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A semiannual Indian Ocean forced Kelvin wave observed in the Indonesian seas in May 1997

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Abstract. Recent observations within the Indonesian exit passages and internal seas highly resolve the arrival and passage of a semiannual Kelvin wave. In mid-May 1997, surface and subsurface currents were to the southeast at a mooring located south of Java in the South Java Current, while local wind forcing was northwestward. Subsequent northward fluctuations in the geostrophic current through Lombok Strait and in observed currents from two moorings located in Makassar Strait are commensurate with the speed and passage of a Kelvin wave through the region. The Kelvin wave was due to westerly wind forcing in the remote equatorial Indian Ocean during the semiannual April/May monsoon transition period. This was confirmed through a simple remote wind-forced analytical Kelvin wave model of velocity at the South Java Current mooring location and sea level in Lombok Strait and also in the numerical general circulation model of *Murtugudde et al.* [1998]. Warm temperature anomalies measured at the south Java mooring and within Makassar Strait are associated with the passage of the Kelvin wave. Salinity anomalies measured at the south Java mooring are consistent with an Indian Ocean source. The observed passage of the Kelvin wave during May 1997 unambiguously demonstrates for the first time that equatorial Indian Ocean remote wind forcing may on occasions influence the internal Indonesian seas

1. Introduction

During the monsoon transition periods of April/May and October/November, westerly wind bursts in the equatorial western Indian Ocean force the semiannual eastward Wyrtki Jet [*Wyrtki*, 1973]. The source waters of the jet stem from the western tropical Indian Ocean, delivered into that region by the South Equatorial Current (SEC). The Wyrtki Jet is weaker during the October/November transition period when the Somali Jet in the Arabian Sea appropriates some of the SEC flow [*Wyrtki*, 1973]. The equatorial and surface-confined Wyrtki Jet generally sets up within a week after the westerly wind onset, and the oceanic adjustment to the wind forces an associated downwelling Kelvin wave. Directly observed speeds of the jet have ranged from 0.7 to 2.1 $\mathrm{m\ s^{-1}}$ [*Wyrtki*, 1973; *Molinari et al.*, 1990; *Michida and Yoritaka*, 1996], which is roughly commensurate with the first model baroclinic mode equatorial Kelvin wave speed of 1.9 $\mathrm{m\ s^{-1}}$, which may have been modified by the mean currents. The Kelvin wave transits from the western equatorial Indian Ocean in about a month to impinge the west coast of Sumatra on the equator in Indonesia. Subsequently, it excites a reflected Rossby wave back into the Indian Ocean as well as northward and southward propagating coastally trapped Kelvin waves (CTKWs) that correlate directly with observed coastal sea level rises along the coasts of Sumatra and Java [*Clarke and Liu*, 1993; 1994].

The fate of the southward propagating CTKW once it reaches the south coast of Java and its impact on the Indonesian internal seas and the throughflow are areas of active debate [*Murtugudde et al.*, 1998; *Qiu et al.*, 1999]. The main issues of contention are twofold: (1) the nature of the "gappy" island boundary of southern Indonesia and whether it permits the CTKW to enter and affect the circulation of the interior Indonesian seas and (2) the modulation of the Kelvin wave signal by the semiannually reversing South Java Current and the throughflow itself. In addition, the role of local versus remote forcing within the Indonesian seas remains a controversial issue.

The suggested impact of the southward propagating, coastally trapped Kelvin wave within the Indonesian seas has mostly come about through numerical modeling experiments [*Murtugudde et al.*, 1998; *Potemra*, 1999; *Qiu et al.*, 1999] and the use of simple analytical models [*Clarke and Liu*, 1993; 1994]. Observational evidence has been mainly limited to sparse monthly tide gauge measurements. Recently, a concentrated observational effort (see Figure 1 for locations) has enabled us to document directly the impact of a Kelvin wave within the Indonesian region using much higher temporally resolved measurements. The fortuitous detection of the Kelvin wave by the suite of contemporaneous measurements is exciting because it not only highly resolves the timing of the event in the Indonesian seas, but the observations also determine the nature of the Kelvin wave and its property characteristics. There is also the advantageous location of the measurements themselves: in the major pathway of Indian Ocean dynamics into the Indonesian seas (via the South Java Current), in the major throughflow conduit from the Pacific Ocean via Makassar Strait, and exiting into the Indian Ocean via Lombok Strait. In section 2 we describe the various oceanographic measurements at each location in

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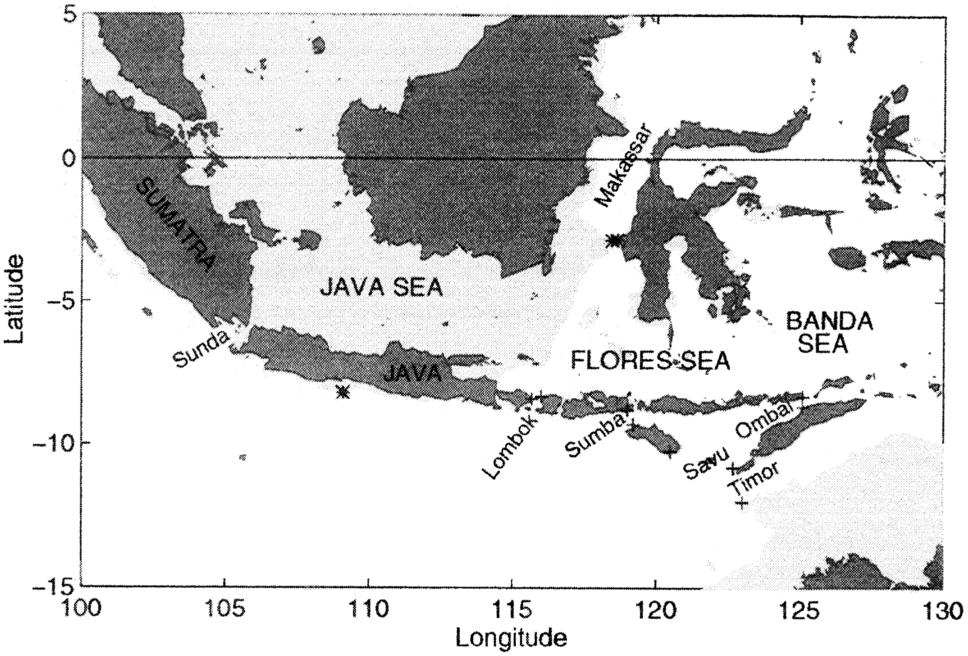

Figure 1. The position of the South Java Current mooring and Makassar Strait moorings (stars), and the shallow pressure gauge array (crosses) within the Indonesian seas. The major straits and seas referred to in the text are shown, and the 200 m and shallower bathymetry are shaded gray.

detail for the period April 15 through June 15 1997. In section 3 we show the Kelvin wave observed in the Indonesian seas in May 1997 to be directly related to the semiannual westerly wind forcing in the equatorial Indian Ocean using a simple analytical model and the numerical general circulation model of *Murtugudde et al.* [1998]. In section 4 we discuss the dynamics of the southward propagating semiannual CTKW and its possible pathways and signals within the gappy Indonesian archipelago. The May 1997 Kelvin wave passage observed in the Indonesian seas coincided with the beginning of the extraordinary 1997-1998 El Nino. However, longer regional time series of winds and altimetric sea surface height suggest that the observed May 1997 event is probably typical of the semiannual Indian Ocean forcing affecting the Indonesian region during the monsoon transitions, at least across the southern Indonesian exit passages. In section 5 we conclude that the observations and results from the model simulations explicitly demonstrate that on occasions remote Indian Ocean wind forcing directly impacts the internal Indonesian seas.

2. Observations of the Kelvin Wave in the Indonesian Seas During May 1997

In this section we will describe the observations from three oceanographic programs that existed concurrently within the Indonesian seas, focusing on the period April 15 to June 15, 1997, which encompassed the May 1997 Kelvin wave event. The reader is referred to the references in each subsection that more fully describe the nature and objectives of each program. For uniformity, which still retains the essence of the Kelvin wave signature throughout the region, the oceanographic observations presented in the following have been hourly or daily averaged from the higher resolved instrumental measurements (typically minutes). Other data processing (for example, removing tidal signatures) are noted where applicable.

2.1. South Java Current

A year-long deployment (March 1997 to March 1998) of a mooring south of Java provides insight into the relatively poorly understood South Java Current (SJC). The moored time series that captures the boundary current was collected at (8°11.5'S, 109°32'E), located at the 200 m isobath, 40 nautical miles south of the coastal town of Cilacap on the south coast of Java (Figure 1). The mooring consisted of current, temperature and salinity measurements at 55, 115, and 155 m, with additional interspersed temperature loggers (at depths indicated in Figure 2f). Details of the full mooring deployment are given by *Sprintall et al.* [1999]. Here we are concerned with the oceanic conditions that existed at the SJC mooring during the period April 15 to June 15 1997 (Figure 2). Winds at Cilacap, representative of the local wind field, are mostly north to northwestward during this period (Figure 2).

In mid-April the near-surface currents episodically reverse direction, gradually turning more southerly on May 6 (at 55 m) before strongly setting toward the southeast on May 16 at 55 m and May 19 at 115 m. At 55 m (115 m) the southeastward current quickly strengthens to reach a maximum current speed of 1.0 (0.8) m s^{-1} that is maintained between May 20 and 25 (May 19 and 29). As we will demonstrate below, this period of strong southeastward flow corresponds to the arrival of the Kelvin wave at the south Java mooring. Gradually, the current speeds decrease, and on June 5, northwestward flow is observed at 55 and 115 m until the end of the time series. At 175 m the currents are mostly to the southeast during April, weakening in early May. Stronger southeastward flow returns in mid-May with a maximum current speed of $\sim$0.3 m s^{-1} attained between

May 25 and 28. Beginning in early June, the current at 175 m turns northwestward and, as in the shallower instruments, remains that way until the end of the record.

Corresponding changes are observed in the salinity and temperature records (Figures 2e-2f). At 55 m a relatively fresh cap (~34.4) exists during the period of low current until May 7, when the near-surface layer salinity increases to the same salinity found at depth (~34.8), probably as a result of upwelling in response to the stronger northwestward winds that existed during late April to early May. The cooler surface (top 100 m) temperatures are also indicative of the upwelling during this period (Figure 2f). Coincident with the timing of the arrival of eastward flow at the mooring site, the salinity at 55 m quickly decreases, reaching a minimum of 33.9 on May 25 (Figure 2e). At 115 and 175 m, salinity slowly increases from ~34.5 at the beginning of the record to ~35, also coincident with the beginning of strong southeastward flow on May 19 at 115 m and May 25 at 175 m. These salinities are consistent with the southeast advection of water from the near-equatorial Indian Ocean west of Sumatra, where a fresh cap

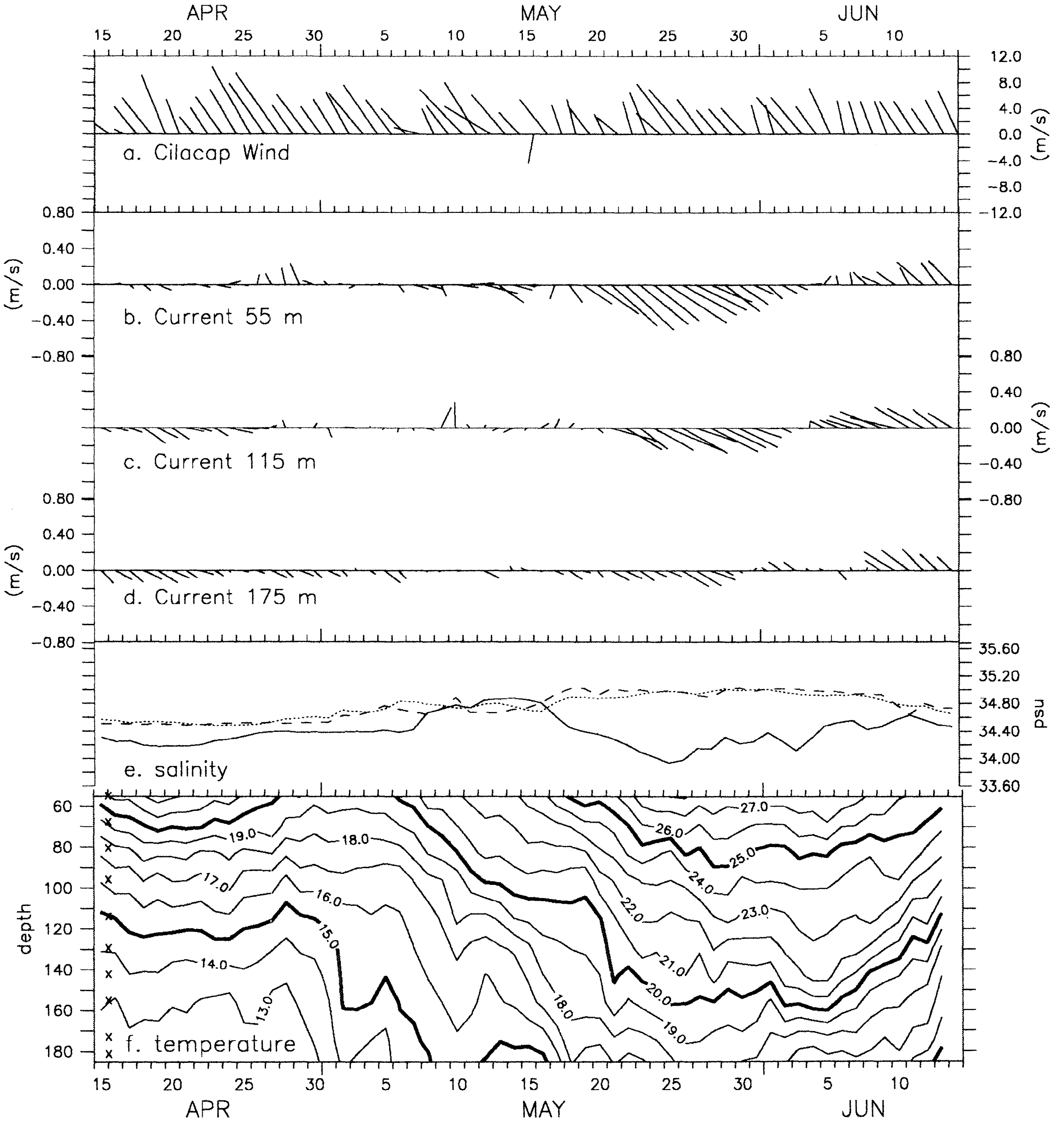

Figure 2.(a) Daily averaged Cilacap wind (m s^{-1}). The south Java mooring current velocity (m s^{-1}) at (b) 55, (c) 115, and (d) 175 m. (e) Salinity at 55 (solid), 115 (dashed), and 175 m (dotted). (f) Temperature section (instrument depths are marked on the left-hand side) for the period April 15 to June 15, 1997.

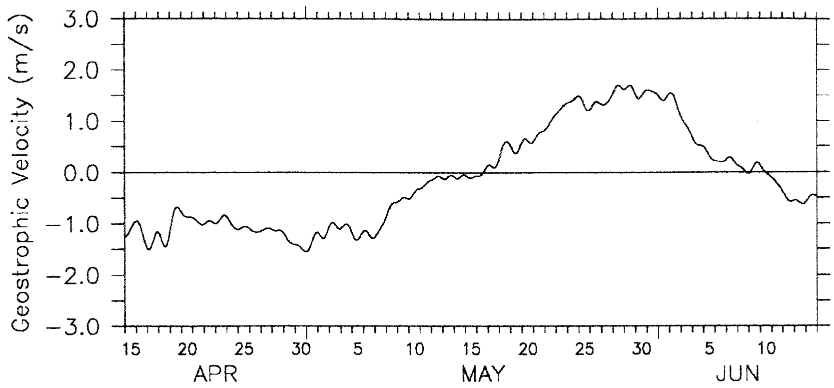

Figure 3. The cross-strait geostrophic surface velocity (m s^{-1}) estimated from the pressure gauges that span Lombok Strait for the period April 15 to June 15, 1997. Negative values indicate southward flow.

overlies the saltier North Indian Intermediate Water found at depth [*Bray et al.*, 1997]. With the subsequent relaxation in southeastward flow, salinity at 55 m increases, while at 115 and 175 m the salinity gradually returns to values found prior to the event.

The eight temperature sensors at the SJC mooring also reveal a remarkable response that correlates to the period of southeastward flow at the mooring site. Temperature increases dramatically throughout the water column, ranging from 20°C on May 6, to 28°C on May 25 at 55 m and from 13°C on May

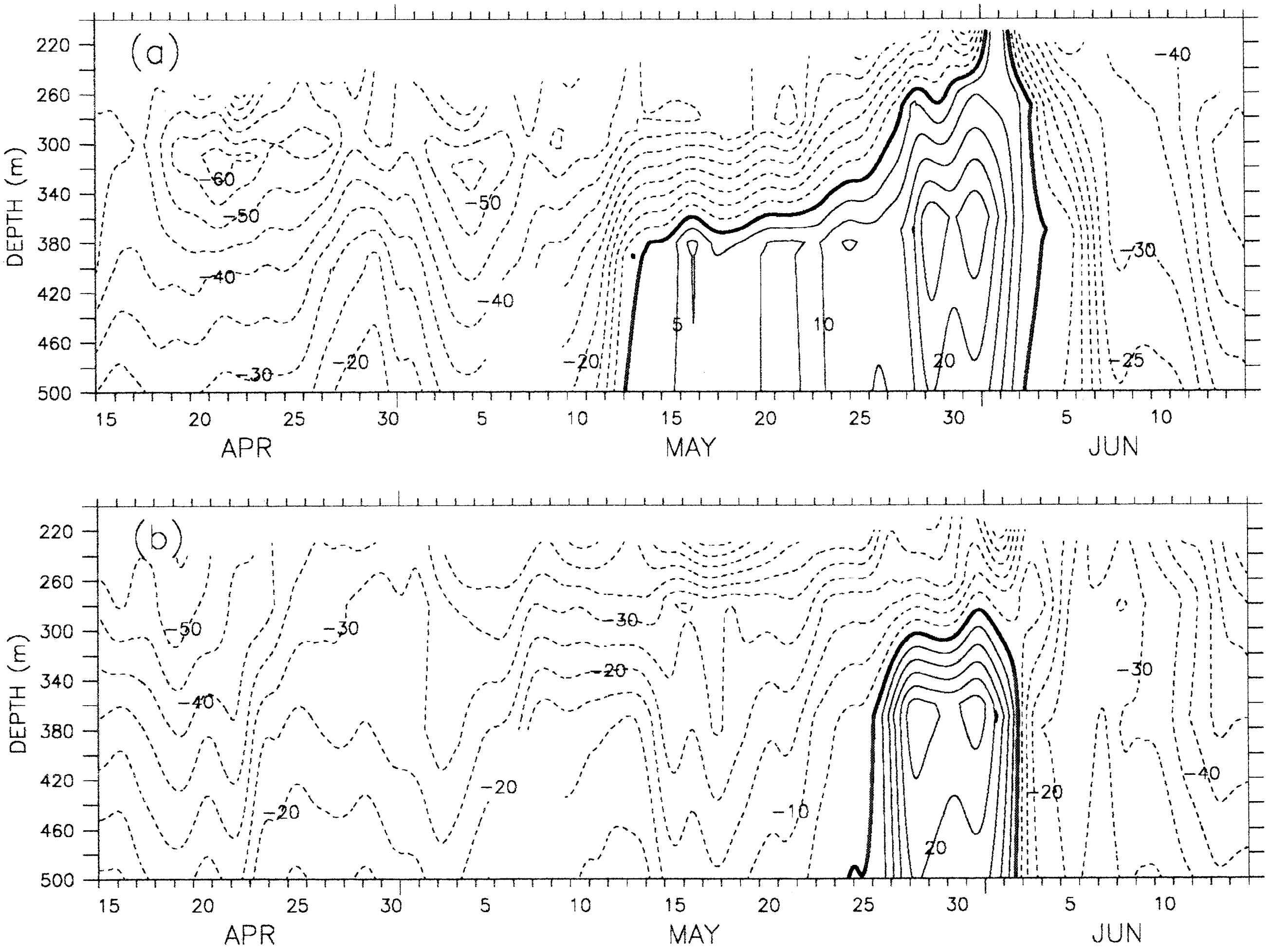

Figure 4. Along-channel velocity (orientation of 170°) from the moorings in Makassar Strait at (a) MAK-1 (2°52'S, 118°27'E) and (b) MAK-2 (2°51'E, 118°38'E) for the period April 15 to June 15, 1997. The data have been corrected for strong semidiurnal pumping present at the moorings. The zero-flow contour is indicated by bold lines, northward flow is indicated by solid lines, and southward flow is indicated by dashed lines.

6 to 18.4°C on May 25 at 180 m. This response is consistent with that of a downwelling Kelvin wave transporting warm Indian Ocean equatorial surface water. Note that the local Cilacap winds, although slightly more variable, are still predominantly toward the northwest during the period of southeastward flow at the mooring, a wind direction that should induce the upwelling of cooler water. Evidently, the advection of the warmer equatorial source water with the passage of the Kelvin wave dominates over local processes during this period. The water column abruptly cools at 55 m (180 m) on June 6 (May 30) with the reversal of currents toward the northwest and coinciding with the winds' strengthening toward the northwest [*Sprintall et al.,* 1999]. The cooler water column in early June 1997 is likely a result of the local upwelling regime again dominating at the mooring location.

2.2. Lombok Strait

An array of nine pressure gauges has been monitoring the outflow straits of the Indonesian Throughflow since December 1995. The pressure gauge pairs span the major exit passages and provide an estimate of the average fluctuations in surface geostrophic velocity through the straits. Further details of this program are given by *Chong et al.* [2000]. One of the passages monitored by the pressure gauges is Lombok Strait, located just east of the south Java mooring site (Figure 1). Lombok Strait transports an estimated 25% of the total Indonesian Throughflow southward and out into the Indian Ocean [*Arief and Murray,* 1996]. Notably, for this study it is the first substantial strait to interrupt the poleward propagation of the CTKW, and it provides an equatorward passage for the wave signal into the internal Indonesian seas.

The fluctuation in geostrophic velocity through Lombok Strait estimated from the pressure gauges is shown in Figure 3 for the period April 15 to June 15, 1997. The data have been averaged into hourly bins, and the tides removed by fitting sinusoids of the 15 dominant tidal frequencies in a least squares sense. The predominantly southward geostrophic flow of April 1997 begins to weaken in early May 1997. Anomalous northward flow through the strait was observed from May 17 onward, with maximum northward flow between May 29 and 31. The northward flow observed through Lombok Strait represents about a 1-day lag from the southeastward surface velocity at the south Java mooring, commensurate with the speed of the Kelvin wave. At the beginning of June the northward flow through Lombok Strait gradually relaxes to southward flow throughout the remainder of 1997 [*Chong et al.*, 2000].

2.3. Makassar Strait

As part of the Indonesian-U.S. Arlindo program, two moorings were deployed in late 1996 within the deep and narrow Labani Channel toward the southern end of Makassar Strait [*Gordon and Susanto,* 1999; *Gordon et al.,* 1999]. Makassar Strait is ostensibly the primary pathway for the Indonesian Throughflow from the Pacific to the Indian Ocean.

The hourly time series of along-channel flow in Figure 4 was reconstructed from current meters nominally deployed at 200, 250, 350, and 750 m depth. The strong semidiurnal tidal pumping in the channel causes the instruments to "blow over," and thus a linear interpolation between the current meters and their position, monitored by pressure sensors, allows the generation of the velocity section with depth in Figure 4 (see *Gordon et al.* [1999] for details).

A marked relaxation occurred in the southward Makassar Strait throughflow velocity during middle-to-late May (Figure 4), although there is evidently a lag between the respective moorings and also the depth, as noted by *Gordon and Susanto* [1999]. Northward flow is first observed at the western mooring MAK-1 below 360 m beginning on May 13. The northward flow gradually intensifies at depth at the MAK-1 mooring. By the end of May to early June, northward velocities are found throughout the water column. The strongest flow (>30 cm s^{-1}) is found between 320 and 500 m from May 29 to June 1. At the MAK-2 mooring, northward flow only occurs below ~300 m, between May 25 and June 2, although the southward flow throughout the upper layer during this period is substantially diminished. The period of strongest northward flow is nearly coincident at the two moorings. Southward flow abruptly returns to Makassar Strait at both mooring sites in early June.

Note that the northward flow measured at depth in the MAK-1 mooring occurs before the first appearances of southeastward flow at the SJC mooring (May 16) and northward flow through Lombok Strait (May 17). Recall that the instrumentation at both the SJC mooring (200 m depth) and the Lombok Strait pressure gauges (the sill depth of Lombok Strait is ~280 m) is shallower than the Makassar moorings (situated in the 2000 m deep Labani Channel and north of the ~650 m Dewakang Sill). Most of the Makassar mooring measurements are made below the Lombok sill depth. If we consider the period of most intensified northward flow (May 25 to June 1 at depth at both MAK moorings), then this is consistent with the timing of the Kelvin wave passage and its appearance at the upstream Makassar moorings at depth. The downward propagation of energy in the Kelvin wave signal between Lombok Strait and the Makassar mooring sites and the evident upward vertical phase tilt associated with the northward advection at the Makassar Strait moorings are also consistent with the downwelling Kelvin wave propagation between the respective passages over different sill depths.

The temperature anomaly from the MAK-1 200 m and MAK-2 205 and 255 m thermisters suggests an anomalous surface warming associated with the relaxation of the southward throughflow observed in May 1997 (not shown) [see *Gordon and Susanto*, 1999; *Ffield et al.*, 2000], as was also observed with the Kelvin wave passage at the SJC mooring (Figure 2).

3. Models Predict a Wind-Forced Kelvin Wave from the Equatorial Indian Ocean

3.1. An Analytical Model

Using a simple analytical model, *Sprintall et al.* [1999] attributed the observed currents at the SJC mooring during May 1997 to the arrival of a Kelvin wave forced in the western equatorial Indian Ocean. For completeness we provide a brief overview of the model as here we wish to apply it to the coastal sea level observations as measured by the pressure gauge at Bali in Lombok Strait (see section 2b). Further, we will use the model to show that the May 1997 event observed in the Indonesian seas can be directly related to a Kelvin wave generated by remote Indian Ocean wind forces, and the signal during this event is not attributable to local wind forcing. The analytical model, suggested by *Gill* [1982; p.399], uses the momentum equation in the alongshore direction x:

$$\frac{du}{dt} - fv = -g\frac{de}{dx} + X, \tag{1}$$

with a cross-shore (y) momentum equation in geostrophic balance:

$$fu = -g\frac{de}{dy}, \tag{2}$$

and the continuity equation:

$$\frac{de}{dt} + D_{\mathrm{n}}\left(\frac{du}{dx} + \frac{dv}{dy}\right) = 0, \tag{3}$$

where u and v are the velocities in the alongshore and cross-shore directions, respectively, f is the Coriolis parameter, g is the acceleration due to gravity, e is the surface elevation, X the projection of wind stress onto a particular vertical mode, and D_n is the equivalent depth of the mode. Combining (1)-(3), and assuming that there is no wind stress curl along the coast, the surface and alongshore velocity exponentially decay away from the coast (a Kelvin wave) and the equation governing the amplitude of sea level A is

$$\frac{dA}{dt} + c\frac{dA}{dx} = \frac{cX}{g}$$

or in the reference frame of a wave traveling at the wave speed c (=sqrt(gD_n)),

$$\frac{dA}{dx} = X(\mathrm{x}, \mathrm{p} + \frac{\mathrm{x}}{\mathrm{c}})g^{-1}, \tag{4}$$

where $p=t-x/c$. Equation (4) predicts how the sea level A will change because of alongshore wind stress X, following a Kelvin wave. For the purposes of this study the model is integrated using daily European Centre for Medium-Range Weather Forecasts (ECMWF) wind stress fields, following a path from the western equatorial Indian Ocean, along the equator to west Sumatra, down the coast to Sunda Strait, and on to the location of the South Java mooring site [*Sprintall et al.,* 1999], and the Bali pressure gauge sensor. No energy is lost in the analytical model to a northward propagating CTKW or reflected Rossby wave, a point we will return to in section 4. The vertical modes are calculated using a JADE 1989 conductivity-temperature-depth profile (CTD) from Sunda Strait [*Fieux et al.,* 1994].

Sprintall et al. [1999] related the zonal velocity to the first three vertical modes of sea level in (4) by geostrophy for comparison with the observed zonal velocity at the SJC mooring, shown here in Figure 5 for the period April 15 to June 30, 1997. The model successfully predicts the arrival of a Kelvin wave at the SJC mooring site on May 16, which matches exactly the eastward flow observed at all current meter depths (Figure 5). However, the duration and magnitude of the May 1997 Kelvin wave event, as measured by the SJC mooring, is moderated compared to that predicted by the analytical model. We will return to possible reasons for this attenuation in section 4.

In Figure 6a we use (4) to predict sea level as observed at the Bali pressure gauge site, shown here for the entire duration of the pressure gauge time series. We have used only the first vertical mode that contains 76% of the variance in the observations. Successively higher modes contribute less and less to the total sea level and subsequently denigrate the correlation. The agreement between model and observations in Figure 6a is remarkable. Not only is the May 1997 event successfully predicted (although a little later than observed), but most other peaks and troughs in sea level at Bali have been captured as well. In producing Figure 6a the model has again been integrated with ECMWF wind stress following the continuous path from the western equatorial Indian Ocean

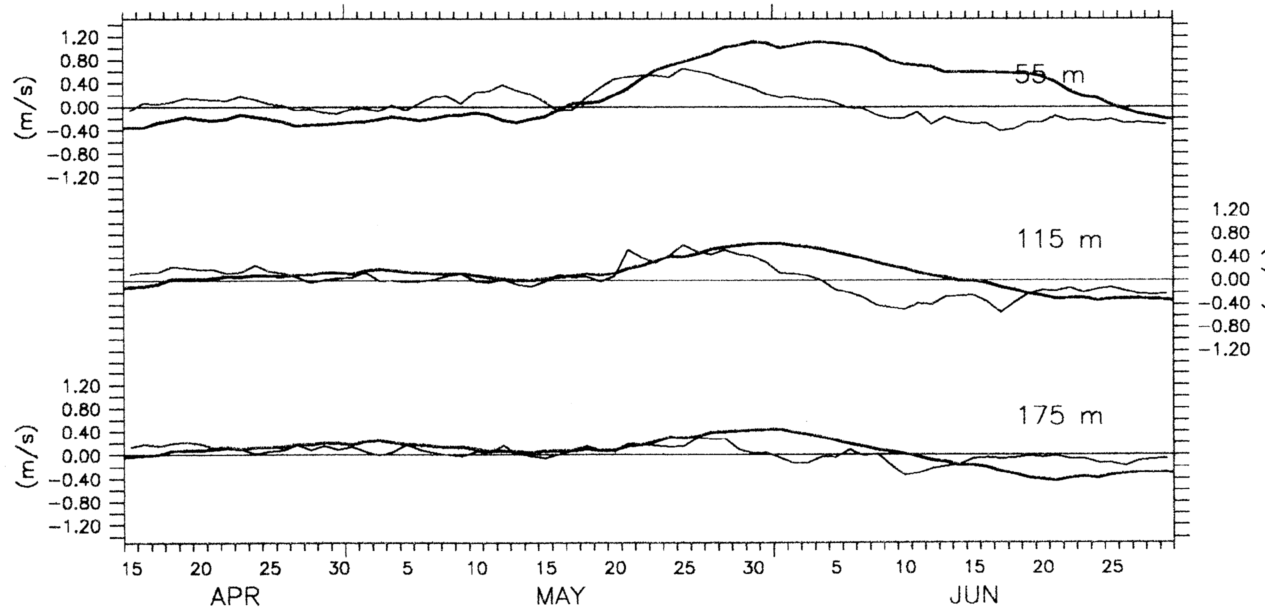

Figure 5. Zonal velocity (m s^{-1}) observed at the SJC mooring (light lines) and as predicted by an analytical Kelvin wave model (bold lines) for the period April 15 to June 30, 1997. The model is forced by ECMWF daily wind stress following the path from the western Indian Ocean along the equator to the coast of Sumatra and down the coast to the mooring located south of Java.

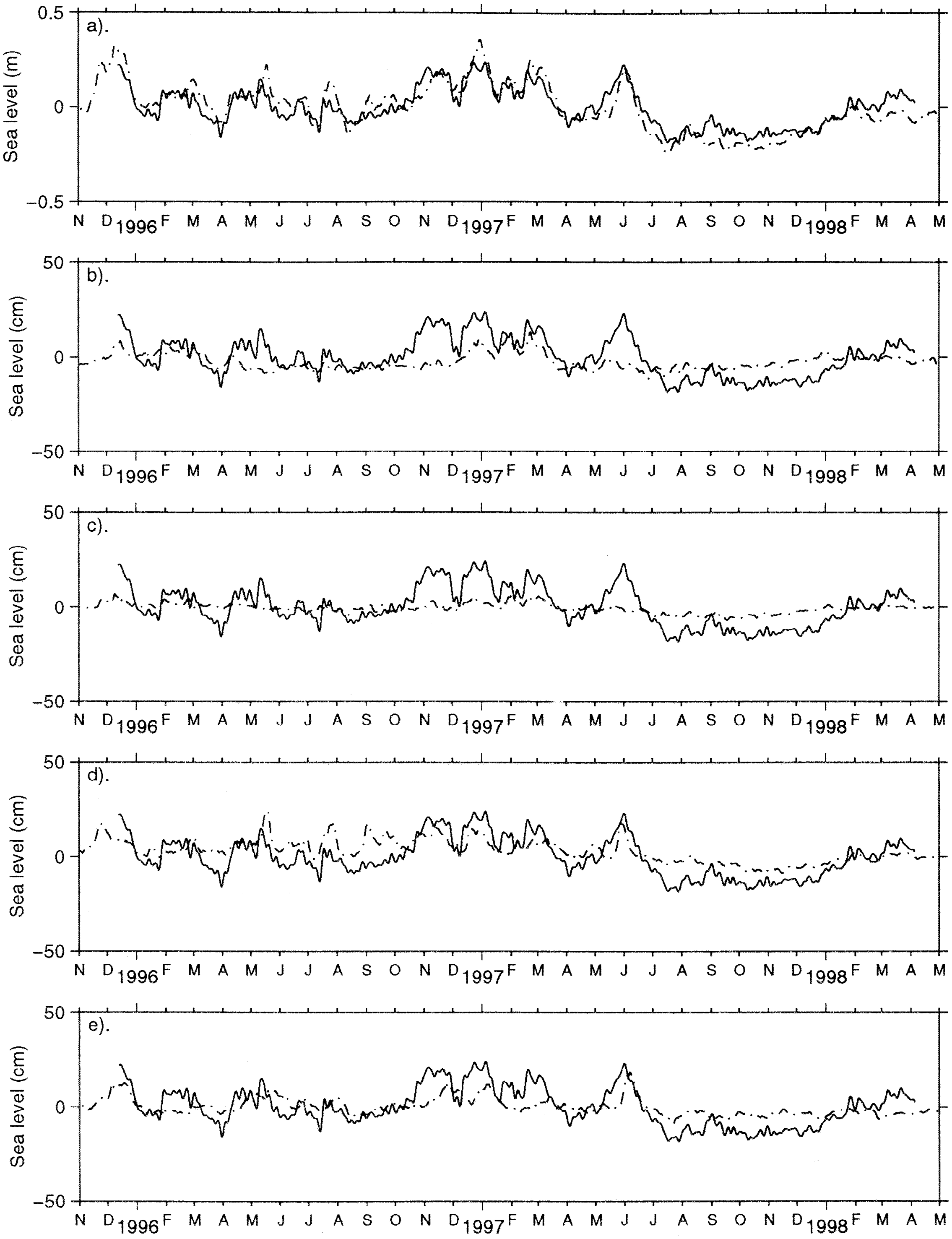

Figure 6. Sea level observed at the Bali pressure gauge in Lombok Strait (solid lines) and predicted by the analytical model (dot-dashed lines) forced by ECMWF daily wind stress following a path (a) from the western Indian Ocean, along the equator and along the Sumatra and Java coastlines, and to Lombok Strait, (b) along the coast from Sunda Strait to Bali, (c) along the coast from Sumatra to Sunda Strait, (d) along the equatorial Indian Ocean from 75°E to the coastline of Sumatra, and (e) along the equatorial Indian Ocean from 45° to 75°E.

(45°E), along the equator to Sumatra, and down the coasts of Sumatra and Java to the Bali pressure gauge site in Lombok Strait. As such, the predicted sea level at Bali will not only contain wind forcing from the western equatorial Indian Ocean but also contributions from regional and local wind forcing. To address this issue, we have separated the relative contributions to Bali sea level of the integrated wind stress into different sectors along the path: Sunda Strait to Bali (Figure 6b), coastal Sumatra (0°, 99°E) to Sunda Strait (Figure 6c), (0°, 75°E) to coastal Sumatra (0°, 99°E) (Figure 6d), and

(0°, 45°E) to (0°, 75°E) (Figure 6e). Clearly, Figures 6d-6e show that nearly all of the observed Bali sea level signals during the May 1997 event are related to remote wind forcing from the equatorial Indian Ocean. The highest covariance (42%) between the predicted and observed sea level at Bali is from the wind stress integrated following the sector from (0°, 75°E) eastward along the equator to Sumatra (Figure 6d). However, the covariance is also good (30%) for wind stress integrated for the sector along the equator from 45° to 75°E in the western equatorial Indian Ocean (Figure 6d). It is this latter sector's contribution that successfully predicts the duration of the May 1997 event as observed in Bali sea level.

Examining the daily ECMWF wind fields indicates that in late April, westerly winds started to develop along the equator across the entire Indian Ocean Basin. The westerly winds quickly intensified and by May 7 were strongest in the equatorial region between 75° and 85°E. The analytical model predicts that a Kelvin wave forced by the westerly wind at 75°-85°E, arrives at the Bali pressure gauge in 17 days. The timing and location of this westerly wind burst indicates that this is the forcing event responsible for generating the Kelvin wave observed within the Indonesian region (Figures 2-4); it was successfully captured by the analytical model (Figures 5-6). The ECMWF wind fields show that anomalously westerly winds also existed along the central Sumatra coastline and locally offshore of eastern Java from May 5 to 8, 1997. These local winds are most likely responsible for the upwelling event during this period, shown in the temperature and salinity fields at the SJC mooring, and are also evident in the relaxation in the Cilacap wind field (Figure 2). However, the model results using only local Java (Figure 6b) or regional Sumatra (Figure 6c) wind forcing suggest that the local or regional winds contribute little to the Bali sea level observed during the mid-May 1997 event. Figure 6b indicates that during other periods, such as January-March 1997, local forcing dominates, while during December 1995 and December 1996, both local and remote wind forcing are responsible for the peaks observed in the Bali sea level.

3.2. A Numerical General Circulation Model

Remote westerly wind forcing in the Indian Ocean was also examined using the reduced gravity, primitive equation, sigma-coordinate model of *Murtugudde et al.* [1998]. This model includes interactive upper ocean hydrology, with surface heat fluxes provided by coupling the ocean general circulation model (GCM) to an advective atmospheric mixed layer model. The model is forced by the National centers for Environmental

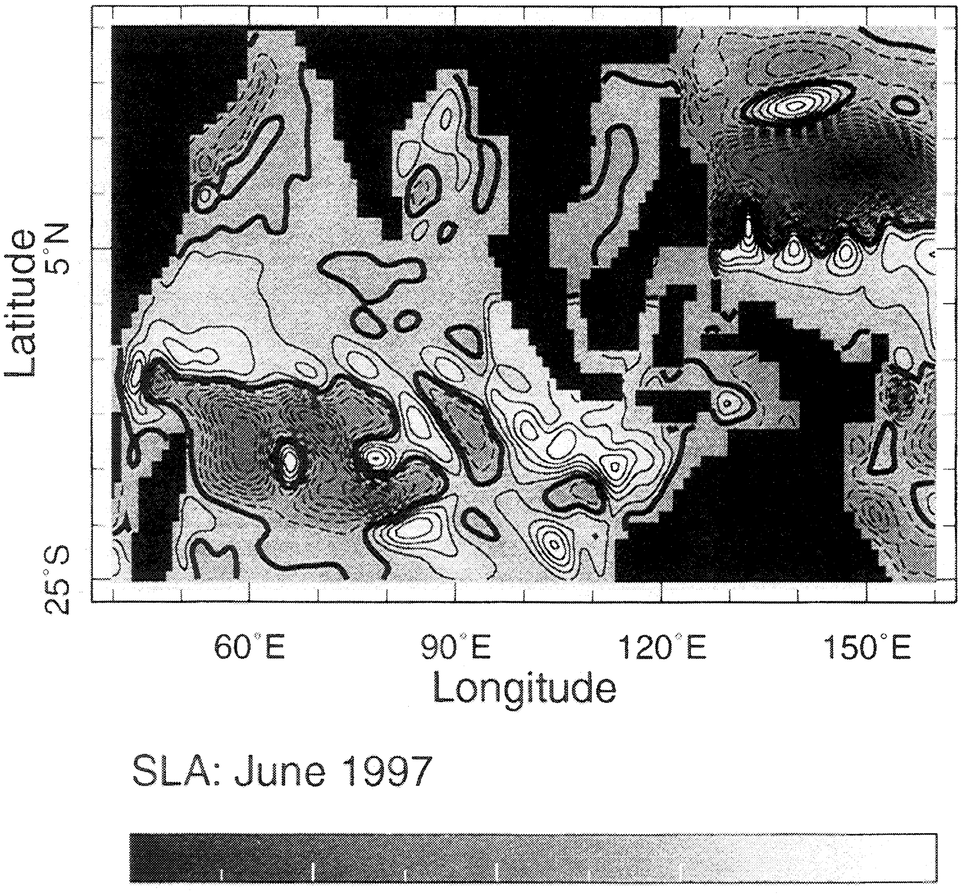

Figure 7. Sea level anomaly in the Indian Ocean for June 1997 for the model control run using real interannual wind forcing. Higher than normal sea level contours are indicated with solid lines and darker shading.

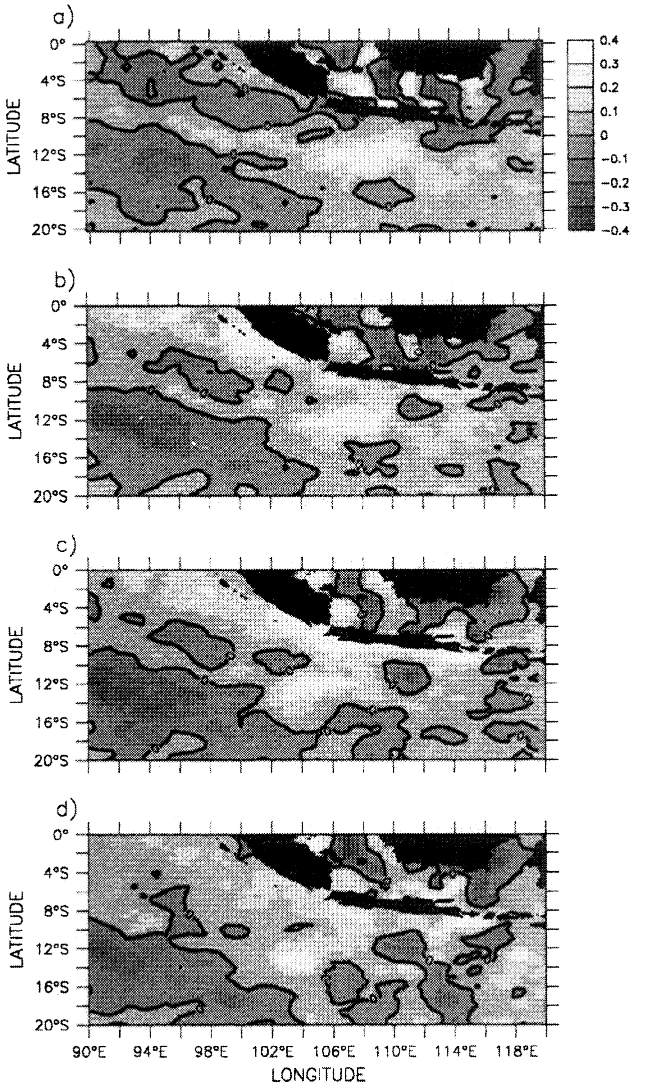

Figure 8. TOPEX/Poseidon altimetric sea surface height anomaly in the southeast Indian Ocean on (a) May 8, 1997, (b) May 18, 1997, (c) May 28, 1997, and (d) June 7, 1997. The zero contour is indicated with bold lines, and anonamously high sea level is indicated with light lines (key shown in Figure a).

Prediction (NCEP) reanalysis winds for the Indo-Pacific basin, and the control run was made from 1958 to 1998.

The anomalously high sea level felt throughout the eastern tropical Indian Ocean in June (Figure 7) is associated with the remotely forced Kelvin wave resulting from the early May westerly wind burst in the equatorial Indian Ocean. The June sea level field shows that the equatorial Kelvin wave has already struck the west Sumatra coastline, and two CTKWs are evidently propagating poleward on either side of the equator. The Southern Hemisphere CTKW that influences the Indonesian region has penetrated northward through Lombok Strait and up into Makassar Strait (Figure 7). We qualitatively compare this to the sea level anomaly as measured by the TOPEX/Poseidon satellite (Figure 8). The series of 10-day snapshots (the sampling cycle of the altimeter) for the Indonesian region shows the arrival of the anomalously high sea level associated with the downwelling Kelvin wave along the Sumatra coastline (Figures 8a-8b) and penetrating down toward the south Java coast. The next available snapshot, 10 days later on May 28, 1997 (Figure 8c), shows that the high sea level anomaly has propagated southeast along the south Java coast and farther east to Bali and the Nusa Tengarra island chain. The TOPEX/Poseidon fields do not show an anonymously high sea level in Makassar Strait during May 1997 (Figure 8), probably because the tidal model used in processing the altimeter measurements does not adequately model the strong tidal forcing that exists in this strait.

To examine the impact of the early May 1997 westerly wind burst and the subsequent generation of the Kelvin wave observed within the Indonesian region, we performed a GCM experiment where the Indian Ocean equatorial westerly wind burst was suppressed, although we allowed the rest of the Indo-Pacific basin to have real interannual winds (referred to as the WWB-OFF run). Figure 9 shows the difference in model sea level for June 1997 between the WWB-OFF run and the control run with the real interannual winds (Figure 7). Without the May 1997 westerly wind burst, no Kelvin wave is generated, and the sea level along the eastern Indian Ocean coastline and within the Indonesian region is lower by over 4 cm. The local winds within the Indonesian region (retained in both runs) are not sufficiently strong enough to produce the anonamously high sea level observed along the Sumatra and Java coasts in the TOPEX/Poseidon altimetric sea surface height shown in Figure 8. Figure 10 shows the differences in net heat flux for May 1997 between the WWB-OFF run and the control run with real wind forcing. Net fluxes into the ocean are larger in the Indonesian seas when the westerly wind burst is suppressed because the sea surface temperatures are cooler without the warm water advected by the downwelling Kelvin wave. The difference in model net heat flux occurs mostly due to a reduced latent heat loss, a function of the sea surface temperature.

Finally, we examine the impact of the May 1997 remote wind-forced Kelvin wave on Makassar Strait transport, which is also representative of most of the model's throughflow transport. With the control run that includes real interannual winds a local minimum exists in the Makassar Strait throughflow transport in May and June 1997 (Figure 11). The minimum in transport during this period agrees favorably with the reduction in southward transport observed at the Makassar Strait moorings during May 1997 [*Gordon and Susanto*, 1999]. This transport minimum is absent in the run where the early May 1997 westerly wind burst in the equatorial Indian Ocean has been turned off.

4. Dynamics Within the Indonesian Seas

How much of the energy from the Indian Ocean semiannual wind-forced Kelvin wave reaches the internal Indonesian seas? Theory suggests that once the equatorial Kelvin wave hits the Sumatra coastline at the equator, its energy will be partitioned into a reflected internal Rossby wave and two poleward propagating CTKWs along the Sumatra coastline. Using a linear model with one baroclinic mode, *Clarke* [1991] demonstrated that in the Indian Ocean, 90% of the energy and transport associated with the incoming equatorial Kelvin wave goes into the CTKWs. As noted, in the analytical model of section 3a describing the Kelvin wave appearance at the south Java mooring and in the sea level measured at Bali, energy is conserved along the entire path of integration between the western equatorial Indian Ocean and the instrument locations.

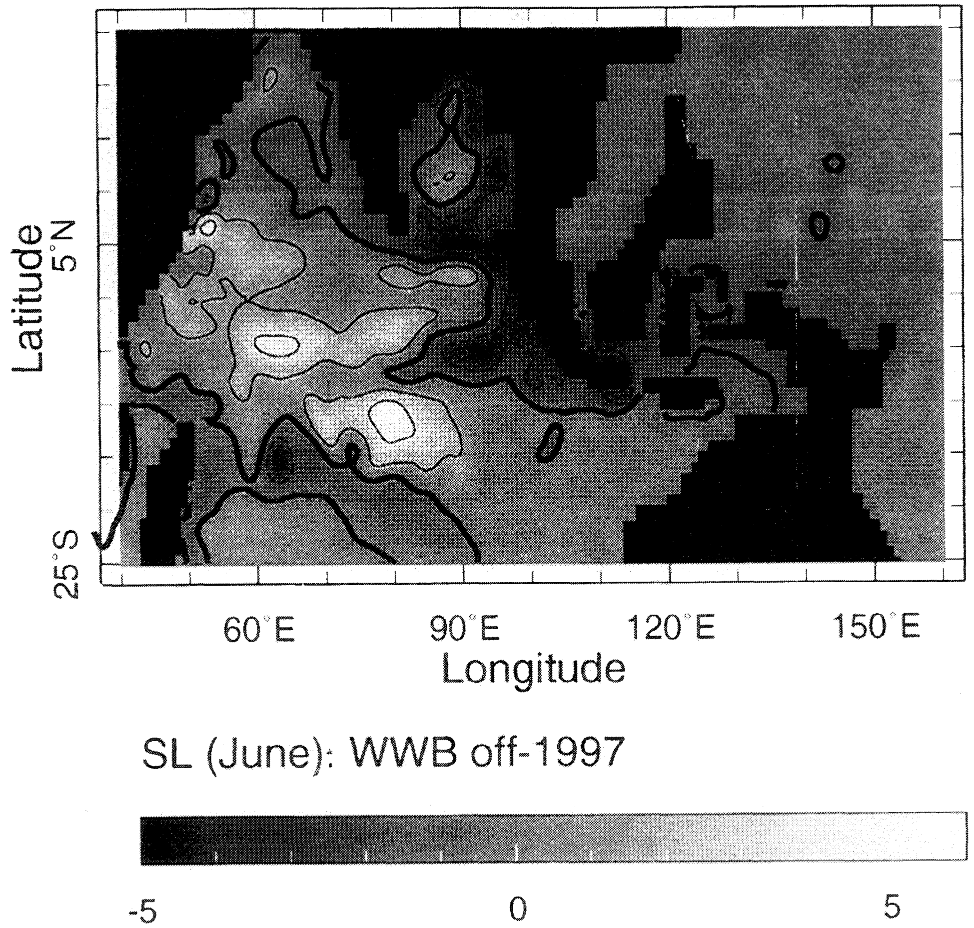

Figure 9. Difference in sea level in the Indian Ocean between the model runs that include the late April to early May 1997 westerly wind burst in the equatorial Indian Ocean and the model run where the wind burst has been suppressed (WWB-OFF run). The zero contour is indicated with bold lines.

That is, no energy is lost to a counterpart Northern Hemisphere CTKW along the Sumatra coastline nor to a reflected Rossby wave. This may in part explain why the analytical model's amplitude and duration of the May 1997 Kelvin wave event are greater and longer, respectively, particularly compared to the observed eastward velocity measured at the south Java mooring (Figure 5). The local coastal wind field may even further moderate the response, as discussed below. Nonetheless, the partitioning of the wind-forced response along the various sectors of the Kelvin wave path from the equatorial Indian Ocean to the Bali pressure gauge (Figure 6) demonstrates that the local wind field contributes little to sea level amplitude during the May 1997 event.

Once the remotely forced Kelvin wave reaches the south coast of Java, it can either follow the (gappy) coastal waveguide poleward around the southern Indonesian archipelago, or it can turn equatorward (northward) through Lombok Strait (see Figure 1). Along either pathway the action is against the mean Indonesian Throughflow. *Chong et al.* [2000] found that the energy in the semiannual spectral peaks of geostrophic velocity, inferred from the shallow pressure gauge measurements, is strongest in Lombok Strait but is only slightly less in Sumba Strait farther to the east and along the waveguide for a poleward moving Kelvin wave. The energy in the semiannual spectral band of the pressure gauge data does not appear to penetrate farther southeast along the poleward waveguide to Savu Strait and Timor Passage or eastward across the Savu Sea to Ombai Strait (see Figure 1 for locations). Interestingly, the pressure gauge geostrophic velocity time series [see *Chong et al.*, 2000, Figure 2] shows eastward flow through Sumba Strait from mid-May to early June 1997 and through Savu Strait in early June. Evidently, some of the wave signal from the May 1997 Kelvin wave bypasses the Lombok Strait gap and influences the flow in the downstream (poleward) straits. Unfortunately, the present state-of-the-art numerical models for the Indonesian Throughflow region cannot adequately resolve the width of these smaller straits and hence unambiguously determine the flow and impact of the Kelvin wave's poleward propagation. Typically, as in the *Murtugudde et al.* [1998] GCM coastal geometry shown in Figure 7, only the outflow passages of Lombok and Timor Straits are wide enough to be resolved. Certainly, Figure 7 indicates that the strongest of the GCM sea level signals within the Indonesian region associated with the semiannual May Kelvin wave event turned northward (and hence equatorward) through Lombok Strait, up into Makassar Strait, and into the Banda Sea. In addition, the timing of the observed

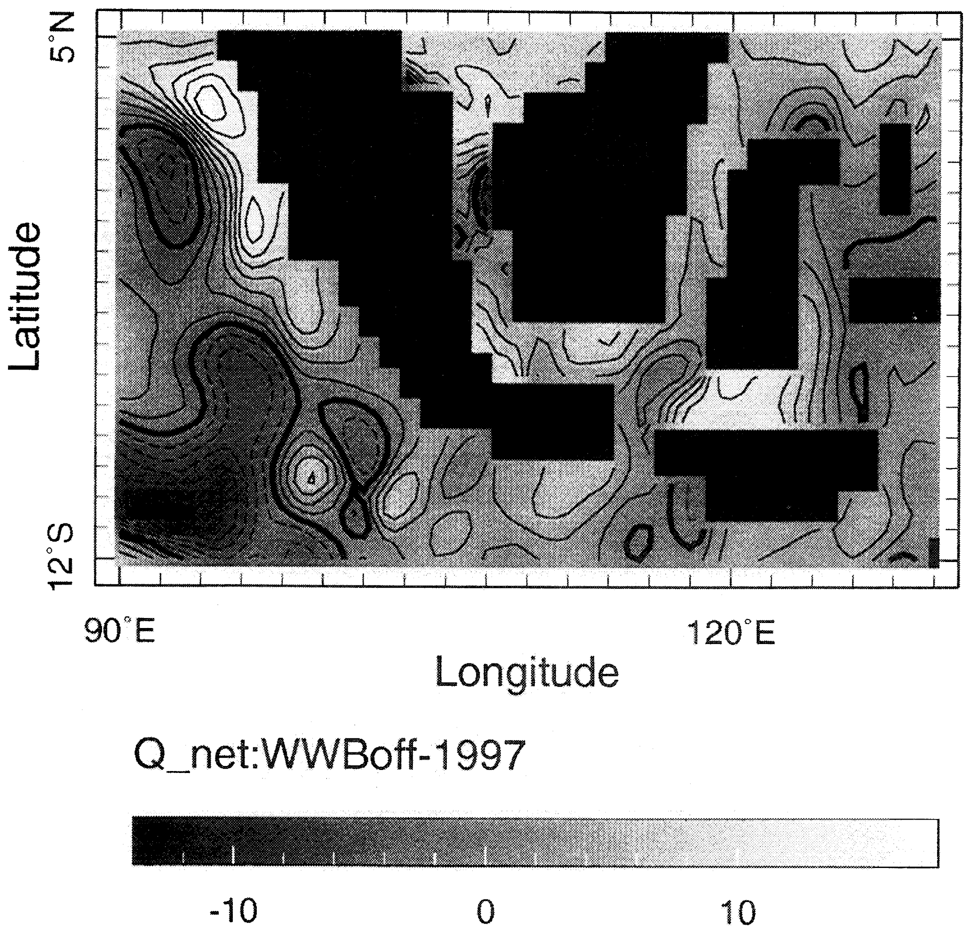

Figure 10. Differences in heat flux in the Indonesian region between the model runs that include the late April to early May 1997 westerly wind burst in the equatorial Indian Ocean and the model run where the wind burst has been suppressed (WWB-OFF run). The zero contour is indicated with bold lines.

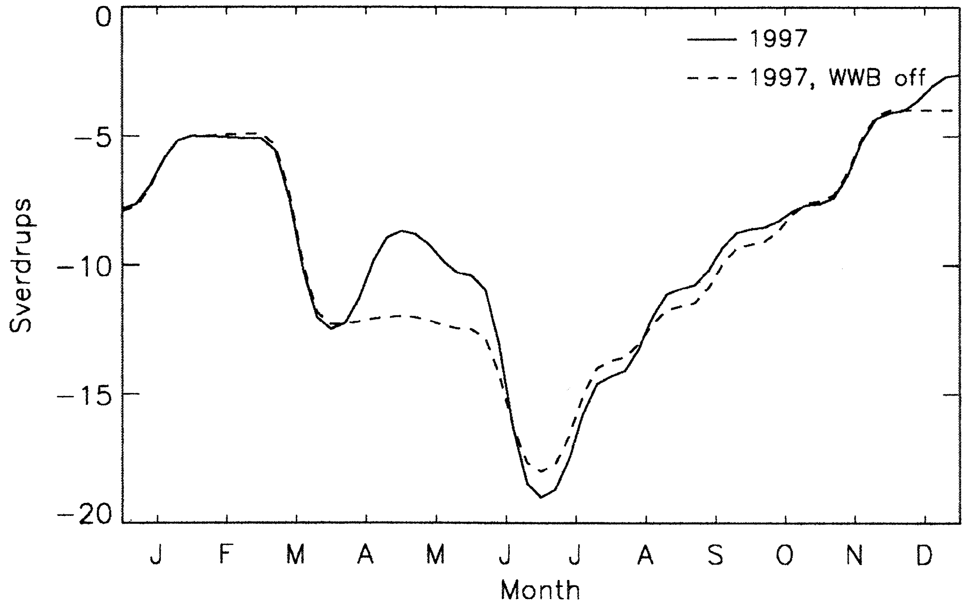

Figure 11. Makassar Strait throughflow for the model run including the westerly wind burst in the equatorial Indian Ocean in May (solid lines) and the model run where the wind burst has been suppressed (WWB-OFF run) (dashed line). Note that the WWB-OFF transport does not capture the relaxation in Makassar Strait transport during May-June 1997.

relaxation of currents and subsequent northward flow through Lombok Strait (Figure 3) and Makassar Strait (Figure 4) corroborates the equatorward pathway of at least some of the Kelvin wave signal observed in the mooring south of Java during May 1997. The reduction in the model's Makassar Strait transport induced by the early May equatorial Indian Ocean westerly wind burst (Figure 10) confirms that some of the Kelvin wave energy follows the equatorward path. These observations and model simulation results undeniably demonstrate that at times, remote Indian Ocean forcing can and does directly influence dynamics within the Indonesian internal seas.

The measurements of the May 1997 Kelvin wave event covered in this paper (April 15 to June 15, 1997) were collected during the strong 1997-1998 El Niño. Clearly, we should try and address the issue of whether the May 1997 event is a "typical" semiannual Kelvin wave event and/or whether it has been modulated by the record-breaking 1997-1998 El Niño that began in the Pacific Ocean in March 1997 [*Climate Prediction Center*, 1997]. Figure 12 shows the TOPEX/Poseidon sea level deviation along the equator in the Indian Ocean basin from late 1992 until early 1998. The higher sea level signal associated with the eastward propagating equatorial downwelling Kelvin wave forced by the semiannual westerly wind bursts is clearly seen in the time series, particularly during the April-May monsoon transition period. As suggested by *Wyrtki* [1973], the semiannual Kelvin wave sea level signal associated with the October/November monsoon transition is typically weaker (Figure 12). The altimetric high sea level anomaly that propagates eastward across the Indian Ocean basin associated with the May 1997 event is not remarkably different from the semiannual high sea level signal that exists during the April-May period of preceding years. This at least suggests that the May 1997 Kelvin wave is related to the expected semiannual westerly wind forcing that occured in late April-early May 1997, although it does not discount that the wind and the wave may have been modulated by the 1997-1998 El Niño. We note that the Kelvin wave sea level signal in April-May 1994 (Figure 12), a mild El Niño year, although still evident, is not as strong as other semiannual events. Interestingly, however, when the equatorial Indian Ocean April-May 1994 westerly wind burst was suppressed in the GCM of *Murtugudde et al.* [1998], the model was unable to reproduce an anomalous interannual throughflow transport event during 1994. Similarly, when the May 1997 westerly wind burst in the Indian Ocean was suppressed, the same model was unable to reproduce the observed relaxation in transport through Makassar Strait (Figure 11). During warm El Niño years the throughflow is expected to be lower than normal. The reversal in the Pacific Ocean tradewinds that occurs during the El Niño-Southern Oscillation (ENSO) reduces the pressure gradient between the Pacific and Indian Oceans thought to be the driving force for the throughflow on long timescales [*Wyrtki*, 1987]. It may be that the reduction in throughflow during ENSO years may render the Indonesian seas more vulnerable to upstream influences driven by Indian Ocean wind forcing. Both the 1994 and 1997 model results of Makassar Strait transport support this notion that the throughflow may have also been largely influenced by the Indian Ocean winds during these ENSO events. This is not to suggest that the internal Indonesian seas are only influenced by remote Indian Ocean forcing during ENSO events. However, the typically short record length of available observations within the Indonesian seas makes it difficult to verify the model results. Certainly, *Chong et al.* [2000] and *Gordon and Susanto* [1999] found transport through Lombok Strait and Makassar Strait, respectively, was lower during 1997 when compared to the previous year. Both of these straits were shown to have been directly impacted by the Kelvin wave forced by Indian Ocean westerly winds during May 1997 (Figures 3 and 4, respectively). Furthermore, *Chong et al.* [2000] observed northward fluctuations in geostrophic velocity through Lombok Strait during May 1996 (a typical year) and again in early June 1998 when La Niña conditions were developing. When the ENSO and annual signal is removed from the Makassar mooring velocity data (Figure 4), the minimum throughflow of the May 1997 event is still evident and balanced an anonamously large southward throughflow event in July 1997 [*Gordon et al.*, 1999]. This leads to a zero anomaly for the May-July 1997 period and suggests that this feature is directly related to the semiannual Indian Ocean wind-forced Kelvin wave event.

Of interest we note the lower sea level along the coast of Sumatra (Figure 12) during most of the latter part of 1997 and early 1998 when the El Niño event was in full swing. After the May 1997 equatorial Indian Ocean westerly wind burst, wind stress was strongly anonamously eastward in the equatorial central Indian Ocean during the rest of 1997 in response to an El Niño-related shift in the Walker Cell circulation [*Yu and Rienecker*, 1999]. No westerly wind burst was observed during the October/November 1997 monsoon transition in the equatorial Indian Ocean; subsequently, no semiannual downwelling Kelvin wave was generated, and no northward flow was observed in geostrophic velocity through Lombok Strait at this time [see *Chong et al.*, 2000, Figure 2].

Finally, local monsoonal wind forcing may also modulate the impact of the semiannual Kelvin wave in terms of throughflow variability and dynamics within the Indonesian seas. Northwesterly local wind forcing along the Java and Sumatra coastlines would lead to onshore coastal downwelling and increase the sea surface height along these coasts with a signal similar to the downwelling coastally trapped Kelvin wave. Possibly, the higher sea level observed in the time series of TOPEX/Poseidon altimetric data along the equator off the coast of Sumatra (Figure 12) during the semiannual Kelvin wave events may be enhanced through favorable local wind forcing. Alternatively, the amplification in sea level here may simply be a result of the pileup of water from the force of the eastward downwelling Kelvin waves accumulating at the west Sumatra coast. In addition, the equatorial shoaling of the thermocline from west to east in the Indian Ocean will act to increase the amplitude of the downwelling Kelvin wave, also raising the sea level signal at the west Sumatra coast. We again invoke Figures 6b-6c to show that local and regional wind forcing does not account for the higher sea level observed at Bali coinciding with the passage of the May 1997 Kelvin wave through Lombok Strait. The attenuation in the duration and amplitude of the eastward currents in the SJC at the end of May 1997, when compared to the analytically predicted features of the Kelvin wave (Figure 5) may, however, be partially attributed to the strengthening of the local south-easterly monsoonal winds inducing upwelling at this time. (It may also be partially attributed to the model deficiencies as discussed above.) This agrees with the modeling work of *Potemra* [1999], who suggests that the April/May semiannual Kelvin

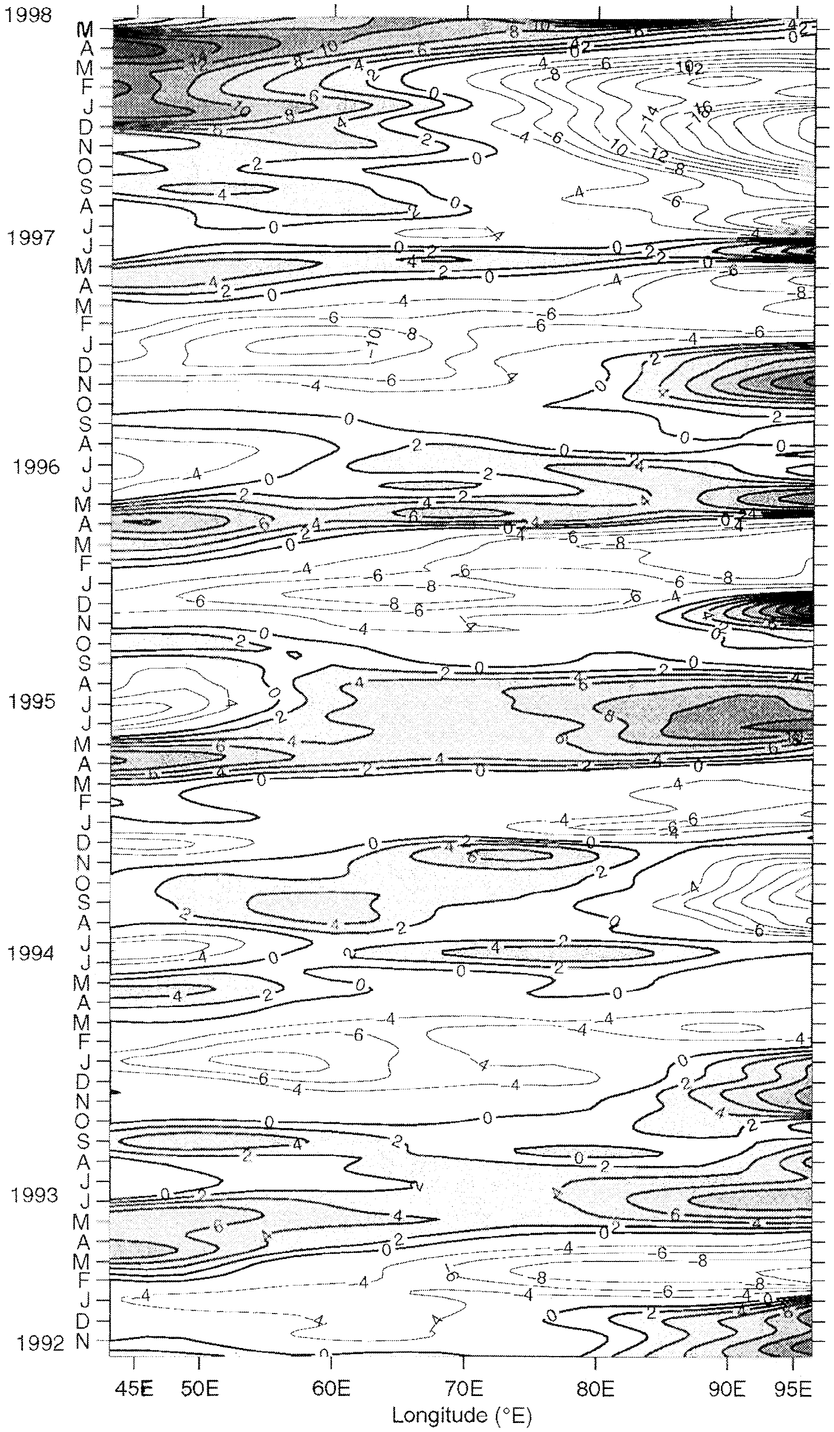

Figure 12. Time-longitude sections of sea surface height anomaly (centimeters) from the TOPEX/Poseidon altimeter (10-day interval) along the equator in the Indian Ocean. The sea surface height anomalies are deviations from the 1992-1998 base period mean. Positive sea surface height anomalies are shaded.

wave halts near Bali in the presence of local easterly windforcing of the opposite sign. Furthermore, *Murtugudde et al.* [2000] found a high correlation between thermocline depth anomaly and the sea surface temperature anomaly occurring off the Java coast after the May 1997 event. They suggest that this is where the coupled interactions that resulted in the late 1997-1998 anomalous Indian Ocean conditions originated. In Makassar Strait, ECMWF wind data indicate that the southeasterly winds began in mid-May 1997. In this case the direction of the winds within the channel may enhance the Kelvin wave as it passes through Lombok Strait and upstream to Makassar Strait. However, the relaxation in currents and transport through Makassar Strait in middle to late May 1997 is not wholly due to local wind forcing as the timing in the propagation of the Kelvin wave can be directly traced from the Indian Ocean via the SJC and up through Lombok Strait. Indeed, the strongest local southeasterly wind forcing in Makassar Strait occurs during July-September when southward flow has returned to the channel [*Gordon and Susanto,* 1999].

5. Summary and Conclusions

A unique set of timely observations from the exit passages and within the internal Indonesian seas document the passage of a Kelvin wave in May 1997. The semiannual Kelvin wave was remotely forced by a westerly wind burst that occurred in the first week of May 1997 in the equatorial Indian Ocean during the transition from the northwest monsoon to the southeast monsoon. The highly temporally resolved measurements presented in this paper enable us to determine accurately the timing of the incoming Kelvin wave and to follow its path and impact within the Indonesian region. First, a strong reversal of currents was observed in a mooring located off the south coast of Java beginning in mid-May 1997. The southeastward flow was composed of warm water with a freshwater cap and saltier water at depth, consistent with characteristics of an Indian Ocean source. Within 1-2 days of the current reversal, northward geostrophic flow was inferred from pressure gauges that span Lombok Strait, the first "entrance" to the internal seas to the east of the south Java mooring location. Similarly, two moorings located downstream of the Kelvin wave path in Makassar Strait showed northward flow at some depths with a substantial relaxation of the throughflow transport occurring from mid-May through early June 1997. Using a simple analytical model and the numerical GCM of *Murtugudde et al.* [1998], the timing and response of these measurements were attributed to the passage of a southward propagating, coastally trapped Kelvin wave generated via an equatorial Kelvin wave impinging the west Sumatra coast at the equator. Local wind forcing did not substantially contribute the higher Bali sea level observed during the Kelvin wave passage. Whether this May 1997 Kelvin wave was influenced by the strong El Niño conditions that existed during 1997-1998 cannot satisfactorily be addressed as comprehensive observational data sets that would enable a comparison with typical conditions are not available in the region. Ongoing measurement programs within the Indonesian seas, such as the Shallow Pressure Gauge Array [*Chong et al.*, 2000] and the Arlindo programs [e.g., *Gordon et al.*, 1999], should possibly document the passage of other semiannual forced Kelvin waves notably occurring under the 1998-1999 La Niña conditions.

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