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Intraseasonal Variability and Tides in Makassar Strait

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Abstract. Intraseasonal variability and tides along the Makassar Strait, the major route of Indonesian throughflow, are investigated using spectral and time-frequency analyses which are applied to sea level, wind and mooring data. Semidiurnal and diurnal tides are dominant features, with higher (lower) semidiurnal (diurnal) energy in the north compared to the south. Sea levels and mooring data display intraseasonal variability which are probably a response to remotely forced Kelvin waves from the Indian Ocean through Lombok Strait and to Rossby waves from the Pacific Ocean. Sea levels in Tarakan and Balikpapan and Makassar mooring velocities reveal intraseasonal features with periods of 48-62 days associated with Rossby waves from the Sulawesi Sea. Kelvin wave features with periods of 67-100 days are seen in Bali (Lombok Strait), at the mooring sites and in Balikpapan, however, they are not seen in Tarakan, which implies that these waves diminish after passing through the Makassar Strait.

1. Introduction

As part of the USA/Indonesian Arlindo Program, two current meter moorings, MAK-1 and MAK-2 were deployed within the approximately 2000m deep, 45km wide Labani Channel of Makassar Strait. *Gordon and Susanto* [1999] and *Gordon et al.*, [1999] report that the 1997 average throughflow in Makassar Strait is 9.3 Sv, with a range of about 2.5 Sv depending on how the surface flow is taken into account. Modulation of the transport by the 1997-98 ENSO event is apparent. Makassar Strait currents also display significant tidal and intraseasonal variability, defined as non-tidal oscillations with characteristic periods of less than 100 days.

Intraseasonal variability has been previously documented in the Indonesian region. *Kashino et al.* [1999], using current measurements in the easternmost Sulawesi Sea, find intraseasonal events with 50-60 day timescales that are possibly due to nonlinear waves derived from the Mindanao and Halmahera Eddies and Madden-Julian Oscillation (MJO). The *Qiu et al.* [1999] model study finds that intra-seasonal variability within Makassar Strait may be derived from Pacific Ocean Rossby waves and Indian Ocean Kelvin waves. They suggest that the 50 day Rossby mode in the Sulawesi Sea matches with Mindanao Eddy shedding from the Mindanao Current. In addition, they find that intraseasonal oscillations with periods of 50-85 days along the Indian Ocean coasts of Java and Sumatra are coastally trapped Kelvin waves. The Indian Ocean Kelvin waves are generated in the equatorial Indian Ocean by atmospheric fluctuations [*Murtugudde*, 1998; *Qiu et al.*, 1999; *Potemra*, 1999], becoming coastally trapped Kelvin waves when they reach the coast of Sumatra. *Arief and Murray* [1996] found that intraseasonal fluctuations with a period of 40-60 days in the transport through Lombok Strait are largely driven by baroclinic coastally trapped Kelvin waves observed in sea level at Cilacap, on the southern coast of Java. *Potemra* [1999] model study shows these coastally trapped Kelvin affects the Indonesian throughflow by modifying sea level along the coasts of Sumatra and Java. *Bray et al.* [1997] have detected transient features within the Indo-Australian basin at the 60 day period.

In summary, Rossby waves with periods of 40-60 days may be expected to enter the Sulawesi Sea, due to eddy shedding of the Mindanao Current, and Kelvin waves from the Indian Ocean with periods of 60-100 days, may be expected to enter the Indonesian Seas through the Sunda Island passages. The 60 day separation may not be precise, and some overlap in period of the two wave types may exist, but in general the Rossby waves are expected to be of shorter period than the Kelvin waves.

2. Objectives, Data and Methods

The objective of this paper is to explore the characteristics of the intraseasonal variability and tides within the Makassar Strait, the main route of the Indonesian throughflow. We use data from the following sources (Fig.1): (1) hourly current meter data from two moorings in Makassar Strait; (2) sea level data from hourly tide gauges at Tarakan and Balikpapan courtesy of BAKOSURTANAL (Indonesian Survey and Mapping Agency);

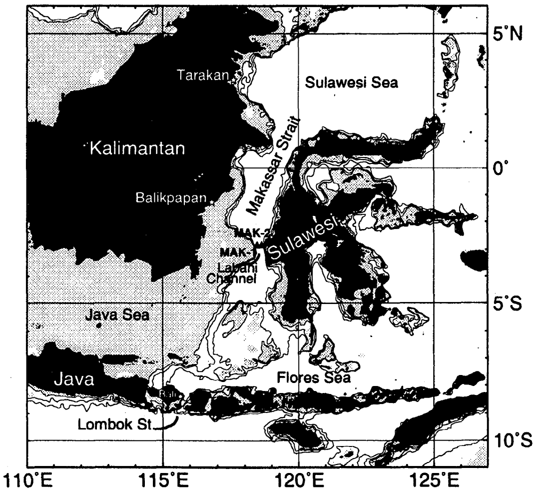

Figure 1. The position (black solid triangles) of the 1996-1998 moorings in Makassar Strait, MAK-1 (2° 51.69' S); 118° 27.51' E) and MAK-2 (2 ° 51.24 S; 118 ° 37.69' E). White stars mark the positions of tide gauges (Tarakan and Balikpapan) and shallow pressure gauge in Bali. Shading delineated water depth of less than 200m.

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hourly data from a shallow pressure gauge at the northeast tip of Bali; and from TOPEX/Poseidon (T/P), 10-day repeat cycle sea surface height anomaly data provided by the NOAA Geoscience Laboratory for October 1992 to May 1998, along the descending track near the MAK mooring locations; (3) Weekly wind data from the European Remote Sensing Satellite (ERS) scatterometer sensor provided by IFREMER from October 1992 to May 1998.

We apply the Hilbert-Huang Transform method [HHT; *Huang et al.* 1998] to present the time-frequency-energy distributions at tidal and intraseasonal scales. HHT has the advantage over spectral analysis in that it gives the frequencies that exist over the entire duration of the data set by investigating predominant frequencies at a particular time. We present the HHT spectrogram (time-frequency-energy plot) and the spectral analysis spectrum of the corresponding signal on the same figure (Figs. 2-4). The higher (lower) energy the darker (lighter) in the spectrogram. The spectrum is the summation of energy at certain frequencies for the whole time series. A monochromatic, linear and periodic signal shows up as a horizontal line in the HHT spectrogram and a single peak in the spectrum; a nonlinear and nonperiodic phenomenon forms a wavy, irregular line in the HHT spectrogram and a broad peak in the spectrum.

3. Results and Discussion

3. 1. Tidal Frequencies

From the spectrogram and spectrum of tide gauge data (Fig. 2a,b), the dominant tides are semidiurnal tides at the Tarakan and Balikpapan tide gauge sites. The spectrogram shows a straight line along narrow band frequencies, representing superposition of some tidal components with a mean frequency of 2.0 cycle/day (cpd) for the whole time series. These spectrograms suggest that the tidal characteristics in these areas are linear and periodic. The Bali pressure gauge spectrogram and spectrum reveal predominantly linear and periodic diurnal tides (Fig. 2c). The narrow band frequencies reveal superposition of some tidal components with mean frequency of 1 cpd.

At the MAK-1 mooring site, mixed tides occur between the diurnal and semidiurnal regimes (Fig. 2d,e). The current meter at 200m (Fig. 2d) and the 250m, 350m and 750m instruments (not shown), includes some non-tidal energy at high frequency. It is likely that this is a product of local wind and internal waves, which are not dealt with in this study. The deepest current meter at 1500m (Fig. 2e), located in the more homogeneous stratification of the Makassar Strait (below the southern Makassar sill depth), reveals a much purer tidal signal. The diurnal and semidiurnal tides are linear and periodic. The interplay between multiple semidiurnal and diurnal components induce strong fortnightly tides, characteristic of the Indonesian Seas [*Ffield and Gordon*, 1996]. The fortnightly tide can be seen in from the spectrogram of the semidiurnal and diurnal tidal components of tide gauge and MAK data, showing an intermittent signal of the energy every 14 days (white-black-white). Similar to semidiurnal and diurnal tides, the fortnightly tide is also linear and periodic.

3. 2. Intraseasonal Frequencies

3.2.1. Wind and Sea Level. From the spectrogram and spectrum of the meridional wind speed at the MAK mooring site (Fig. 3a), one can clearly see intraseasonal and seasonal oscillations. The intraseasonal signals split into two frequencies with a period 22-28 days and 35-55 days. These results are consistent with the *Webster et al.* [1998] observations of wind and precipitation variability on 20-30 day timescales. The 35-55 day oscillations are probably due to MJO influences over the Makassar Strait. The lower frequency of the spectrogram shows seasonal features, with wind speed increasing during the north monsoon (October to April). The T/P 10 day repeat cycle displays intraseasonal oscillations with peak energy between 60-68 days (Fig. 4b). T/P signals could be aliased with a period of 60 days due to strong tidal S2 and M2 components in this region [*Marshall*, 1996]. However, the Tarakan tide gauge displays a small peak at 62 days, and both the Balikpapan tide gauge and mooring data reveal energy in the 60-68 day band, thus the T/P peak may not entirely be a product of aliasing.

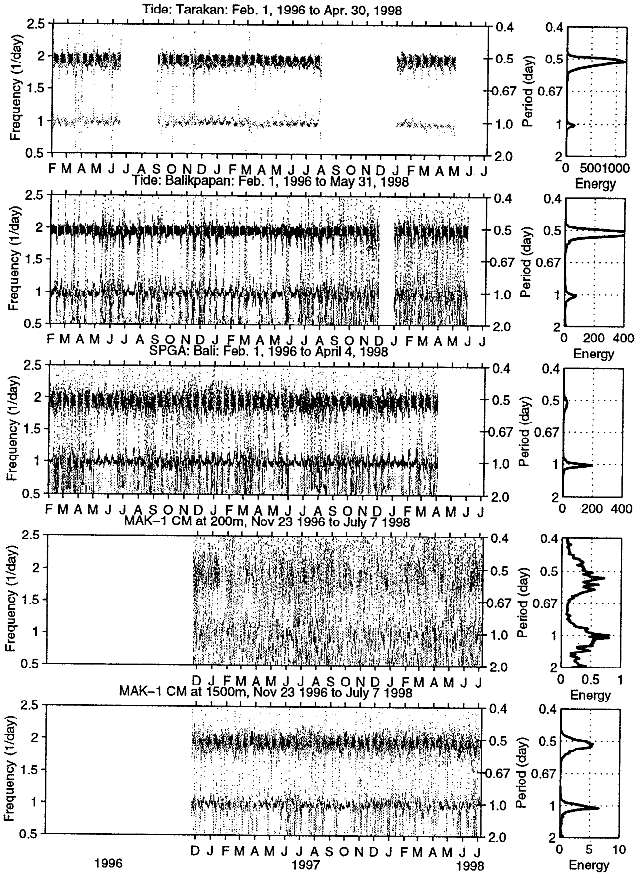

Figure 2. The spectrogram (time-frequency-energy distributions) and spectrum at tidal frequency of sea level tide gauges (a) Tarakan and (b) Balikpapan; (c) shallow pressure gauge in Bali; along channel speeds of current meter at (d) 200m and (e) 1500m of MAK-1. The linearity and periodicity of strong semidiurnal, diurnal tides and fortnightly tide modulation are clearly seen.

Nonlinear and nonperiodic intraseasonal oscillations with mean wave periods of 22 - 26 days, and 62 days are clearly seen in the spectrogram and spectrum of Tarakan sea level (Fig. 3c). Because of nonlinear and nonperiodic, the intraseasonal feature has a frequency changing in time, manifested as an irregular/ discontinuous and wavy line in the spectrogram. The higher frequency peaks may be due to wind forcing, while the lower frequency peaks are most likely due to Rossby waves. Regional wind data exhibits similar peaks to the higher frequency signals, while the lower frequency peaks approximate Rossby periods observed in the Sulawesi Sea [*Kashino et al.*, 1999 and *Qiu et al.*, 1999]. The spectrogram shows that this feature is present from

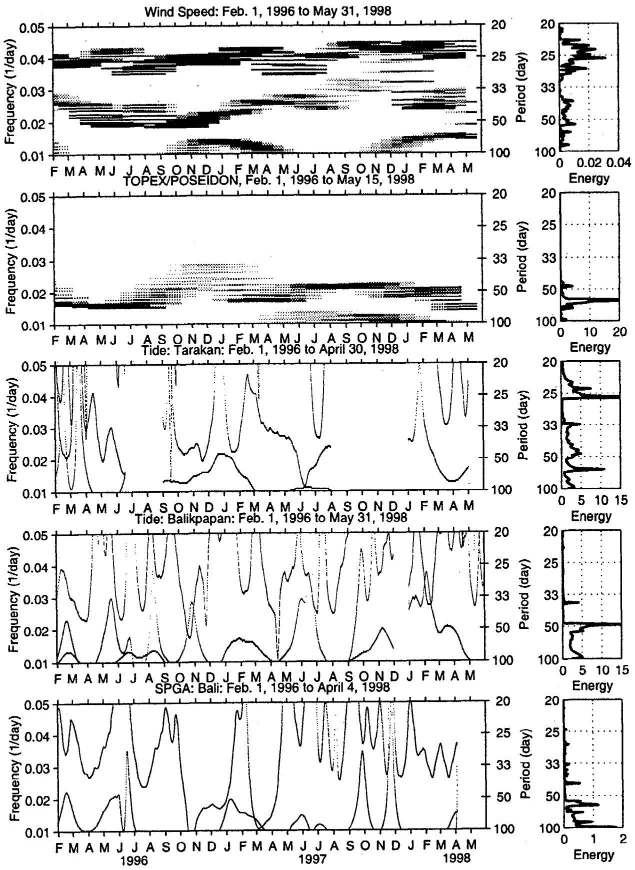

Figure 3. The spectrogram (time-frequency-energy distributions) and spectrum at intraseasonal frequency of (a) weekly meridional ERS wind speed at the mooring site; (b) 10-day TOPEX/Poseidon sea surface height anomaly; sea level tide gauges (c) Tarakan and (d) Balikpapan; (e) the shallow pressure gauge in Bali.

September 1996 to March 1997. Unfortunately, there is a data gap between September 1997 and January 1998, making determination of the annual cycle impossible.

Time-frequency and spectrum analyses of Balikpapan sea level (Fig. 3d) reveal intraseasonal oscillations with wave periods of 48-55 days and 85-100 days with the strongest peak energy at 48 days. From the spectrogram, these features are apparent during February-March 1996; June 1996 to April 1997; and September to December 1997. At Bali, intraseasonal oscillations with periods of 54-100 days are evident (Fig. 3e). The spectrogram shows intraseasonal features between February to June 1996; November 1996 to March 1997; and May to June 1997. These oscillations are probably due to remotely forced coastal Kelvin waves along the Sumatra/Java coast entering the Lombok Strait [*Arief and Murray*, 1996; *Potemra*, 1999; *Qiu et al.*, 1999; and *Sprintall et al.* 2000]. From the spectrum, there is no clear evidence of shorter period (< 50 days) events, suggesting that Rossby waves from the Pacific do not pass through Lombok Strait. Numerical modeling results [*Qiu et al.*, 1999] support this evidence. They show that Rossby waves after passing through Makassar Strait turn eastward within the Flores Sea.

Tarakan sea level data does not reveal intraseasonal features at the 70-100 day period, which suggests that either Kelvin waves from the south do not cross the equator to enter the Sulawesi Sea, or their amplitude diminish significantly. Balikpapan frequencies do not match the frequencies from the north (Tarakan) or from the south (Bali), which suggests modification of the transient features as they travel into the narrow Makassar Strait. This is possibly related to nonlinear interactions between reflected/transmitted Rossby wave signals entering the Sulawesi Sea from the Pacific and Kelvin waves from the Indian Ocean through Lombok Strait and friction within the variable width of Makassar Strait.

3.2.2. MAK currents. Both the spectrogram and spectrum of MAK moorings within thermocline depth (300m) and below thermocline depth (450m) display nonlinear and nonperiodic intraseasonal signals (Fig. 4). Intraseasonal oscillation with a wave period between 45-100 days is clearly seen at both moorings. Energy within the longer periods increases with depth. From the MAK-1 mooring at 450m depth, separation is evident between two intraseasonal oscillations with wave periods between 35-60 days and 70-100 days. The first band is probably associated with incoming Rossby waves from the Sulawesi Sea, while the second represents incoming Kelvin waves from the south (Lombok Strait).

4. Conclusions

This study provides a first look at the Hilbert-Huang Transform (HHT) analysis of tidal and intraseasonal features along Makassar Strait. A more detailed analysis will follow. Both spectrogram and spectrum analyses of MAK current meter

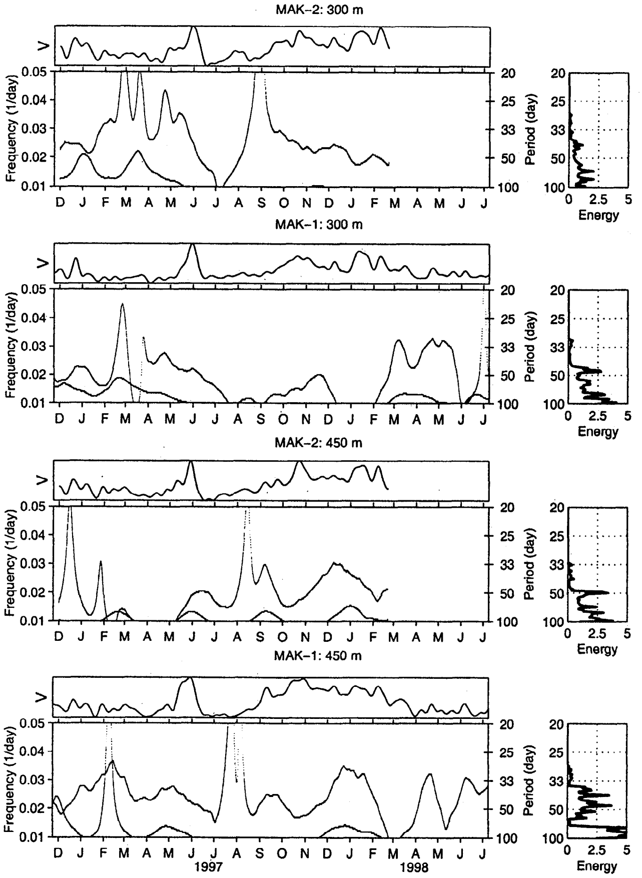

Figure 4. The intraseasonal time series, spectrogram (time-frequency-energy distributions), and spectrum of along channel speed of current meter of MAK-1 and MAK-2 at 300m and 450m depths.

moorings and sea level at Tarakan, Balikpapan, and Bali reveal the intraseasonal signals probably associated with Rossby waves entering Sulawesi Sea, and Kelvin waves passing through Lombok Strait from the Indian Ocean. Kelvin waves diminish after passing through the Makassar Strait, while Rossby waves probably turn eastward within the Flores Sea, after passing the Makassar Strait. As with the spectrogram of sea level at Tarakan, Balikpapan and Bali, the higher frequency oscillations are more sporadic compared to the lower frequency features. One reason for this is the doppler shift between the Rossby wave speeds and current through the Makassar Strait, where both speeds have the same order of amplitude. In addition, the thermocline depth in Makassar Strait may change through ENSO variability [*Ffield et al.*, 1999], thus changing the Rossby radius of deformation and affecting the Rossby wave speed. Moreover, the Kelvin wave propagation speed is much higher than that of the Makassar current, therefore the lower intraseasonal frequency features are more consistent in terms of frequency variability. Nonlinear interaction between these waves in Makassar Strait may occur, making it difficult to interpret the results.

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