On the Seasonal and Interannual Variability of the Pacific to Indian Ocean Throughflow

John C. KINDLE, Harley E. HURLBURT and E. Joseph METZGER
NORDA, Code 323
Stennis Space Center, MS 39529 - U.S.A.

1. Introduction.

The Pacific to Indian Ocean transport through the Indonesian Archipelago may play an important role in a variety of ocean circulation regimes. Gordon (1986) suggested that the Indonesian throughflow is a crucial component of the global thermohaline circulation associated with the formation of the North Atlantic Deep Water. Additionally, the extent to which the throughflow modifies the regional circulation may be an important factor in the maintenance and variability of the heat content within the warm pool of the western Pacific and the interannual variability of the coupled ocean-atmosphere system in that region. Furthermore, determination of accurate mass and heat budgets for Pacific and Indian Oceans requires an adequate assessment of the magnitude and variability of the throughflow.

There are no long term direct measurements of the net Indonesian throughflow. Estimates of the mean value and seasonal variability of the transport have been determined from a variety of in-situ and indirect observations as well as from modelling studies. Gordon (1986) presents a summary of the estimated values. The magnitudes of the mean throughflow inferred from observations generally range from 5-15 Sv (10 m s^{-1}). The only year long direct measurement of a portion of the throughflow was provided by Murray and Arief (1988) who observed a mean transport through the Lombok Strait of about 1.7 Sv for 1985.

Results from modelling studies yield a similar scatter for the values of the throughflow. Multi-level global simulations forced by the Hellerman and Rosenstein (1983) wind stress climatology yield a mean value of approximately 15 Sv (Semtner and Chervin, 1988). A global Sverdrup model by Godfrey (1989) predict a mean Pacific to Indian Ocean throughflow of 16 $\pm$ 4 Sv. The one-layer reduced gravity global model described in Kindle et al. (1987) utilized the Fleet Numerical Oceanographic Center (FNOC) surface winds from 1977 to 1984 and yielded a mean value for the Indonesian throughflow of approximately 8 Sv with a seasonal variation (maximum in August and minimum in January) of about 4 Sv.

Wyrtki (1987) discussed the pressure gradient between the western Pacific and the eastern Indian Oceans as a mechanism which drives the mean and seasonal variation of the Indonesian throughflow. His examination of sea level and dynamic height in this region supports the hypothesis that the mean pressure gradient between the two basins drives the mean transport and that the dynamic height difference between Davao, Phillipines and Darwin, Australia (~16 dynamic centimeters) is an adequate measure of the inter-basin pressure gradient. In addition, Wyrtki (1987) found that the seasonal variation of the sea level difference between Darwin and Davao exhibited a similar phase to the seasonal variation of the throughflow from a NORDA 1-layer reduced-gravity model simulation provided by Kindle. The model used in the calculations was identical to the one described in Kindle et al.(1987) except for a longer spin-up and the inclusion of the Macassar Strait. Wyrtki hypothesized that the low-frequency variations of the interbasin pressure gradient (as denoted by the Davao-Darwin sea level difference) could be used to monitor the variability of the Pacific to Indian Ocean throughflow.

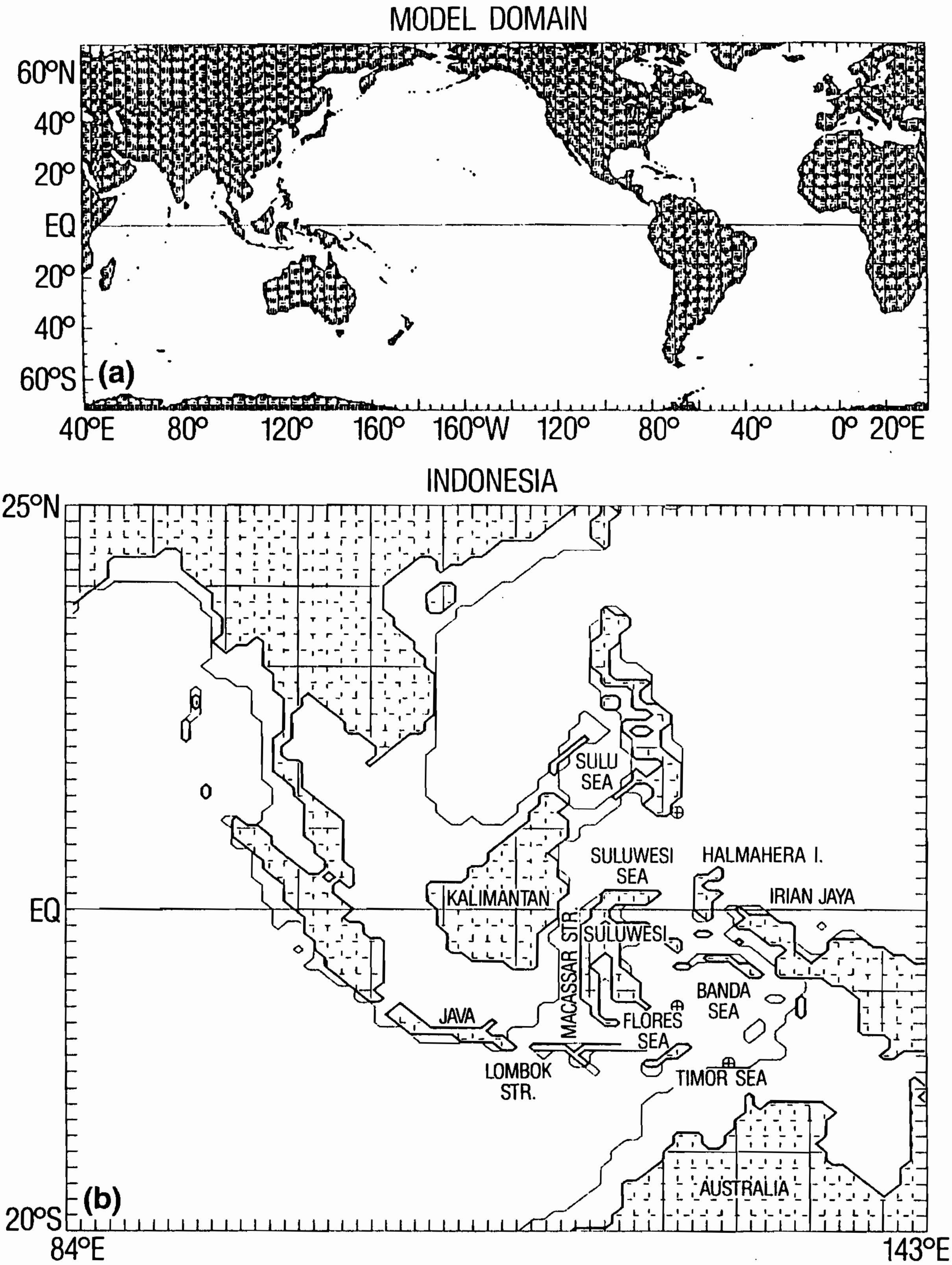


FIG.1. Model Domain a) Coastline geometry for global model. b) Enlargement of western Pacific-east Indian Ocean region. Thin line denotes 200 m isobath; ocean areas with depths shallower than 200 m are treated as land by the model.

In the present study, we use the most recent version of the NORDA Global model forced by the Hellerman and Rosenstein (1983) thereafter, (HR) wind stress climatology and the European Center for Medium-Range Weather Forecasts (ECMWF) 1000 mb winds from 1980 through 1987 to examine the mean, seasonal and interannual variability of the Pacific to Indian Ocean throughflow and the forcing mechanisms responsible for the variability.

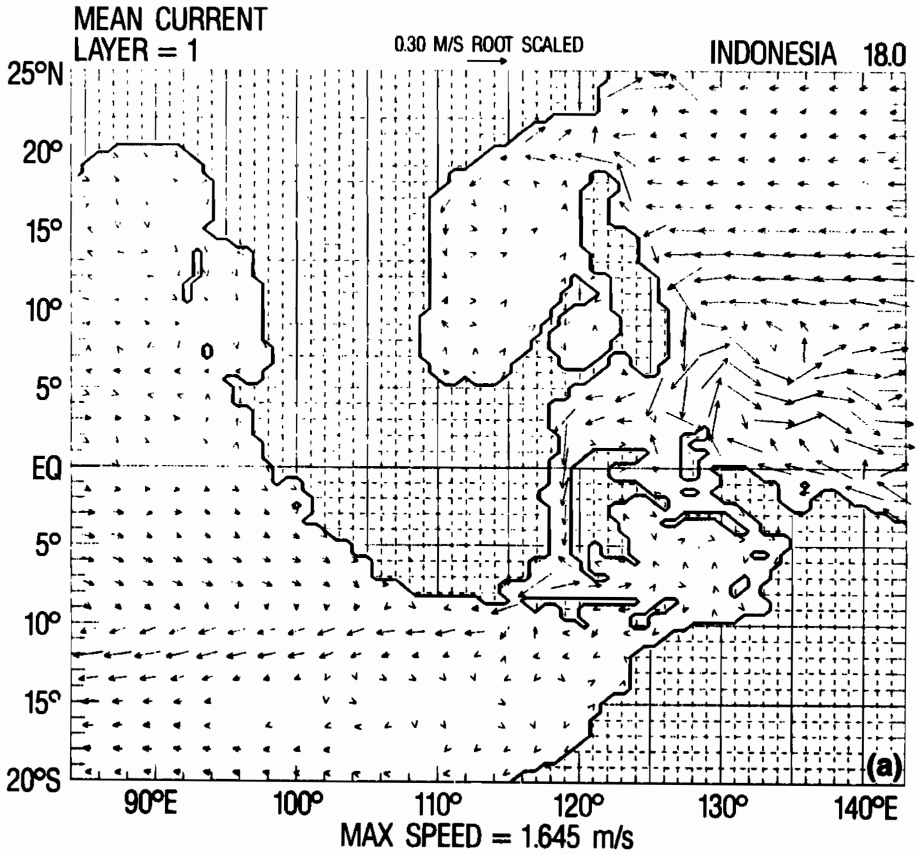
The NORDA global model is a multi-layer, primitive equation formulation which incorporates a free surface, arbitary coastline geometry, full scale bottom topography in the lowest layer and a semi-implicit time scheme. A more detailed description of the model can be found in Wallcraft (1989). The model equations are formulated in spherical geometry over a latitudinal extent ranging from 71°N to 72°S. The model global geometry and an enlargement of the Indonesian Archipelago are shown in Figure 1. Lateral boundaries are located at the 200-m contour using bathymetric data from the SYNBAPS (Van Wyckhouse, 1979) data base. The walls are rigid and the no-slip condition is prescribed on the tangential flow.

The simulations described in this paper use a one active layer reduced gravity version of the model which includes the effects of mixing and mean thermodynamics. Density gradients within the upper layer are permitted and are modified by horizontal advection, entrainment, eddy diffusion and relaxation to a mean density climatology based on Levitus (1982). The model formulation permits the specification of surface heat fluxes, but that option was not utilized in these simulations. The model grid resolution for the experiments described in this report is .5 degree in latitude and .7 degree in longitude. A full list of model parameters is given in Table 1.

TABLE 1

PARAMETER	DESCRIPTION	VALUE
A(m)	Horizontal eddy viscosity (Momentum)	1500 m^2 s^{-1}
A(d)	Horizontal eddy viscosity (density)	5000 m^2 s^{-1}
g	Gravity	9.8 m s^{-2}
dx	Grid spacing in longitude	.7 deg
dy	Grid spacing in latitude	.5 deg
dt	Time step	60 min.
H	Initial layer depth	250 m
hm	Maximum layer thickness for which mixing is initiated	60 m

This section examines the results of two experiments: the climatology case forced by the HR wind stress data set (Exp 18.0) and the ECMWF case forced by the ECMWF 1000 mb winds from 1980 to 1987 (Exp 14.5). Prior to integrating the model with ECMWF product, the 12-hourly 1000 mb winds are averaged to form a mean for each month from 1980 to 1987 and reduced in strength by 20 percent. A constant drag coefficient of .0015 is applied to form a wind stress. No directional changes are made in reducing the winds from the 1000 mb level. It is recognized that such winds may provide only a coarse approximation to the actual 10 meter winds. However, in the absence of a better alternative, it was judged worthwhile to examine the interannual variability of a global ocean circulation model driven by such a product. As a check, the winds will be compared in the near future to the recently available ECMWF/TOGA 10 meter winds for the period 1985 to 1988.



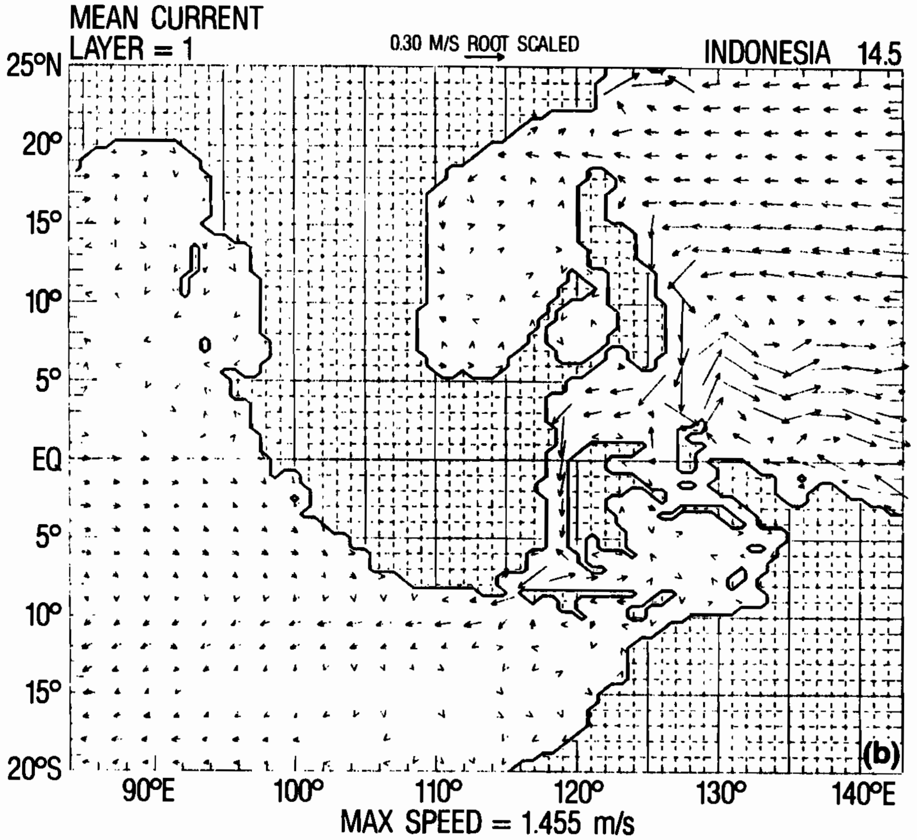


FIG.2. Current vectors for mean model velocity fields of a) Experiment 18.0 and b) Experiment 14.5 for PAC-IO region.

The mean model current fields in the Western Pacific-East Indian Ocean (PAC-IO) region for experiments 18.0 and 14.5 are shown in Figure 2. Note that qualitatively, the means from the two experiments are quite similar. The path of the model Pacific to Indian Ocean throughflow begins as a southwestward branch of the Mindanao Current and is directed through the Suluwesi Sea and the Macassar Strait. In both cases, most of the Indonesian throughflow enters the Indian Ocean through the Lombok Strait; this behavior is discussed in more detail below. The excess of Macassar Strait over Lombok Strait transport passes east through the Flores Sea and, upon entering the Banda Sea, branches north and south. The north branch returns to the Pacific Ocean through the Halmahera and Molucca Seas and adds to the North Equatorial Countercurrent. The branch that turns south from the Banda Sea enters the Indian Ocean both north and south of Timor.

It is recognized that the Lombok Strait transport is larger than observed values (approximately 1.7 Sv) as given by Murray and Arief (1988). The large model values are due to the fact that the minimum model width of an east-west port is .7 degree whereas the actual Lombok Strait is significantly smaller. In terms of studying the net throughflow, this deficiency of the model is not a serious one, because even if the Lombok Strait is blocked, most of the transport which would have exited through Lombok enters the Indian Ocean through the Timor Passages. This aspect is discussed further in Murray et al. (1989) in which the model Lombok Strait transport from Exp. 14.5 is compared to observations for the period January, 1985 to March 1986. Future experiments will address the problem by using finer grid resolution and/or increased friction at the port.

Table 2 lists the mean model transport values through the major passages listed above for Exp. 18.0 and 14.5. The mean throughflow transport for the HR case (Exp. 18.0) is 7.5 Sv versus a value of 4.5 Sv for the ECMWF case (Exp. 14.5). Given that the patterns of the circulation in the throughflow region is very similar for both cases, the different magnitudes may be the result of a calibration problem in reducing the winds from 1000 mb to 10 meters.

TABLE 2

MEAN TRANSPORT VALUES (IN SVERDRUPS)

	EXPERIMENT #	
	18.0 (HR)	14.5 (ECMWF)
SECTION		
Net Indonesian Throughflow	7.5	4.5
Lombok Strait	5.5	4
Macassar Strait	8.5	5.5
Suluwesi-Irian Jaya	1	1
Timor	2	.5

One distinct difference between the circulation patterns of Experiments 18.0 and 14.5 is that the bifurcation of the North Equatorial Current (NEC) at the Phillipines coast occurs at 15°-16°N in Exp. 18.0 and at 17°-18°N in Exp. 14.5. Observations (Wyrtki, 1961; Levitus, 1982) show the NEC splitting at 13°-14°N. Hence, the ECMWF case (Exp. 14.5) results in a particularly unrealistic north-south extension of the Countercurrent trough. The degree to which this property of the model solution modifies the height field in the western Pacific and the mean throughflow is not clear. It will be of interest to note whether future simulations using the ECMWF/TOGA 10m winds also display this characteristic.

Figure 3 shows the model mean seasonal variability of the low pass filtered net Indone-

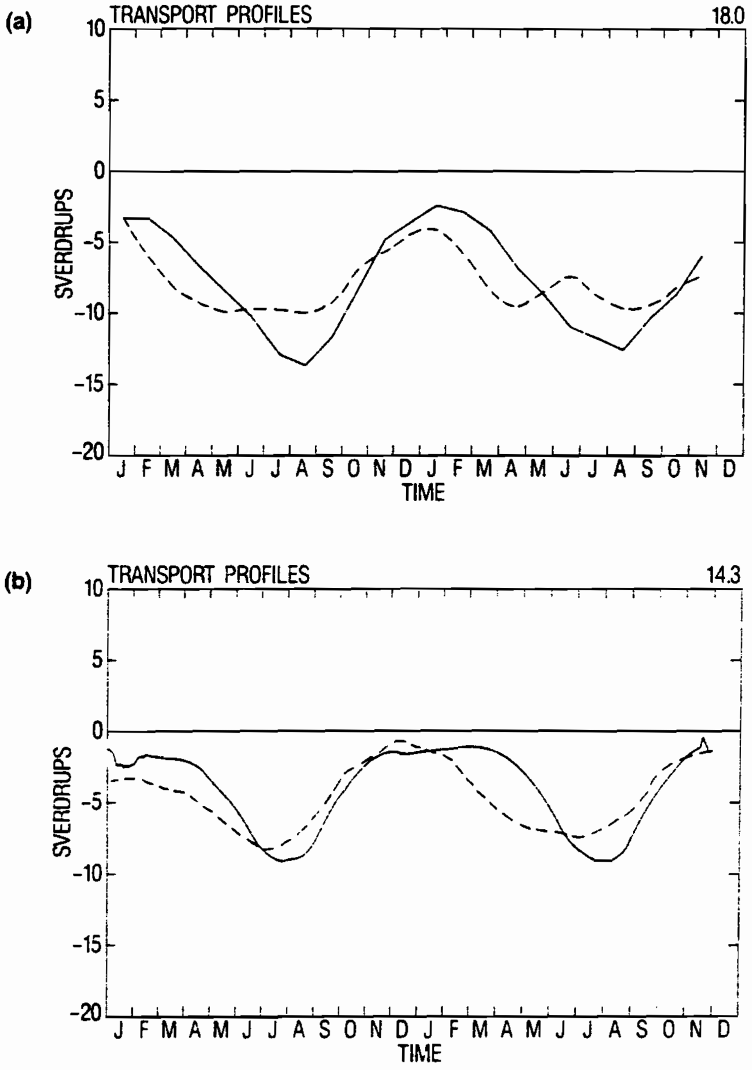


FIG.3. Transports (3-month running mean) vs. time of Pacific to Indian Ocean throughflow for a) Exp. 18.0 and b) for Exp. 14.5. Solid line denotes Indian Ocean section while dashed line represents equatorial section as defined in text.

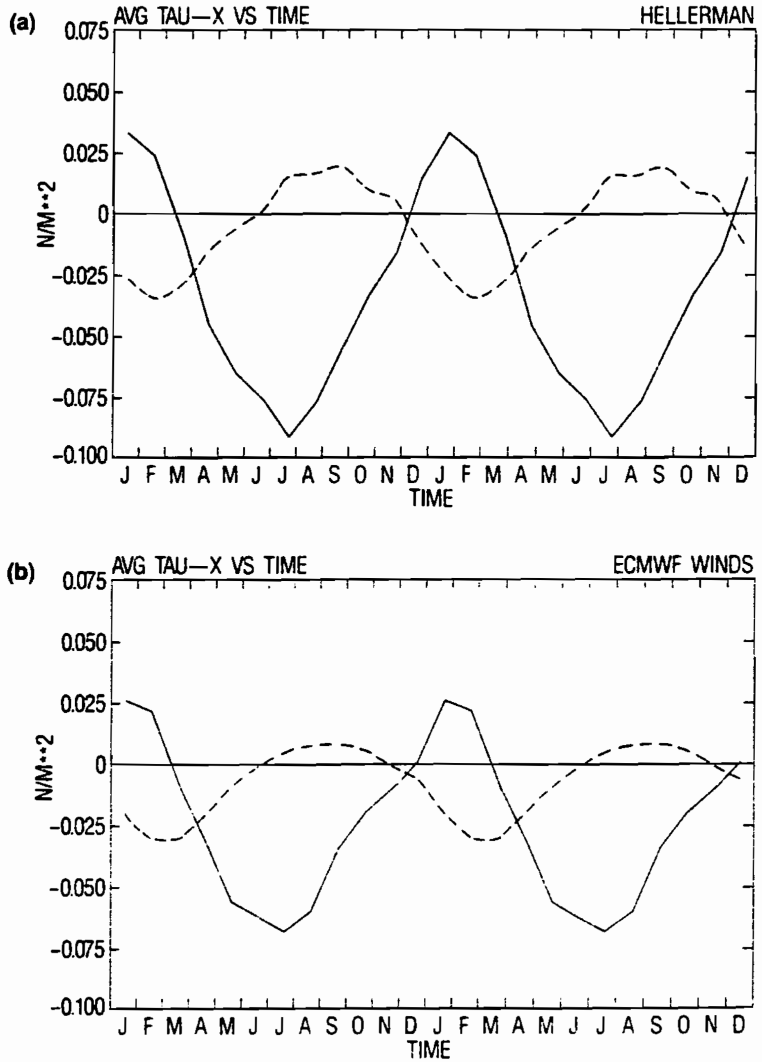


FIG.4. Area average of zonal wind stress component vs time for a) Hellerman and Rosenstein Climatology and b) ECMWF 1000 mb winds. Solid line represents average over an area bounded by 9°S and 19°S extending from 105°E to 120°E; dashed line is for an area bounded by the equator and 10°N extending from 125°E to 140°E.

sian throughflow from Exp. 18.0 and 14.5. Two sections are shown for each experiment: 1) the net throughflow extending from south Java to Australia at 114°E and 2) the net Pacific to Indian Ocean transport across an equatorial section extending from Kalimantan to Irian Jaya. Note that in each experiment, mass convergence occurs in the region bounded by the two sections during the north monsoon while divergence is present during the south monsoon. This is in agreement with Wyrtki (1961, 1987) who described downwelling in the Banda Sea during the north monsoon and upwelling during the period May to September.

The phases of the seasonal variation of the model free surface elevation for two points which are nearest the location of Davao and Darwin do not agree with the observations of Wyrtki (1987) who discovered a 180 degree phase change between the annual sea level variations at Davao and Darwin. The model free surface difference between Davao and the east Timor Sea (nearest model point to Darwin) displays a weak annual signal. The exclusion of the shelf circulation on the north coast of Australia and the resolution of the intense sea level gradients near Davao are factors contributing to the discrepancies. However, the lack of a strong seasonal cycle in the model sea level differences between Davao and Timor suggests that the seasonal variability of the Pacific to Indian Ocean throughflow is not regulated by the seasonal variation of the inter-basin pressure gradients or that Davao-Darwin in the model is not a good measure of this.

An examination of the seasonal variability of the wind-stress forcing, though, provides some insight into the seasonal variability of the throughflow. We form a mean value of the x-component of the wind stress for two regions: 1) an east Indian Ocean area bounded by the latitudes 9°S to 19°S extending from 105°E to 120°E and 2) a west Pacific region bounded meridionally by the equator and 10°N extending from 125°E to 140°E. The temporal variability of these means for both the HR and ECMWF winds are plotted in Figure 4. Note that both data sets display a maximum westward wind stress in the Indian Ocean region in July and the Pacific region in February.

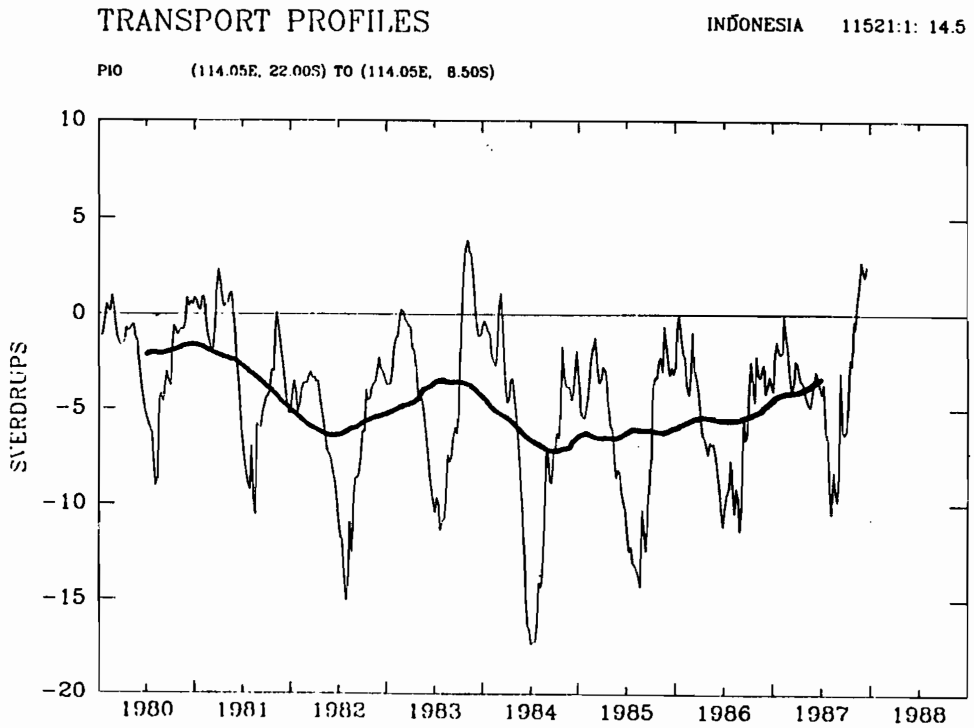
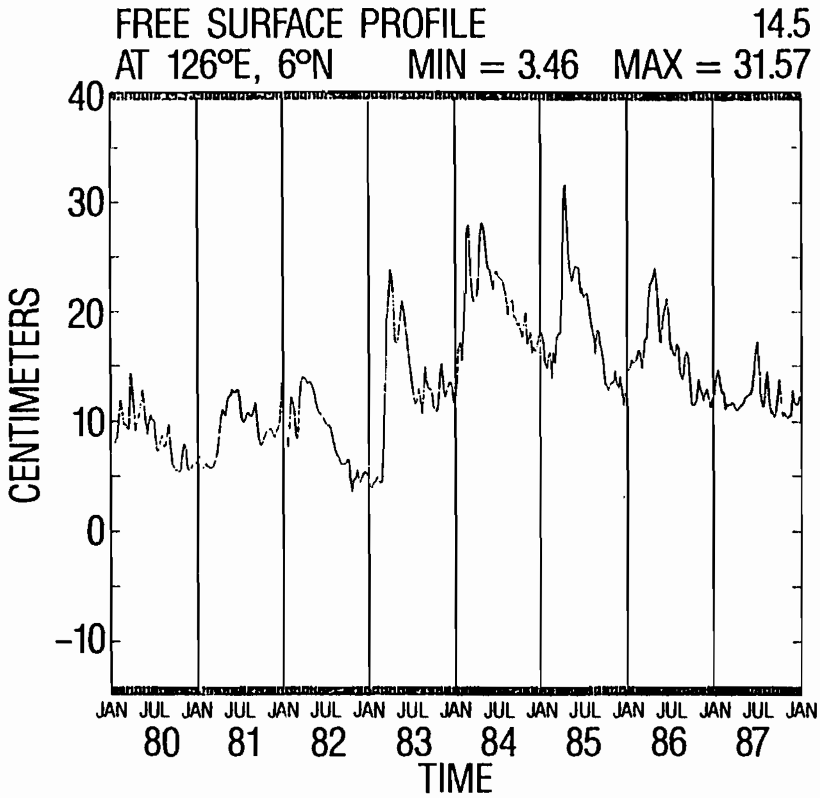


FIG.5. Pacific to Indian Ocean transport across a section from Java to Australia at 114°E for the years 1980 to 1987 (Experiment 14.5). Solid line is 12-month running mean.

a



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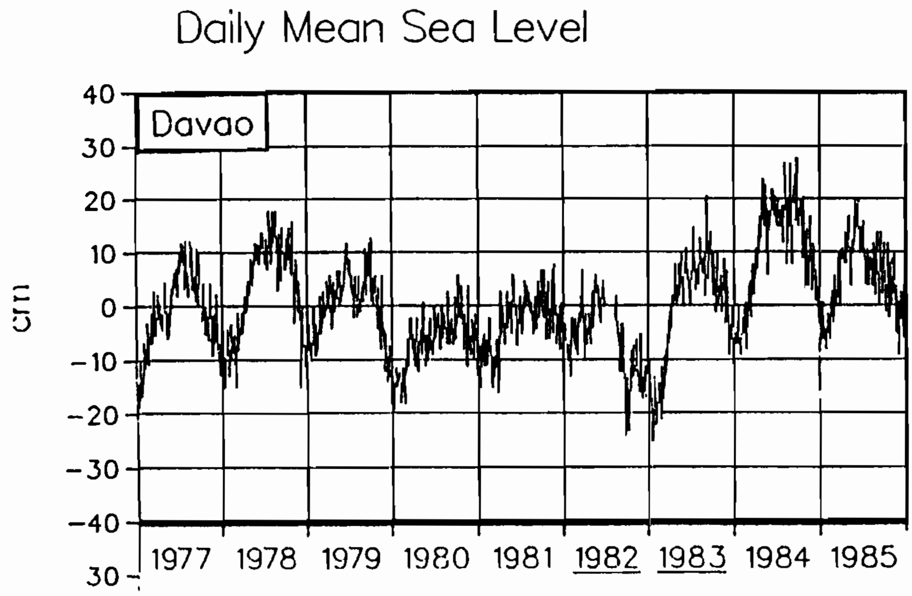
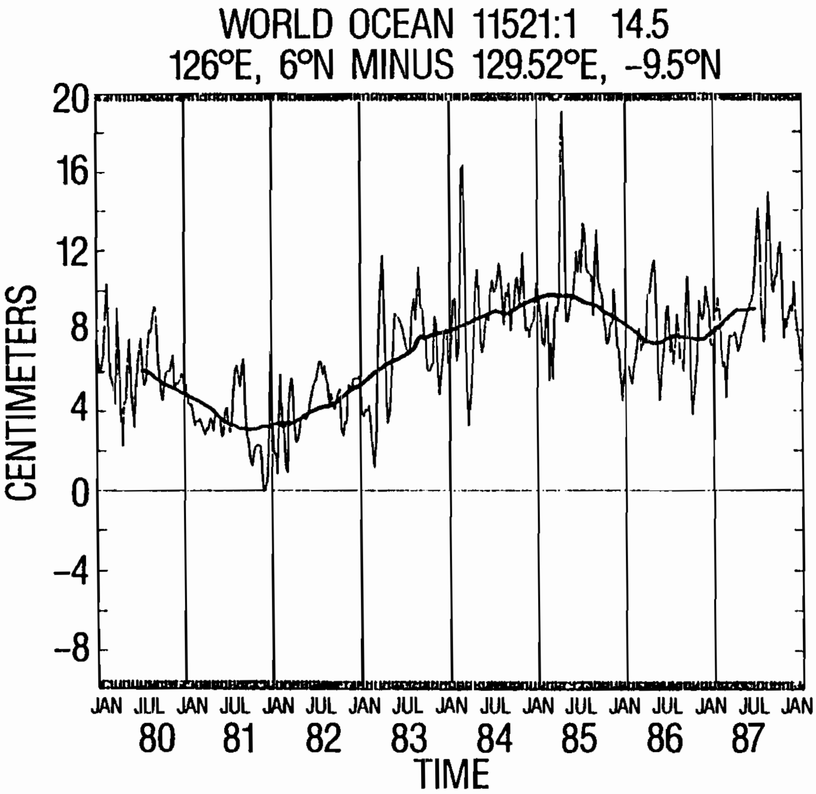


FIG.6. a) Model free surface deviation versus time at 126°E, 6°N for the period 1980 to 1987 from Exp. 14.5. b) Observed daily mean sea level at Davao from 1977 to 1985 (from Lukas, 1988).

(a)



(b)

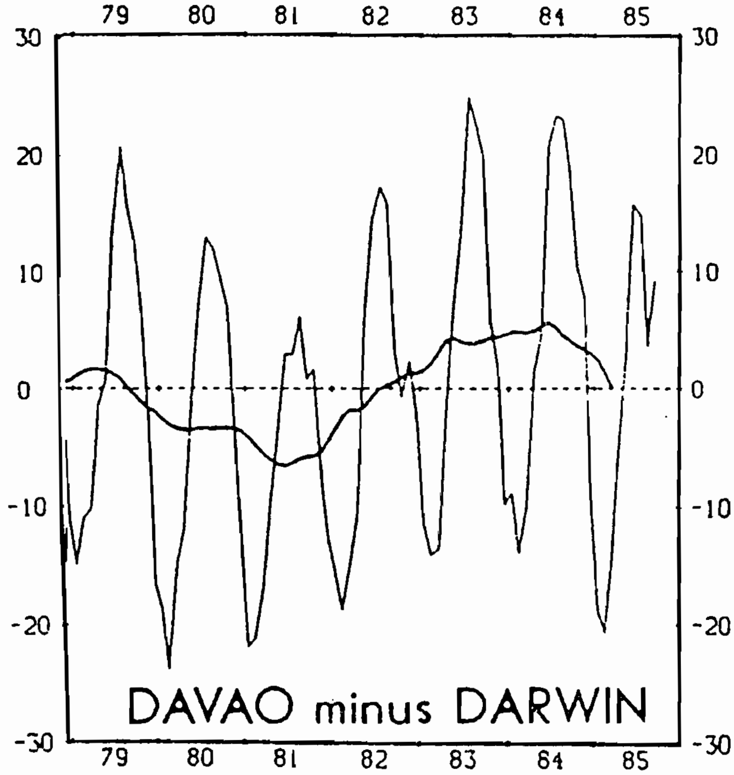


FIG.7. a) Model free surface difference between (126°E, 6°N) and (129°E, 9.5°S) for the years 1980 to 1987 from Exp. 14.5. These points represent the model locations of Davao and Darwin. b) Observed sea level difference between Davao and Darwin from 1980 to 1985 (from Wyrtki, 1987). Dark line in both curves is 12-month running mean.

A comparison of Figures 3 and 4 suggests that the seasonal variation of the zonal winds in the east Indian Ocean dominates the seasonal signal of the net throughflow. However, the convergence/divergence cycle of the winds over the entire region is large enough to produce a mass convergence/divergence within the throughflow domain. Additional analysis of model sea level, wind stress and wind stress curl using EOF and Principal Pattern Analysis (PEP) will be described in a future report.

The net model Indonesian throughflow between Java and Australia is plotted in Fig. 5 for the period 1980 to 1987 as given by Exp. 14.5. As stated previously, the mean is 4.5 Sv with an annual variation of 4 Sv. The July maximum of the Pacific to Indian Ocean transport ranges from 9 Sv in 1980 to 17 Sv in 1984. With the exception of 1983, the maximum transport increases monotonically from 1980 to 1984 and decreases from 1984 to 1987. The low pass filtered values of the throughflow show a similar variation although not as pronounced. The 12-month running mean average of the throughflow varies from a low of 2 Sv in 1980 to 7.5 Sv in 1984. Also note anomalous seasonal changes such as 1983-84 when the model transport increased by nearly 20 Sv from December, 1983 to July, 1984.

In order to examine whether the interannual variability of the model inter-basin pressure gradient is an adequate measure of the throughflow, the model sea level variability of the points representing Davao and Darwin are analyzed. Fig. 6 is a comparison of the model sea level for Davao and the observed sea level as presented by Lukas (1988). The model is able to represent the interannual variability of the observed Davao sea level quite accurately, such as the relatively weak variability from 1980 to mid-1982, the large drop in sea level associated with the 1982 ENSO and the subsequent rise to a peak in 1984 followed by a fall which in the model continues into 1987. Although the amplitude of the variability is less than observed values, the relative scale of the variability is reproduced. The interannual sea level variations at Darwin are also represented quite well by the model (not shown).

The difference in free surface elevation between the model Davao and Darwin points for the period 1980 to 1987 is plotted in Fig. 7 along with the observed sea level values from Wyrtki (1987) for the period 1979 to 1985. Except for a slight (relative to the time scale of the interannual variability) phase shift, the model and observations show a similar interannual variation given by a decrease from 1980 to 1981-82 followed by a rise to a peak in 1984-85 and a subsequent decrease during 1985. The amplitude of the model variations are approximately 60% of observed values. The close correspondence between the model results and observations of the Davao-Darwin sea level difference on interannual time scales is intriguing in view of the significant discrepancy for the annual signal.

The increase in sea level difference between Davao and Darwin during the period 1982-84 and the subsequent decrease suggest a rough correspondence to a similar variation in the Pacific to Indian Ocean transport (Fig. 5). Noteable exceptions are the years 1980-81 and 1983. There are other measures of the inter-basin pressure gradient that agree more closely with the interannual variability of the Indonesian throughflow. For example, the north Sulu-wesi Sea - Darwin difference exhibits a monotonic increase from 1980 to late 1984 followed by significant decrease (not shown). This suggests that an appropriate measure of the inter-basin pressure gradient may be used to monitor the interannual variability on longer time scales, but that variations from one year to the next may not be well represented by such sea level differences. A more detailed analysis of the relationship between model sea level, wind forcing and the Indonesian throughflow on interannual time scales will be reported in a future study.

Finally, we note that future investigations will examine the influence of the throughflow on the circulation of the Indian Ocean (including the Leeuwin Current) and the variability of the path of the throughflow from the western Pacific Ocean. In addition models with finer resolution, multiple layers and bottom topography will be utilized to investigate the roles of the New Guinea Coastal Undercurrent, the intermediate and deep Indonesia throughflow and the effects of bottom topography on the circulation.

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