Comparison of Observations and Numerical Model Results in the Indonesian Throughflow Region

Stephen P. MURRAY[(1)], John KINDLE[(2)],
Dharma ARIEF[(1)] and Harley HURLBURT[(2)]

[(1)]*Coastal Studies Institute and Department of Geology and Geophysics, Louisiana State University, Baton Rouge, Louisiana 70803 - U.S.A.*
[(2)]*Naval Oceanographic Research and Development Activity, Code 323, Bay St. Louis, Mississippi 39529 - U.S.A.*

ABSTRACT

Observations of currents, transport, sea level, and sea level slope in Lombok Strait and west Flores Sea in 1985 and 1986 have been compared to a simulation of the NORDA global ocean model in the Indonesian throughflow region. Despite the relatively coarse grid scale of the model compared to topographic length scales in the region, the model appears to be realistically reproducing many of the observed features. The predicted transport through the Lombok Strait, for example, agrees with detailed observations of phase and magnitude, especially when corrected for grid size limitations. The sea surface fluctuations and sea surface slopes predicted by the model agree within less than a factor of 1.5 with sea level changes and slopes observed on tide gauges. There do appear to be several cases of phase difference of several months between model and observations that require further investigation.

1. Introduction

The importance of a net transport of mass, heat, and salt from the Pacific Ocean to the Indian Ocean through the Indonesian archipelago is now well recognized. Present estimates of the magnitude of the net transport (popularly referred to as the Indonesian throughflow) by various indirect methods vary greatly, from 1.5 to 20 Sv (1 Sv = 10^6 $m^3.s^{-1}$) (Cox, 1982; Fine, 1985; Fu, 1986; Godfrey, 1981; Piola, and Gordon, 1984; Wyrtki, 1961). For a general review, see Gordon and Golding (1986). It has been generally assumed that the throughflow is concentrated in the wide, deep passages bracketing Timor. The first direct observations of the throughflow, however, were taken in the Lombok Strait, presumably of secondary importance to the Timor passages on the basis of cross-sectional area. These observations (Murray and Dharma Arief, 1986) showed a net Indian Ocean-directed transport reaching 4 Sv in August 1985 with a 1985 annual average of 1.7 Sv. Extrapolating these results solely on the basis of cross-sectional area above the 200-m depth level suggests a total throughflow of 10-12 Sv. There could, however, be considerable differences between the pressure gradients driving the flows in the Lombok and Timor areas.

Recently Wyrtki (1987), using sea level data from Davao and Darwin and dynamic height data from the areas south of Mindanao and south of Java, showed that the strong pressure gradient between the Pacific and Indian oceans is concentrated in the upper 200 m. Interannual variations of the sea level differences agree well with the throughflow transport predicted by the NORDA wind-driven numerical model (Kindle et al., 1987).

The initial NORDA numerical model (Kindle et al., 1987) did not include the Lombok Strait, but the results in (Murray and Dharma Arief, 1986) instigated its inclusion in the updated version discussed here. The objective of this paper is a comparison and evaluation between current and sea-level observations made in the Lombok Strait and west Flores Sea in 1985-1986 and the model results.

2. Observational program

In order to understand the processes controlling circulation in the Lombok Strait and adjacent sectors of the Java and Flores Seas (see Fig. 1), field work and data collection were conducted from January 1985 to March 1986. Seven current moorings were deployed, five in the Lombok Strait and two in the bathymetric trough (in the western Flores Sea) linking the Makassar Strait outflow to the Lombok Strait. More than 120 current meter months of data were collected. A total of 234 CTD casts were taken in the Lombok Strait, its Indian Ocean approaches, and the western Flores Sea extending as far north as the Makassar Strait and east into the Flores Sea to 119°E. Thirty-four meter months of sea level (pressure gauge) data were taken in the Strait and at the Makassar trough mooring site. Data on the regional sea level during our observations were collected from tide gauges in the Philippines and northwest Australia courtesy of Klaus Wyrtki, University of Hawaii, and the Flinders Tidal Observatory, Australia.

The annual cycle of current velocity in the Lombok Strait is best shown from the data obtained at the 35-m depth level at site 2 (Fig. 2). The period January 10 through February 15, 1985, was characterized by persistent strong southerly flows reaching 60 cm.s^{-1} in late January. Large flow reversals to the north through most of February and again in late April appear closely controlled by tropical cyclone activity in the Timor Sea (Murray and Dharma Arief, 1986). Southward currents increase in magnitude from May through July, reaching peaks of 90 cm.s^{-1} in August and September at the height of the Southeastern Monsoon. Late October through December 1985 is a period of weak flow with distinct northward flow reversals in early December 1985 and a strong reversal in January 1986. Monthly block average values from all the current meter data at sites 1 and 2 are used in reference (Murray and Dharma Arief, 1988) to compute the annual transport cycle discussed earlier.

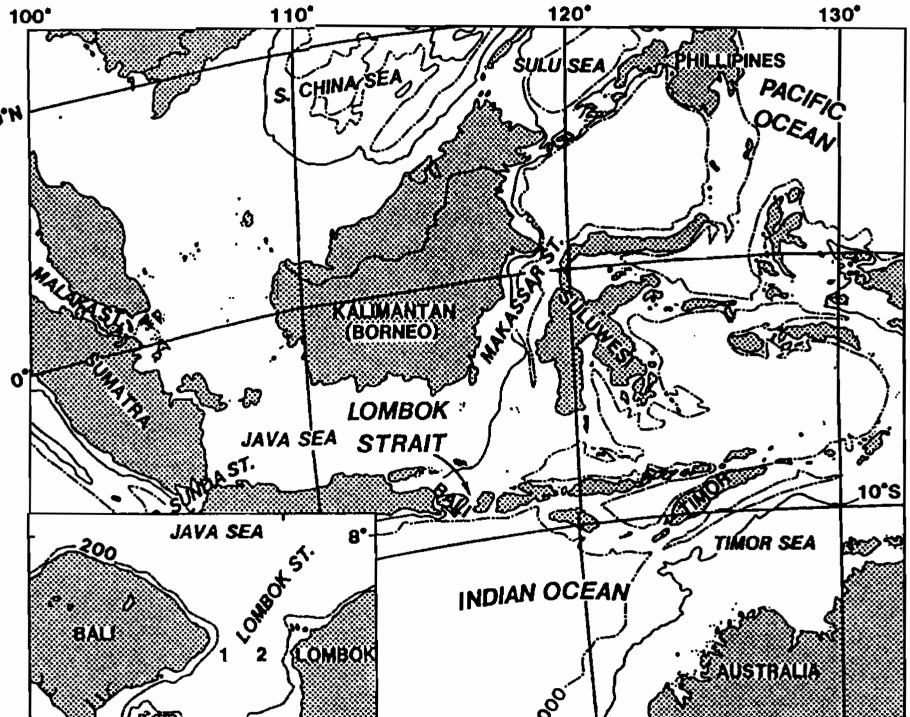

FIG.1. Map of the Indo-Pacific convergence zone with an inset showing mooring sites in the Lombok Strait

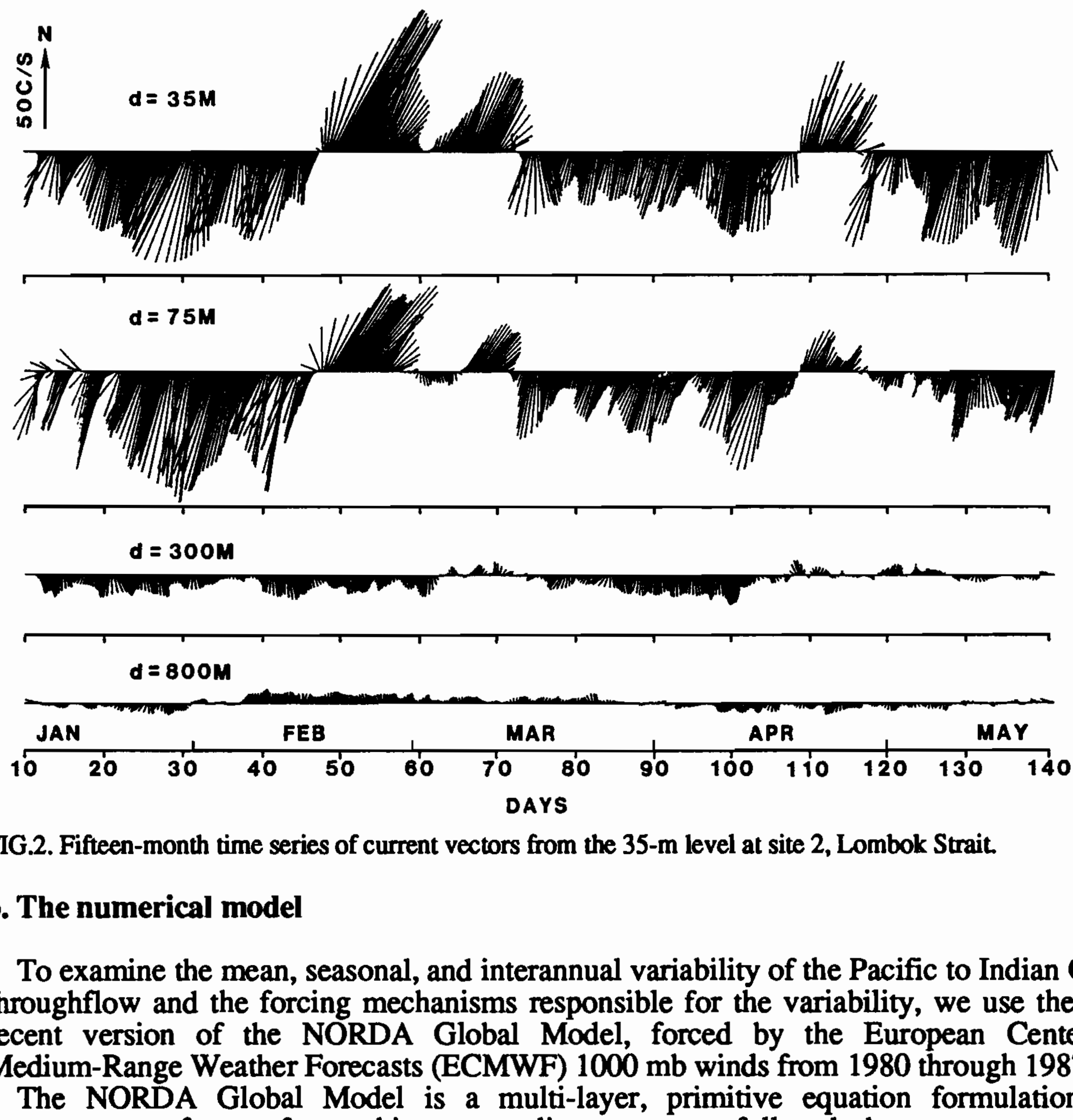

FIG.2. Fifteen-month time series of current vectors from the 35-m level at site 2, Lombok Strait.

3. The numerical model

To examine the mean, seasonal, and interannual variability of the Pacific to Indian Ocean throughflow and the forcing mechanisms responsible for the variability, we use the most recent version of the NORDA Global Model, forced by the European Center for Medium-Range Weather Forecasts (ECMWF) 1000 mb winds from 1980 through 1987.

The NORDA Global Model is a multi-layer, primitive equation formulation that incorporates a free surface, arbitrary coastline geometry, full-scale bottom topography in the lowest layer, and a semi-implicit time scheme. The numerical simulation utilizes a one-active-layer, reduced-gravity version of the model, which includes the effects of mixing and mean thermodynamics. Hence all transport is concentrated in the upper layer. The model grid resolution is 0.5° in latitude and 0.7° in longitude. For further details of the model, see accompanying papers by Kindle et al., and Hurlburt et al., in this volume.

a. Observations and Model Results

The annual mean wind stress in the western equatorial Pacific Ocean, especially these arising from the steady westerly directed trade winds, create a persistent elevated water surface south of the Philippines, clearly illustrated in both the model simulation (not shown) and the GDEM dynamic height climatology of the same area (O/1000 db), which shows a 21-24-cm drop in sea level from south of the Philippines to the Indian Ocean south of Java. A persistent southward flow down the Makassar Strait results throughout the year, as shown in both the ship drift observations and our model results. Figure 3 illustrates the model

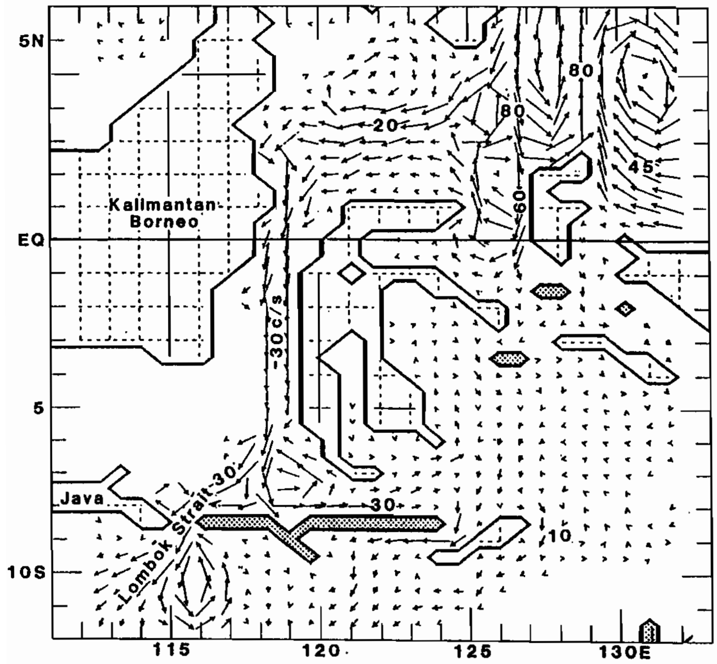

FIG.3. The model velocity field in the study area on May 28, 1985. Representative current speeds (cm/sec) are shown at a few locations.

results for the upper layer velocity field in the throughflow region on May 28, 1985. The strong southward flow in the Makassar Strait (30-60 cm.s^{-1}), fed from the Sulawesi Sea, bifurcates at the archipelago, one branch entering directly into the Indian Ocean through the Lombok Strait and the other branch flowing east through the Flores and Banda seas. The time series of transport predicted by the model for 1985-1986 is compared to our observations in Figure 4.

The computations of observed transport through the Lombok Strait presented in (Murray and Dharma Arief, 1988) are based on monthly block averages of current meter data, which allowed for temporal variation in the vertical current profile. In order to increase temporal resolution for a comparison to the model output, the carefully determined monthly average transports were regressed against monthly average velocity components from various current meters. A best-fit relation (R^2 = 0.79) determined over the range of the monthly averages ($5 \leq v \leq 55$ cm.s^{-1}):

$$T = 0.64\, e^{.032\, v}$$

where T is transport in Sv and v is the monthly average north-south component of current speed at the 35-m level (v_{35}) at the site 2 mooring, gave best results. Utilizing this relationship, the v time series from this current meter was passed through a 30-day low-pass filter (v (LP)) and used to compute transport. For the limited amount of data outside the range of the monthly averages where v (LP) < 5 cm.s^{-1}, we let T $\rightarrow$ 0 linearly with v (LP). Correspondingly, when v (LP) > 55 cm.s^{-1}, an algorithm where v = constant = v_{35} in the upper 100 m and decreases parabolically to 0 at 200 m gave good results.

Figure 4 shows a comparison between transport through the Lombok Strait calculated from the observations in this manner and from the numerical model. In all figures, eastward- and northward-directed flows are positive; westward- and southward-directed flows are negative. Owing to restrictions on the model grid size, the Lombok opening in the model for the upper active layer is about 2.2 times the actual cross section of the strait above the 200-m depth level, where the net transport is calculated. Note a transport scale adjusted for this discrepancy on the figure. We note the general agreement in phase

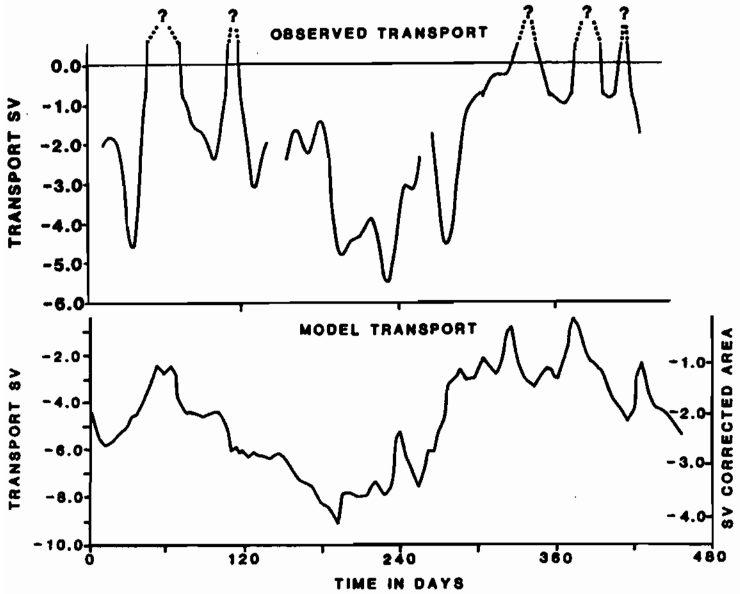

FIG.4. The transport through the Lombok Strait predicted by the model compared to the transport observed in the north strait. The right side of the lower panel is a scale corrected for excess cross-sectional area mandated by model limitations.

between the major pulse in southward transport and the good agreement in magnitude between the model adjusted transport and the observations. The distinct pulse of low southward transport in February because of intense cyclonic activity in the Timor Sea is present in both the observations and the model despite the fact that the model is driven by monthly averaged winds. The period of low transport in the observations from November 1985 to February 1986 appears to be well modeled also.

In Figure 5 the observed transport in Lombok is compared to the observed sea level difference between Davao and Darwin. While the period of largest southerly transport certainly occurs in the months of the northern summer, when the sea level difference is high, there does appear to be a 2-month lag of maximum Lombok transport with the greatest sea level difference. This suggests Darwin, with its location on the inside of the extremely wide Sahul shelf, is not the best index for the sea level in the Timor Sea. Despite this disagreement in phase, the long temporal drop in sea level slope from September 1985 to February 1986 is accompanied by decreasing transport.

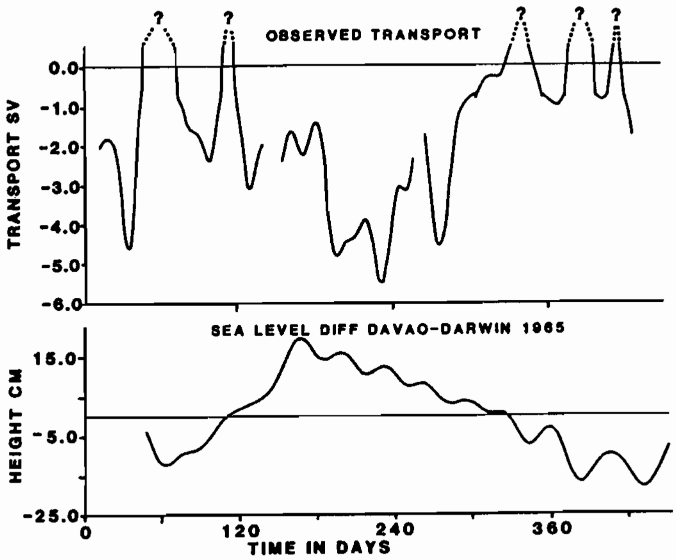

FIG.5. The observed transport in the strait compared to the Darwin minus Davao sea level difference, January 1985-March 1986.

The surface dynamic height field (0/500 db) determined during the first week of June 1985 is shown in Figure 6, and the model simulation of the free surface elevation is given in Figure 7. The general agreement in the overlap area, the west Flores Sea-Makassar Strait junction, is encouraging. A bulge of the sea surface south of Sulawesi and a drop in sea level of 8-10 cm from the Flores Sea south of Sulawesi to the Java shelf is present in both model and data.

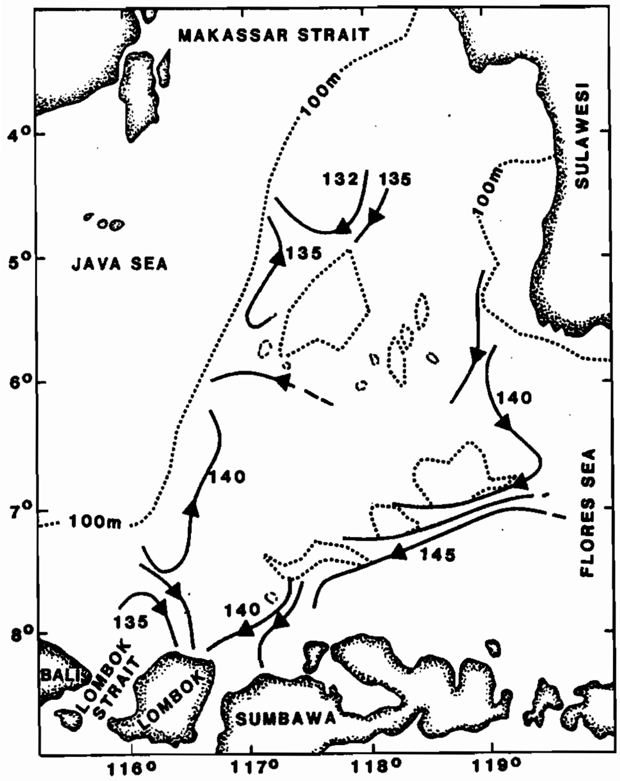

FIG.6. Dynamic height (dyn. cm) as observed on our cruise in the first week of June 1985.

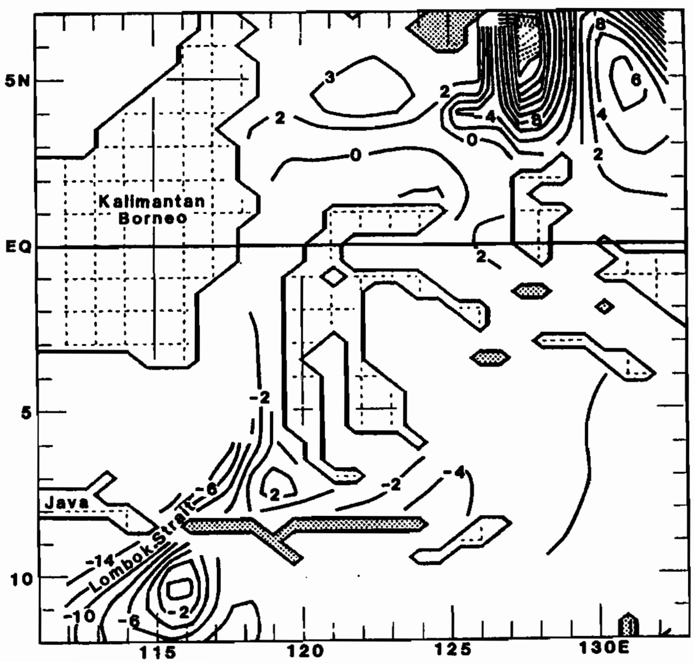

FIG.7. Deviation of the free surface predicted by the model for 28 May 1985. Compare the overlapping areas in Figures 6 and 7.

With a certain degree of confidence now established in the model, it is interesting at this point to investigate the model results relating the Lombok Strait transport to the total Indonesian throughflow. In Figure 8 the total throughflow (PACIO) computed across 114.75°E in the Indian ocean between Java and Australia reaches maximums of 17.5, 14, and 10 Sv in 1984, 1985, and 1986, respectively. Lombok (LBK) is predicted to carry roughly half the flow during maximum transport phases and the entire southward throughflow during low transport phases, there arising a back flow into the Banda Sea during these periods. The transport southward down the Makassar Strait predicted during these three years (Fig. 8, lower panel) suggests Makassar is carrying ~70% of the throughflow during peak periods. At certain times, however, as in the first quarter of 1986, the southward transport in the Makassar Strait exceeds the throughflow, indicating storage within the archipelago or a recirculation back into the Pacific through the passages between Irian Jaya and northeastern Sulawesi.

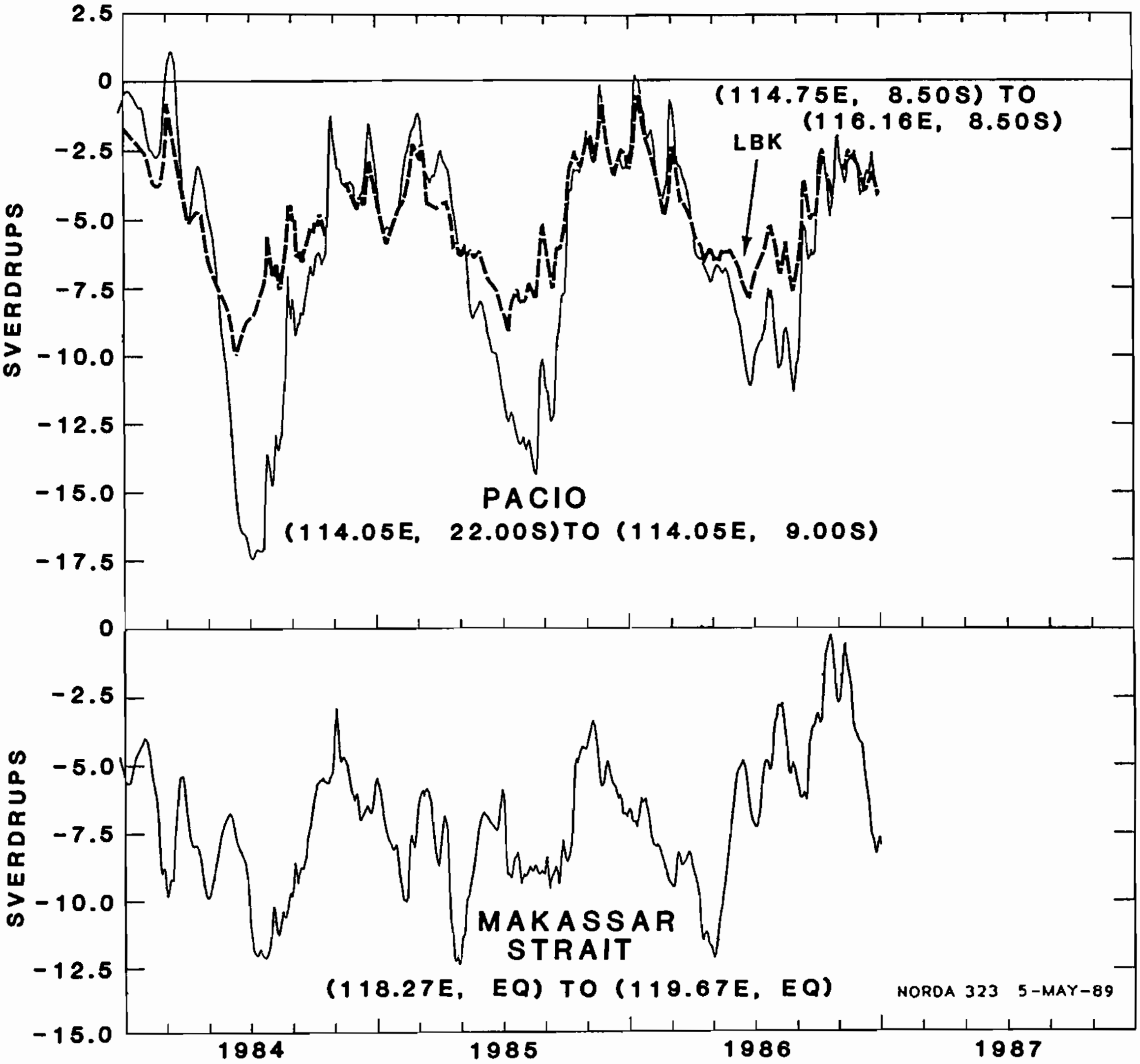

FIG.8. Transport through the Lombok Strait (LBK), the total Pacific-Indian throughflow (PACIO) across 114.75°E, and southward transport in the Makassar Strait across the equator, 1984-1987. Negative values of flow for Lombok and Makassar are southward directed, but westward for the PACIO flow.

b. Sea Level Differences

The observed Davao-Darwin sea-level difference and the observed zonal wind stress in the Indian Ocean south of the archipelago during our observation period are compared to the model transport through the Lombok Strait in Figure 9. The interrelationship between the three signals is clear. The westward zonal wind stress in the Indian Ocean appears to be a key factor in depressing the Timor Sea water level and in pulling water southward through the Lombok Strait.

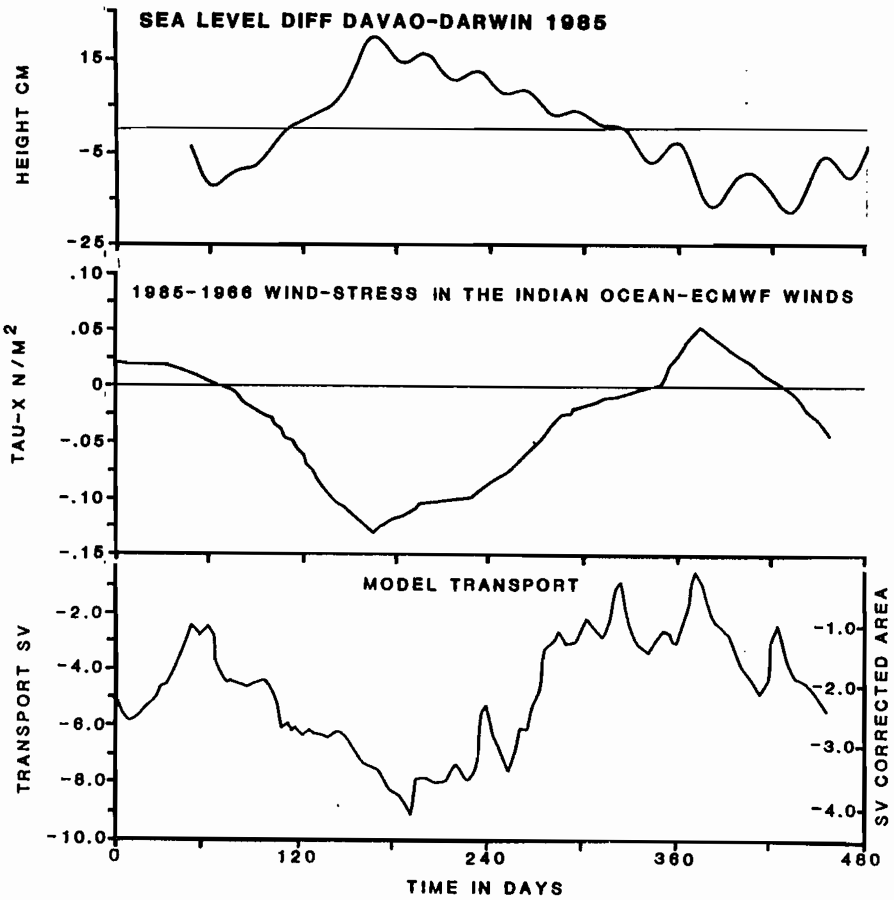

FIG.9. The model transport through the Lombok Strait compared to the average ECMWF wind stress in the Timor Sea and Davao-Darwin sea level difference for the period January 1985-April 1986.

The change in the free surface elevation in the model at 126°E, 6°N (off the Philippines) is compared to the observed Davao sea level in Figure 10. The 15-20 cm range in both signals and the sharp rise in the first 4-5 months of 1985, followed by a gradual 8-month drop, also in both signals, are all encouraging. The sea level difference between the Philippine grid point and the Lombok grid point compared to the observed Davao minus Darwin signal (Fig. 11) is considerably less satisfactory. We suspect Darwin is not a good representative point for sea level in the Timor Sea, a point that needs to be explored further.

The ranges of sea level differences at 20-30 cm and the occurrence of the maximum relative slope in mid-summer in both cases, however, supports the general validity of the model.

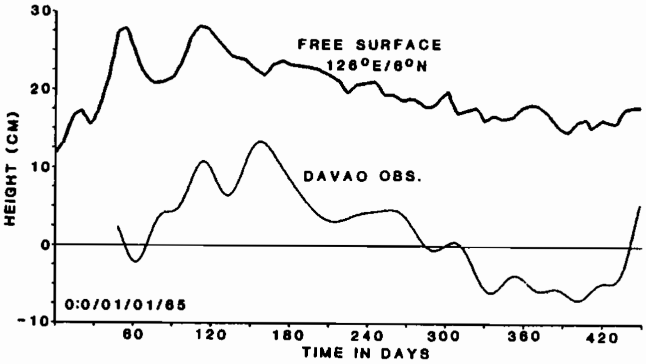

FIG.10. Observed sea level at Davao compared to sea level at the model grid point off the southern Philippines at 126°E, 6°N.

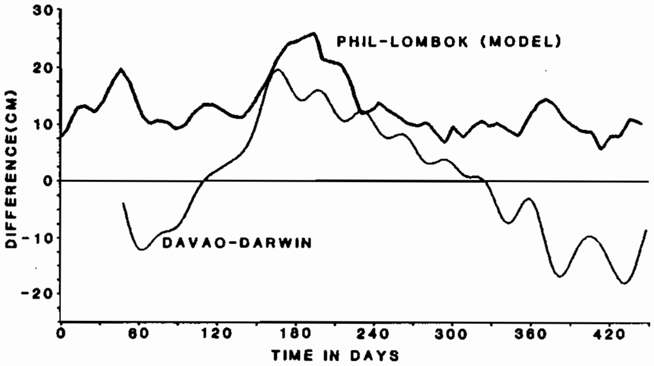

FIG.11. The Davao-Darwin sea level differences, January 1985-March 1986, compared to the sea level difference between the model grid points off the southern Philippines and the Lombok Strait.

4. Summary

Observations of currents, transport, sea level, and sea level slope in Lombok Strait and west Flores Sea in 1985 and 1986 have been compared to a simulation of the NORDA global ocean model in the Indonesian throughflow region. Despite the relatively coarse grid scale of the model compared to topographic length scales in the region, the model appears to be realistically reproducing many of the observed features. The predicted transport through the Lombok Strait, for example, agrees with detailed observations of phase and magnitude, especially when corrected for grid size limitations. The sea surface fluctuations and sea surface slopes predicted by the model agree within less than a factor of 1.5 with sea level changes and slopes observed on tide gauges. There do appear to be several cases of phase difference of several months between model and observations that require further investigation.

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