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Current measurements in the Maluku Sea

John L. Luick

National Tidal Facility Australia, Flinders University of South Australia, Adelaide, South Australia, Australia

George R. Cresswell

Commonwealth Scientific and Industrial Research Organisation, Marine Research, Hobart, Tasmania, Australia

Abstract. A current meter mooring was deployed in the eastern Indonesian archipelago, in the Maluku Sea, between the islands of Sulawesi and Halmahera, to contribute to estimates of the volume of the Indonesian Throughflow, for 13 months (June 1993-July 1994), with meters located at 740, 1250, 1750, and 2240 m below the surface. Hydrocasts for salinity and temperature were made at the time of deployment. The current meter and hydrographic data indicate a predominantly southward flow at the upper three meters throughout the year and a steady northward flow at the bottom meter. T-S and oxygen properties below 1800 m indicate a clockwise circulation in the Maluku Sea, with a vertical velocity of about 2 m/d. If the currents at the mooring, which is located on the western side of the Maluku Sea, are typical of the entire basin width, the average southward through flow between 740 m and 1500 m below the surface, 7 Sv (1 Sv = 10^6 m^3/s), is comparable in magnitude with estimates of upper layer transport and should be accounted for in estimates of the Indonesian Throughflow.

1. Introduction

Water exchanged between the Pacific and Indian Oceans passes through a series of circuitous channels between the islands of the Indonesian archipelago. *Wyrtki* [1961], on the basis of hydrographic data and taking into account the restrictions due to sills and narrow channels, concluded that the Indonesian Throughflow was confined mainly to the upper few hundred meters. Godfrey and Golding [1981], using indirect evidence, estimated a seasonal maximum through flow volume of 10 Sv (1 Sv = 1 x 10^6 m^3/s) in the upper layer. A number of studies have since provided estimates of similar magnitude.

Wyrtki [1961] suggested two main through flow routes: a western route passing through the Celebes Sea and Makassar Strait and an eastern route passing through the Maluku Sea, across Lifamatola Strait, into the Banda Sea, and finally through the Sawu Sea into the Indian Ocean. The western route is thought to carry most of the upper layer transport, but it is blocked by a 500-m sill in southern Makassar Strait, while the eastern route is unimpeded to about 1500 m (the sill depth between the Sawu Sea and Indian Ocean at the northeast end of Timor Strait). The eastern route flows through the following basins: Pacific Ocean, Maluku Sea, Banda Sea, Sawu Sea, and Indian Ocean. Direct exchange between the Pacific Ocean and Banda Sea (a potential shortcut) must cross a sill at 600 m [*Cresswell and Luick*, this issue]. Thus ignoring vertical exchange, virtually all the "middepth" (600-1500 m) flow between the Indian and Pacific Oceans must pass through the Maluku and Banda Seas. These basins are connected at the Lifamatola Strait, whose minimum depth is 1940 m.

Before the present study, few current observations had been made in the eastern route. Of these, three were short-term moorings in Lifamatola Strait. During the *Snellius I* expedition of 1929-1930 [*Lek*, 1938], the ship anchored in Lifamatola Strait for several days and repeatedly lowered a current meter. After subtracting the tidal signal, the deepest current (at 1500 m) was found to be southeastward at 5 cm/s. During the INDOPAC expedition of 1976, two current meter moorings were installed for 28 days on Lifamatola Sill [*Broecker et al.*, 1986]. They were 10 m off the bottom in about 2000-m depth. Both recorded steady southward flow of about 25 cm/s, with strong baroclinic tidal oscillations superimposed. Finally, during the *Snellius II* expedition of 1984-1985, a mooring with current meters at 1525 m and 1825 m was installed for 108 days [*Van Aken et al.*, 1988]; mean currents of 40 cm/s and 61 cm/s, respectively, flowed to the southeast. From this, *Van Aken et al.* [1988] estimated southward transport below 1500 m to be 1.5 Sv. This flow cannot pass through to the Indian Ocean because of the Timor Strait sill.

This report describes current meter observations at a mooring in the northern entrance to the Maluku Sea (Figure 1). They were part of the Association of Southeast Asian Nations (ASEAN)-Australia Regional Ocean Dynamics Expeditions 1993-1995, itself a part of the ASEAN-Australia Economic Cooperation Program.

2. Methods

A current meter mooring was established in the western Maluku Sea at 1°41'N, 125°40'E. Aandera RCM8 current meters were deployed at 400, 740, 1250, 1750, and 2240 m below the surface at 2250-m depth. An acoustic Doppler current profiler mounted at 200 m failed owing to errors in manufacture. The 400-m RCM8 flooded and yielded no data. All other meters operated for 13 months (June 1993–July 1994). Data were recorded at hourly intervals.

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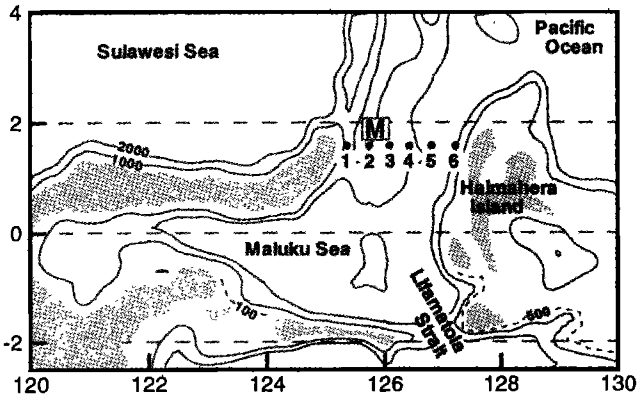

Figure 1. Map of Maluku Sea, showing mooring location (M) and hydrographic stations (solid circles).

Six conductivity-temperature-depth (CTD) casts were taken along a transect across the Maluku Sea at the time of deployment. These casts included bottle samples for oxygen and calibration of CTD salinity.

3. Current Meter Observations

A summary of the subtidal currents is presented as stick plots in Figure 2. Tides were removed before plotting by *Thompson's* [1983] method, after which daily averages were computed. The currents at 740 and 1240 m were relatively episodic; in fact, the pressures recorded by the 740-m instrument indicated that the mooring was blown over to an angle of 45° during March 1994. The currents at 1750 m, by contrast, were southward virtually every day of the year. A striking feature of this plot is the flow in the deepest meter (2240 m), which is generally in the opposite direction to that of its neighbor above and persistently near northward, parallel to the bathymetry.

Wind vectors at 2°N, 126°E (the vicinity of the mooring), plotted as the top panel of Figure 2, show the strongly monsoonal nature of the winds in this region. However, none of these current meters suggests that the direction of the deep flow is coupled with the local monsoonal winds (a result foreseen by *Van Aken et al.* [1988].

The mean velocities over the deployment interval are shown in a schematic (Figure 3). For the purposes of this

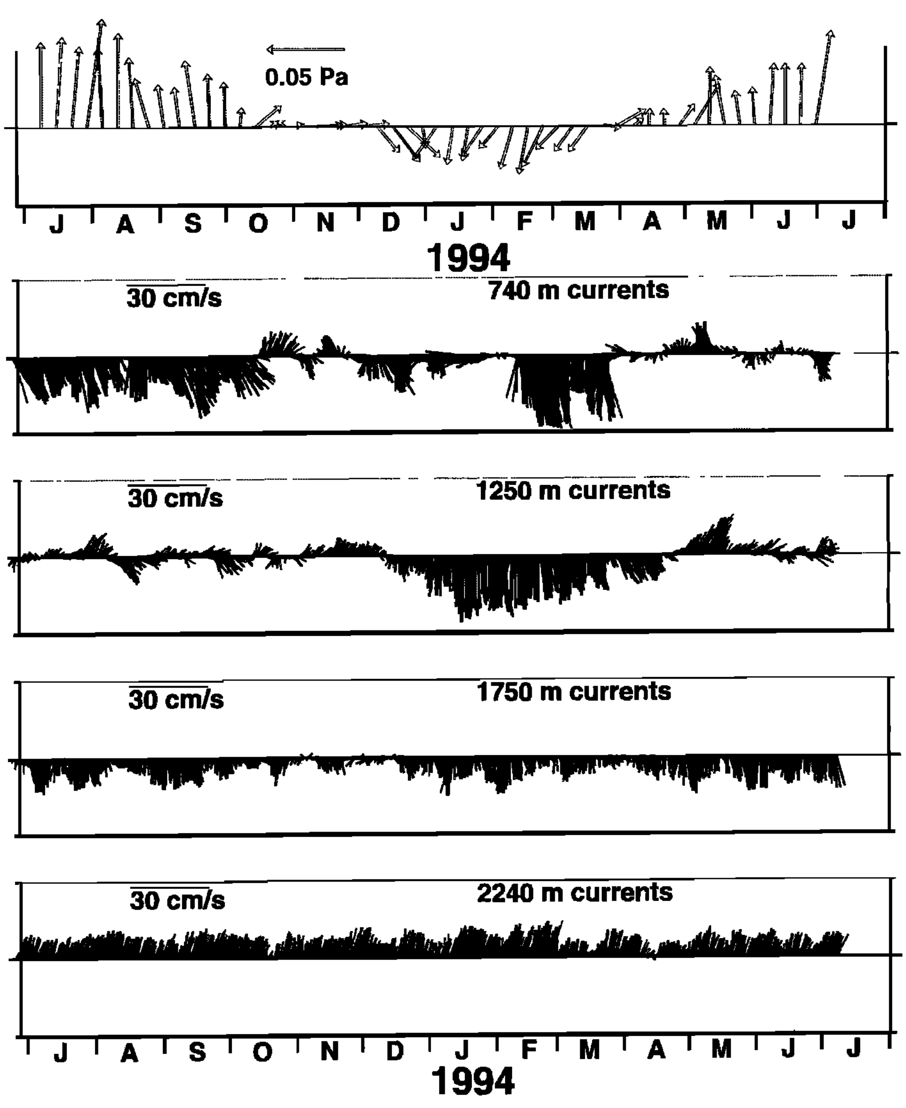

Figure 2. Surface wind stress (top panel) and observed currents at the mooring. The wind stress vectors are weekly averages of National Meteorological Cente global analyses at 2°N, 126°E [*Ji et al.*, 1995] Currents are hourly values after tides are removed.

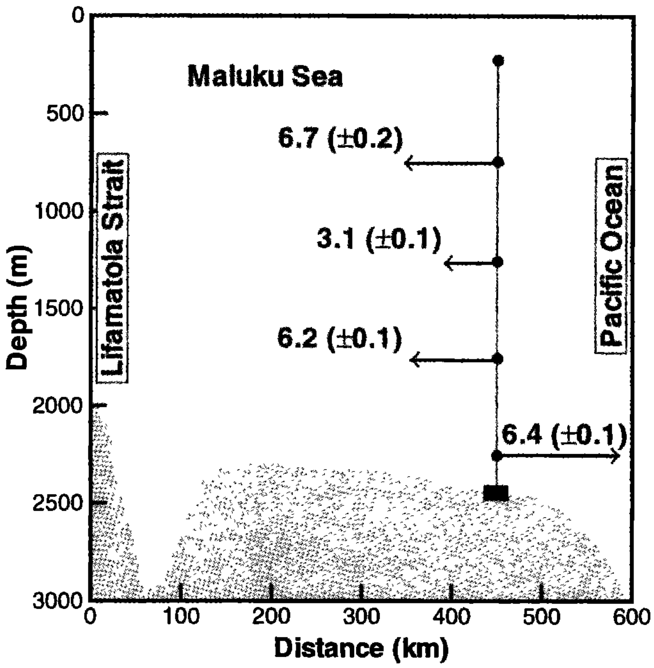

Figure 3. Schematic of mean along-stream currents at the mooring. Currents were rotated into the principal axes and tides were removed before the average was taken. Standard errors of the mean velocities are given in parentheses.

figure, the principal axis of the subtidal currents was found at each depth, and the mean is of the principal axis component. The schematic shows the bottom depth along the channel between the mooring and Lifamatola Strait. The bottom current meter (2240 m) is more than 200 m below Lifamatola Sill depth. Flow was southward (toward the Indian Ocean) in all current meters except the deepest, with a subsurface minimum near 1240 m. Magnitudes were 6.7 cm/s at 740 m, 3.1 cm/s at 1250 m, 6.2 cm/s at 1750 m, and 6.4 cm/s at 2240 m.

The possibility of instrument error in the deepest current meter was checked, and discounted, by comparing the tidal phase of the two deepest meters. Had there been a 180° compass error, for example, the M_2 phase would have differed by nearly 180°. On the contrary, the two were nearly in phase (Table 1).

The volume transport or "through flow" was estimated. The cross-sectional area spans the width of the Maluku Sea at the mooring site; that is, it is assumed that the flow at the mooring is representative of the flow through the section shown in Figure 1. It extends from 750 m down to 1500 m (maximum sill depth for Pacific to Indian Ocean through flow). The mean flow between 740 m and 1500 m was computed on the basis of the means at 740, 1250, and 1500 m (the latter being interpolated between 1250-m and 1750-m instruments). Allowance was made for the existence of a midchannel ridge, which reduced the cross-sectional area. With these assumptions, the mean through flow over the 13 months was found to be about 7 Sv (toward the Indian Ocean). With the same assumptions, an additional 4 Sv on average also flowed southward into the Banda Sea between 1500 m and 1940 m (Lifamatola Strait sill depth). However, being below the Sawu Sea sill depth (1500 m), this flow would have been unable to contribute to the through flow.

Harmonic analysis of the currents along eastward (u) and northward (v) axes found that the major semidiurnal and diurnal components were mainly barotropic (Table 1), despite the known presence of internal tides (*Ffield and Gordon*, 1992) and much stronger surface tidal flows reported in some parts of the archipelago [*Wyrtki*, 1961]. For comparison, the tidal velocity constants from a global tidal model [*Egbert et al.*, 1994] are included in Table 1. The model overestimates the tidal current amplitudes observed at 740 m from the surface, but the phases are in good agreement, aside from the u (cross-stream) diurnal components.

Tidal currents were rotated into principal axes (along-stream and cross-stream components). Only the alongstream component is discussed. At all levels the currents are mixed semidiurnal. The M_2 component is more than twice as large (12.2 cm/s) as the next largest (S_2, 5.9 cm/s). For all major components the tidal currents at the bottom are advanced with respect to those above. For example, for M_2, S_2, O_1, and K_1, the tidal current at the bottom leads that at 1750 m by 27, 31, 26, and 28 min, respectively. However, the tidal currents at 1750 m are nearly in phase with the top current meter (740 m), implying that the bottom friction dominates the inertia of the near-bottom oscillations, as is commonly observed in shallow water. The tidal "mix" varies rapidly between Indonesian basins; for example, tidal currents at 1525 m and 1825 m at Lifamatola Sill were found to be mixed, predominantly diurnal [*Van Aken et al.*, 1988].

4. Hydrographic Data

Six hydrographic stations (labeled 1 through 6 in Figure 1) were occupied at the time of deployment (June 1993). A T-S diagram of the data is shown in Figure 4. Surface water

Table 1. Amplitude (Centimeters/Second) and Phase Lags (Degrees, UT) (in Parentheses) of Major Tidal Current Constituents.

Nominal depth (m)	M_2		S_2		O_1		K_1	
	u	v	u	v	u	v	u	v
. . .	2.0	7.4	1.2	3.2	0.8	2.8	0.8	3.3
	(71)	(222)	(74)	(257)	(145)	(304)	(183)	(304)
740	3.6	11.6	2.3	5.5	3.4	2.8	0.9	5.3
	(67)	(236)	(116)	(282)	(3)	(290)	(47)	(311)
1240	0.6	8.3	0.9	3.3	1.3	3.3	0.6	4.7
	(144)	(242)	(83)	(288)	(287)	(307)	(308)	(312)
1750	2.1	11.5	2.0	3.7	1.4	3.8	1.0	2.9
	(348)	(236)	(38)	(283)	(271)	(319)	(351)	(304)
2240	5.1	11.2	2.6	3.7	0.6	4.1	1.8	2.6
	(350)	(226)	(47)	(273)	(89)	(316)	(269)	(292)

The first row contains tidal constants from "tpxo.3", a global tidal model [*Egbert et al.*, 1994].

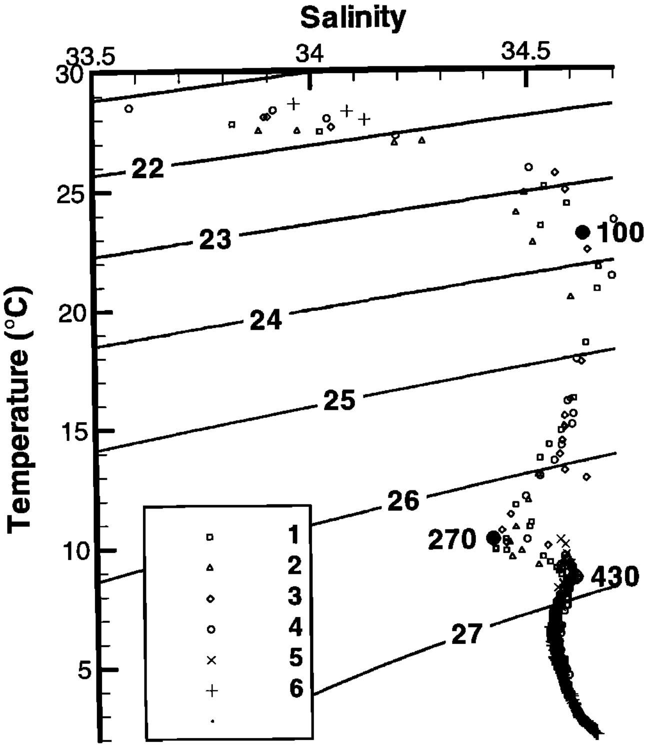

Figure 4. Temperature-salinity plots for the six Maluku Sea stations (data plotted at 20-m intervals). Depths (m) shown are for station 1. Also shown are lines of constant density (σ_θ).

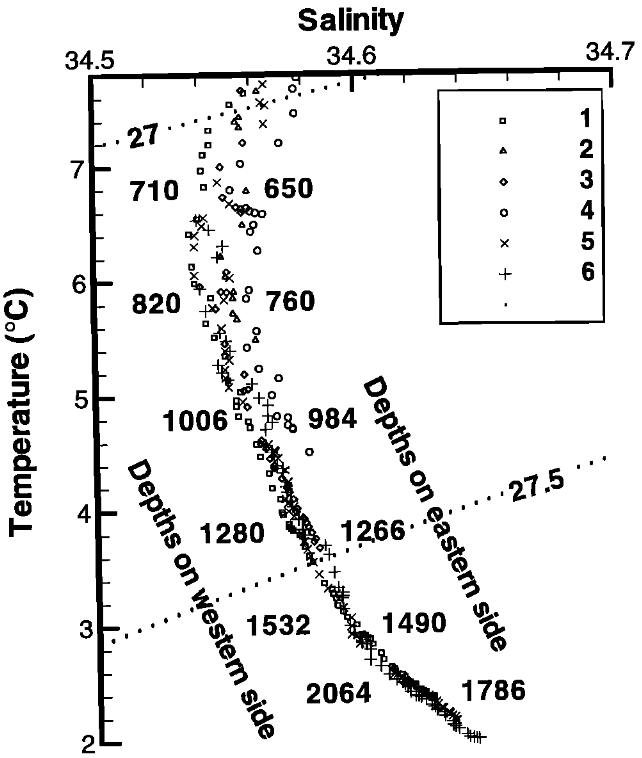

Figure 5. Deep temperature-salinity plots, with depths indicated for station 1 ("western side") and station 6 ("eastern side"). Data plotted at 20-m intervals. Depths shown are for Station 1. Also shown are lines of constant density (σ_θ).

temperatures were above 28°C, and salinity was less than 34. Salinity rose rapidly to a maximum at 100 m (typical Subtropical Lower Water of the Pacific Ocean). The 270-m level marked the bottom of the thermocline and the top of a sharp halocline, which fell between 270 and 430 m. The salinity minimum at about 300 m is also a typical feature of the adjacent Pacific Ocean (see, for example, *Wyrtki* [1961, Figure 6.10]).

The deeper (below about 600 m) T-S profiles are given in Figure 5. They show that waters of similar T-S character are found at 14- to 278-m greater depth on the western side of the basin. Comparing water at the same depths, the data at station 6 indicate that the water at the western end is warmer and fresher (hence less dense). The difference is about 50 m greater at station 5. Although vertical displacements of this magnitude due to internal waves have been found throughout the archipelago [*Ffield and Gordon*, 1992], the depths in question and the consistency of the difference suggests that the isopycnals slope down from east to west (in the correct sense for southward geostrophic flow in the Northern Hemisphere).

Samples obtained at the positions indicated in Figure 6 were analyzed for oxygen. Selected values are given in Table 2. Note that at equivalent depths, the oxygen concentration is lower on the western side (station 2).

5. Discussion

The current meters detected mean southward flow at 740 m, 1250 m, and 1750 m and mean northward flow at 2240 m. A submarine ridge forms a spine running down much of the length of Maluku Sea (Figure 6). Above the Lifamatola Sill depth, flow is toward the Indian Ocean throughout the Maluku Sea. The deeper circulation is more complex. There appears to be a clockwise recirculation of water, such that water arriving at Lifamatola Sill below sill depth (1940 m) is turned back toward the Pacific.

The bottom topography and the directional persistence of the bottom flow at the current meter is suggestive of hydraulic control. This raises the possibility that the deepening of the water properties at the mooring site, which is most pronounced (about 280 m) at the bottom, is the result of flow

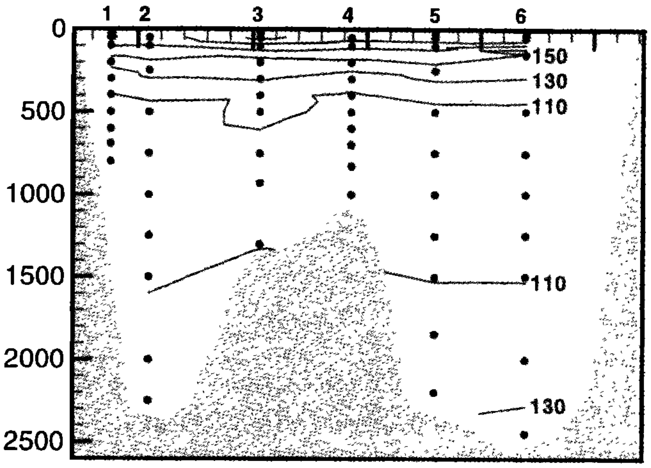

Figure 6. Oxygen transect showing sample depths. Contours are in μmol/dm^3.

Table 2. Oxygen Concentration (μmol/dm^3) at Selected Depths.

Depth (m)	Station 2	Station 6
1500	108.03	109.07
2000	118.80	122.11
2250	120.84	-

over a shoal just south of the site. The second possibility follows the model of *Van Aken et al.* [1988, Figure 2]. In their scheme, the deep waters of the enclosed basins are ventilated by water gradually sinking as it flows around lateral boundaries in a downward-spiraling path. The rate of sinking can be calculated by comparing the depths of water on either side. Water passing southward through the eastern end of the transect at 1820-m depth, sinking below sill depth at Lifamatola Strait, and arriving at the western end of the transect at 2100 m will have fallen 280 m. The travel path is about 900 km (Figure 3). At an average speed of 7 cm/s, the water would take about 150 days to complete the round trip back to the transect. Thus the vertical rate of sinking is about 2 m/d.

Oxygen concentrations provide a check on the above calculation. Interpolating values in Table 1 to 2100 m at station 2, we have $[O_2] = 118.9$ μmol/dm^3. This same value, adjusted by 0.04 μmol/dm^3 to allow for oxygen consumption of 0.083 μmol/dm^3/yr [*Postma and Mook*, 1988] over a period of 150 days, would be found at 1880 m at station 6. This value is 60 m deeper than what would be estimated from the T-S properties alone, indicating that the vertical sinking rate may be an overestimate.

The suggestion that the deep (greater than Lifamatola Sill depth) water property contours sink deeper from north to south through the eastern Maluku Sea is supported by transects of silica concentration [*Van Bennekom*, 1988] and oxygen and temperature [*Van Aken et al.*, 1988]. In fact, the presence of oxygenated water in the deep Banda Sea reported in these studies implies vertical exchange, which, if accounted for, would modify the through flow estimate below (based on zero vertical exchange).

A "through flow" estimate was made. It must be understood that this is not meant to be representative of the total Indonesian Through flow. It does, however, indicate that the middepth transport should not be ignored. The value itself, 7 Sv, is uncertain on several counts, including the assumption that the velocities at the mooring are representative of the entire width of the passage. According to *Wajsowicz* [1999], the through flow tends to concentrate on the western sides of the passages. However, even if the velocities represent only the western portions, the implication to exchange between the Pacific and Indian Oceans is significant. (The ideal placement of the mooring site would, of course, have been Lifamatola Strait; however, under the agreement with the Indonesian government this was not permitted.) The volume estimate is supported by the slope of the isopycnals, which was shown to be in the correct sense for southward geostrophic flow, and by the results of Molcard et al. [1996], which estimated through flow volumes ranging between –0.5 and +4.8 Sv, between the depths of 500 m and 1250 m, over the course of a 1-year period of observation in the Timor Passage.

Recent numerical models [*Gordon and McClean*, 1999; *Morey et al.*, 1999; *Lebedev and Yaremchuk*, 2000] have provided important insights into the flow paths and interocean exchanges. The models emphasize upper layer flow. For example, *Gordon and McClean* [1999] point out that their model does not distribute momentum to the lower levels (of the 20-level model), resulting in unrealistically high flows in the upper layer. *Lebedev and Yaremchuk* [2000] use 32 levels and are able to contrast the total through flow above and below 175 m as a function of time over a standardized 1-year period. According to their model, most of the variability (and flux) is confined to the upper layer. They also found (K. B. Lebedev and M. L. Yaremchuk, personal communication, 1999) two other points of significance in this study: first, there was no westward intensification of the southward flowing middepth currents, and second, at the 1/6° grid cell nearest the mooring, the near-bottom flow (which is below Lifamatola Sill depth) was weakly northward, though irregular. The Lebedev and Yaremchuk model combines realistic topography and high spatial resolution with climatological winds and density. This result hints that as resolution continues to improve, models will in time be able to accurately simulate the complex three-dimensional circulation of the Maluku Sea.

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G. Cresswell, CSIRO Marine Research, GPO Box 1538, Hobart, TAS 7001, Australia. (george.cresswell@marine.csiro.au)

J. Luick, National Tidal Facility Australia, The Flinders University of South Australia, GPO Box 2100, Adelaide, SA 5001, Australia. (john.luick@flinders.edu.au)

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