler oceanic state, the air temperature at Cilacap dropped from 28.1°C in early June to 22.4°C by mid-July. The water column was relatively isohaline, and salinity returned to Banda Sea levels (~34.4) with the westward flow now found at all depths

The currents at the mooring again reversed to south-eastward in August, despite the persistent and strong south-easterly monsoon winds. This is completely opposite to the north-westward flow expected in the SJC from June to October [*KNMI,* 1949]. In fact, the SJC remains predominantly cool and to the south-east at all depths from August until October. The salinity transition towards higher levels from August suggests wind-driven upwelling of the salty NIIW supplied by the eastward SJC, and the strong evaporation expected during this season [*Wyrtki,* 1961].

Flow diminishes, and reverses to north-eastward at 55 m and 115 m, and the water column warms during November. From

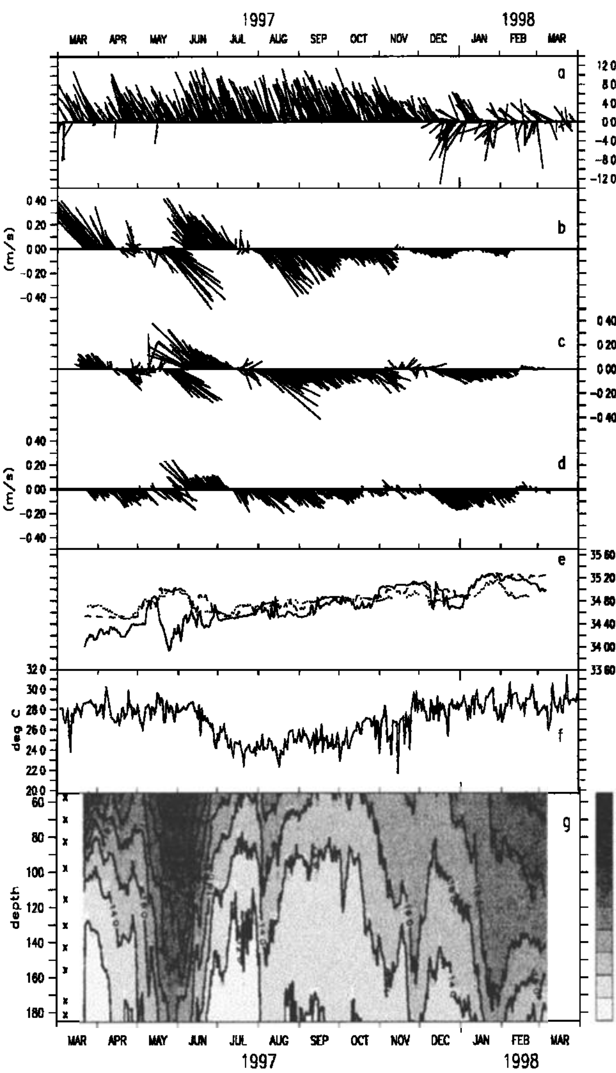

Figure 2. Daily averaged Cilacap (7°25'S, 109°45'E) meteorological measurements of (a) wind velocity vectors and (f) air temperature; and mooring data from (8.5°S, 110°E) of current velocity vectors at (b) 55 m, (c) 115 m, and (d) 175 m; (e) salinity at 55 m (solid), 115 m (dashed), and 175 m (dotted); and (g) temperature section (instrument depths marked on left-hand side).

late November onwards the winds gradually transition towards the variable weak winds of the north-west monsoon. Flow at all depths is south-eastward from December until the mooring recovery in March, consistent with the historical record [*KNMI*, 1949]. Salinity continues to increase, apart from a slight decrease in December, until the end of the record. This increase in salinity, for example over 0.6 at 55 m from September until February 1998, was also observed in two salinity sensors located further east in Lombok Strait, and so not likely due to instrument failure (for instance, bio-fouling in conductivity sensors results in a decrease in salinity). We will examine this further in the discussion section.

Discussion

The dynamics within the SJC, and within the IAB in general, appear to be a complex interplay between regional and remote monsoonal wind forcing, and the variations in the pathways of the major regional currents. It is well documented that the SJC is modulated on semi-annual time-scales by remote westerly winds in the equatorial Indian Ocean [*Quadfasel and Cresswell*, 1992; *Clarke and Liu*, 1993]. To examine the impact of remote forcing during the mooring time period we employ a simple model. The analytical model predicts changes in coastal sealevel due to alongshore wind stress by decomposing the momentum equations into vertical modes, and integrating along the path taken by a Kelvin wave. Details of the model can be found in *Gill* [1982, p. 399] and we outline them briefly here.

Assuming there is no wind stress curl along the coast, the alongshore and surface velocity exponentially decay away from the coast (a Kelvin wave) and the equation governing the amplitude of sea level is,

$$\frac{dA}{dt} + c\frac{dA}{dx} = c\frac{X}{g} \qquad (1)$$

where g is gravitation acceleration, c is the wave speed $\sqrt{gD_n}$ and D_n is the equivalent depth of the mode, A is the mode's amplitude of sealevel, and X is the projection of the alongshore wind stress onto that particular mode. In a reference frame of a wave traveling at speed c, equation [1] becomes,

$$\frac{dA}{dx} = g^{-1}X(x, p + \frac{x}{c}) \qquad (2)$$

where p are the wave characteristics. For this analysis, we calculate the first three vertical modes using a CTD profile from the JADE 1989 cruise in Sunda Strait [*Fieux et al.*, 1994]. Using daily ECMWF wind fields, we determine sealevel (A in equation [2]) corresponding to the time period of the mooring deployment by integrating wind stress across the equator from the western Indian Ocean, down the coast of Sumatra to the mooring site off Cilacap, Java. The zonal velocity of each vertical mode is then related to sea level by geostrophy,

$$u = \frac{gA}{c} \qquad (3)$$

The comparison of the zonal velocity predicted by the analytical model with that of the mooring observations is shown in Figure 3. Clearly the eastward velocities at all depths during May 1997 are related to the arrival of a Kelvin wave on the south coast of Java. The downwelling Kelvin wave, generated by equatorial Indian Ocean westerly wind stress

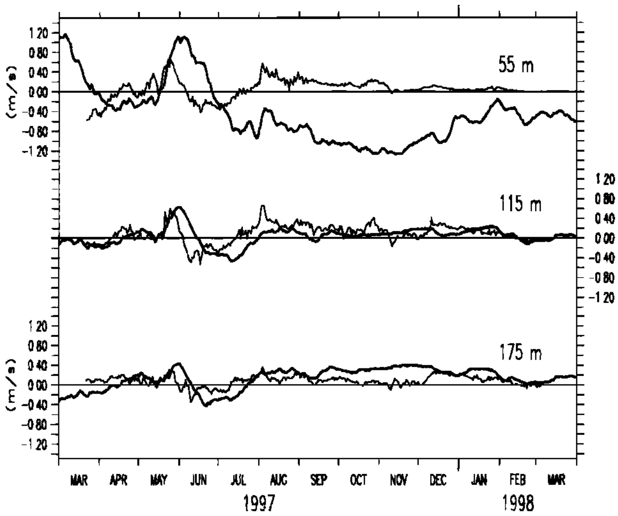

Figure 3. Zonal velocity (m/s) observed at the SJC mooring (light), and as predicted by an analytical model (bold).

during the monsoon transition period, strikes the west coast of Sumatra and propagates warm water poleward to the south Java coast and the SJC mooring. In fact, from the SJC mooring, the passage of the Kelvin wave was observed in pressure gauge records downstream in Lombok Strait and in two moorings within Makassar Strait [Sprintall et al., A semi-annual Indian Ocean forced Kelvin wave observed in the Indonesian seas in May 1997, submitted to *J. Geophys. Res.*, 1999]. This suggests that, at times, eastward flow in the SJC may effectively redistribute Indian Ocean source water into the Indonesian internal seas.

The timing of the event at the SJC mooring predicted by the model matches well with the observations, although the duration and magnitude have been curtailed. The attenuation in the observations is particularly noticeable at 55 m, and is probably due to locally opposing stronger south-easterly winds seen in the Cilacap wind record in June (Figure 2). This is consistent with *Potemra* [1999] who found that the semi-annual Kelvin wave in his 1.5 layer reduced gravity model, halts near Bali in the presence of the local easterly wind forcing. The steady local winds drove the SJC north-westward in June to mid-July, and Ekman-induced upwelling caused a subsequent rapid drop in both water and air temperature. By July, the water column has become isohaline at levels consistent with a Banda Sea throughflow source.

After the May 1997 Kelvin wave event, the model predicts sustained westward flow in the SJC at 55 m. However, apart from the north-westward flow from early June to mid-July, the observed currents are anonamously eastward during the south-east monsoon from August to mid-November (Figure 3), and opposing the steady local south-east monsoonal winds (Figure 2). At deeper levels (115 m and 175 m), the model predicts westward flow from mid-June until the end of July, then eastward flow until early 1998 (Figure 3). This agrees well with the observed deeper currents, although the change in observed flow leads the predicted flow by about 12 days. *Yu and Rienecker*, 1999] found prolonged easterly wind anomalies occurred in the near-equatorial Indian Ocean during June-December 1997. They attributed the anomalous winds to a shift in the Walker Cell in response to the 1997-98 El Niño. The anomalous easterlies forced a series of upwelling Kelvin waves that impact the Sumatra and south Java coastlines, lifting the thermocline and bringing the colder water to the surface, and depressing sealevel (see Figures 1 and 4 of SST and sea surface height in *Yu and Rienecker*, 1999). The scenario fits well with the timing of the eastward flow observed at the SJC mooring from mid-July, and predicted (12 days later) at 115 m and 175 m depth by the analytical Kelvin wave model (Figure 3). Interestingly, at the beginning of August the eastward flow is warmer than that found at the mooring during the upwelling period of July, although not nearly as warm as during the May 1997 Kelvin wave event. For example, the 16° isotherm drops from the surface to 110 m in a matter of days in early August, but relatively quickly rises to the surface in early September. As noted, the eastward flow observed at 55 m is not predicted by the model, although note the 0.6 m/s drop in the westward predicted flow occurring coincidentally with the observed arrival of eastward flow at the end of July (Figure 3). It is possible that some local coastal processes influence the mooring currents during this period, and these are not described by our simple model. *Yu and Rienecker* [1999] found the anomalous south-east winds remained near the equator in November 1997, possibly dampening the typical monsoon transition forcing of the downwelling Kelvin wave and its expected passage to the mooring site at this time. A November Kelvin wave is not predicted by the analytical model (Figure 3), although the observed currents do turn slightly north-eastward at 55 m and 115 m, and the water column warms.

In the Pacific Ocean during El Niños, the equatorial Pacific trades are weakened, and the lower sea level in the western Pacific diminishes the throughflow transport. *Chong et al.*, [Chong et al., Transport through the outflow straits of Indonesia, submitted to *Geophys. Res. Lett.*, 1999] and *Gordon et al.*, [1998] found that the transport was lower than normal during 1997 through Lombok and Makassar Straits, respectively. If the observed eastward flow in the SJC during August-November 1997 penetrated downstream of the mooring and through Lombok and Makassar Straits, as it did during May 1997 [*Sprintall et al.*, submitted to *J. Geophys. Res.*, 1999], this would act to reduce throughflow transport.

Finally, we return to the trend of increasing salinity observed in the mooring record from August 1997 through February 1998 (Figure 2). At depth, the trend towards increasing salinities is most likely related to the increased inflow of the saltier NIIW into the region, due to the passage of the upwelling Kelvin wave from the Indian Ocean during the south-east monsoon. Upwelling favorable local winds, present at the mooring during this time, would bring the NIIW to the upper layer, acting to increase the salt content. Further, during the 1997-98 El Niño the center of atmospheric convection normally found over Indonesia shifted eastward toward the central Pacific [*Climate Diagnostics Bulletin*, 1997]. Consequently drought conditions were observed over most of the Indonesian archipelago reducing the normally voluminous fresh water outflow from the rivers in the region and transported by the SJC. In addition, NCEP latent heat flux anomalies (not shown) indicate anomalously high values near Sumatra and Java from July 1997 until September 1997. The evaporative dominance of this south-east monsoon period [*Wyrtki*, 1961], possibly further enhanced by stronger than normal easterly wind speeds [*Yu and Rienecker*, 1999], would also lead to increases in upper layer salinity.

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