Observations of the Low-latitude Western Boundary Circulation in the Pacific during WEPOCS III

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Introduction

In 1985, US and Australian investigators began a series of cruises to explore the hydrography and currents of the western equatorial Pacific Ocean. The first two sets of cruises in this Western Equatorial Pacific Ocean Circulation Study (WEPOCS) took place in July-August 1985 (WEPOCS I) and January-February 1986 (WEPOCS II; Lindstrom et al., 1987). They were designed to study the ocean response to the monsoon in the region from 143°E to 155°E, and to determine the source waters of the Equatorial Undercurrent (Tsuchiya et al., 1989). In the US part of the third WEPOCS cruise sequence (WEPOCS III), the focus of attention shifted further west, to the region from 124°E to 143°E, and north to the Mindanao Current and the North Equatorial Countercurrent (NECC). The South Equatorial Current (SEC) was also of interest as a source of water for the NECC.

The US WEPOCS III cruises, during June and July 1988, included the launch of satellite-tracked drifters, continuous acoustic Doppler current profiling (ADCP) along the entire cruise track, and CTD stations with water samples at close intervals along much of the cruise track. In this paper we will show the changing structure of the Mindanao Current as it flows south along the coast of the Philippines, the signature of the Mindanao Current in the salinity field, and the structure of the Halmahera Eddy and the beginning of the NECC (Figure 1). Currents along 141.5°E (and the characteristics of the ADCP data)

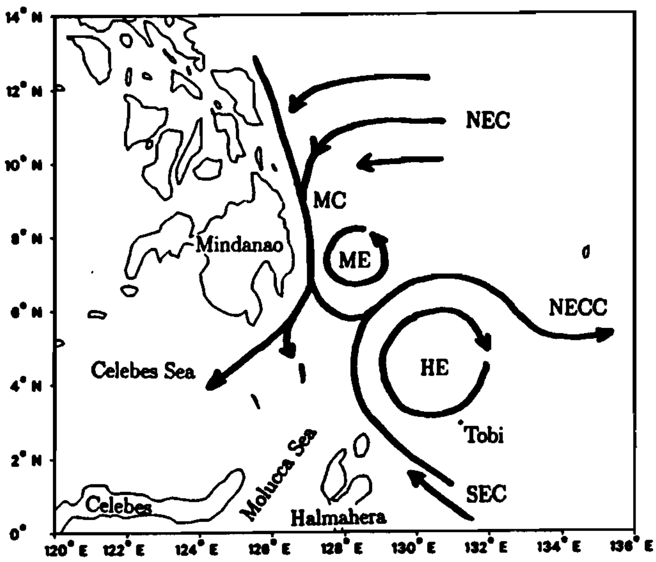

Figure 1: Currents of the low-latitude western boundary region during WEPOCS III: the North Equatorial Current (NEC), the Mindanao Current, the Mindanao Eddy (ME), the South Equatorial Current (SEC), the North Equatorial Countercurrent (NECC), and the Halmahera Eddy (HE).

are discussed by Firing and Jiang (1989). Upper-ocean water properties and air-sea interaction during WEPOCS III are presented by Lukas (1989).

Drifter trajectories

Thirty-five satellite-tracked buoys drogued at 15 m were launched from the R/V Moana Wave during WEPOCS III. During the first three months (July–September) they provide for the first time a quasi-synoptic Lagrangian picture of the surface flow in the region (Figure 2). One group of drifters followed the SEC northwestward along the New Guinea coast, turned around the quasi-stationary (anticyclonic) Halmahera Eddy centered near 4°N 130°E, and proceeded eastward in the NECC. Four buoys made a complete circuit around the Halmahera Eddy. Buoys in the NECC meandered with meridional displacements of 300 km and wavelengths of 600–700 km. Of eleven buoys in the Mindanao Current, two continued through the Makassar Strait, five turned eastward into the NECC, joining those that had retroflected from the SEC, and the rest were grounded or stolen. Three buoys looped cyclonically around the Mindanao Eddy centered near 7.5°N 129°E.

Averaging all July-September drifter velocity measurements in 1° squares and lightly smoothing the gridded values (Figure 3), we find a remarkable similarity to the climatological mean ship drifts (Figure 4) averaged from May through November and smoothed in the same way. (Smoothing was done with the diffusion equation. An anomalous value was reduced by 83% relative to the background field, with 60% of the reduction going to the 8 nearest neighbors.) The Halmahera Eddy is not seen as a closed circulation in the climatology, as it is in the July 1988 drifter tracks, but it is indicated by a southward dip in the NECC at about 135°E. Note also the sharp northward bump in the NECC between 135°E and 140°E in both the drifter measurements (Figure 3) and the ship drifts (Figure 4). The similarity between the drifter tracks and climatology suggests that the WEPOCS III observations were not atypical, despite the cold event that was underway (Kousky, 1989).

The tangled appearance of the 3-month drifter trajectories, with a multitude of crossing paths (Figure 2), illustrates the temporal variability of the flow. For example, the 3 drifters launched in the region of the Mindanao Eddy initially travelled eastward. In early August they reversed course and during that month each made slightly more than one circuit around the eddy. During September their path was predominantly eastward. It appears that the eddy was present (at least in that location) only during August. Similarly, all the circuits around the Halmahera eddy occurred in July; in August, buoys in the NECC proceeded eastward with only a moderate southward dip near 132°E, which previously had been the east side of the eddy.

Currents as measured by the ADCP

The dominant features in the map of upper-ocean ADCP currents are the Mindanao Current and the Halmahera Eddy (Figure 5). The Mindanao Current appears to begin near the northern limit of the measurements, 13.5°N, and accelerates southward along the Philippine coast until it separates at the southern tip of Mindanao and extends as a jet into the Celebes Sea. There is a suggestion of an eddy just west of the separation point, but the cruise tracks there did not extend far enough from the coast to resolve this circulation. Along 130°E, between 12°N and 10°N, the North Equatorial Current (NEC) can be seen flowing west to supply the Mindanao Current. The southern limit of the NEC is not resolved by the WEPOCS III cruise track; it appears to have been between 10°N and 8°N during this cruise. The Mindanao Eddy, distinguished by closed loops in the drifter trajectories during August (Figure 2), is not evident in the ADCP measurements, which were made in July.

East-southeast of Mindanao and north-northeast of Halmahera is the Halmahera Eddy. There is little indication in this near-surface current field of eastward flow in the NECC. Instead, it appears that water enters the Halmahera Eddy north of Halmahera, circulates anticyclonically around the eddy, and exits southward near 133°E on the southeast side of the eddy. This picture is confirmed by the drifter trajectories during July. The partition of NECC source waters among three possible sources—the SEC, the Mindanao Current via the Celebes Sea, and the Molucca Strait (in which water may also come from the Mindanao Current via the Makassar Strait)—is not at all clear from the ADCP currents and the drifter tracks, and remains to be studied through isopycnal analysis.

In the mid-thermocline, 200-250m (Figure 5), the Mindanao Current looks much as it does near the surface apart from a reduction in speed by roughly a half. Elsewhere the mid-thermocline currents differ substantially from the near-surface currents. There is little westward flow in the thermocline that can be identified as the NEC, and little indication of anticyclonic circulation in the region of the Halmahera

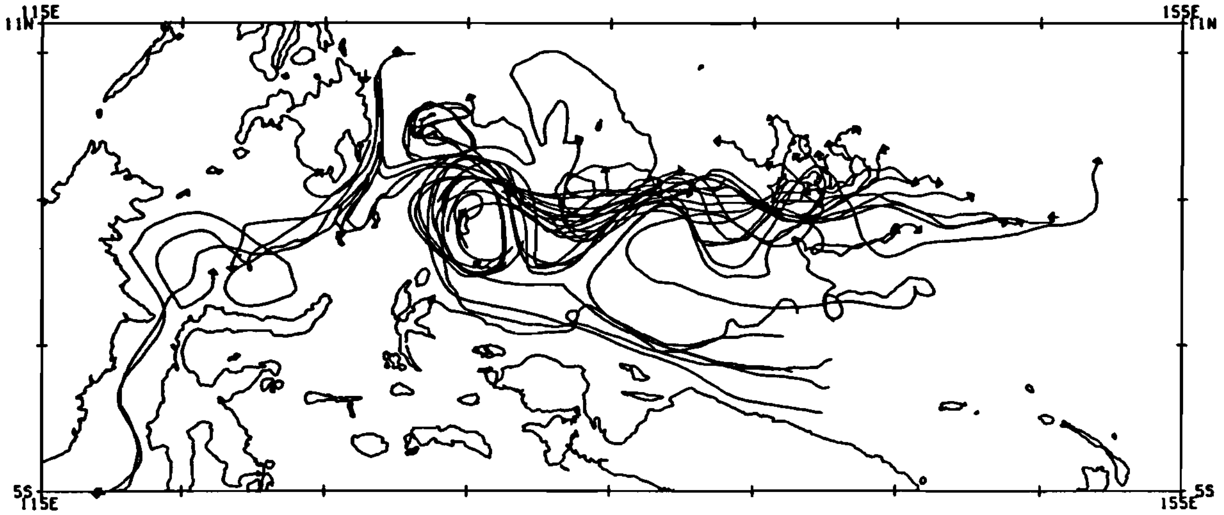

Figure 2: Trajectories of the WEPOCS III drifters, July–September.

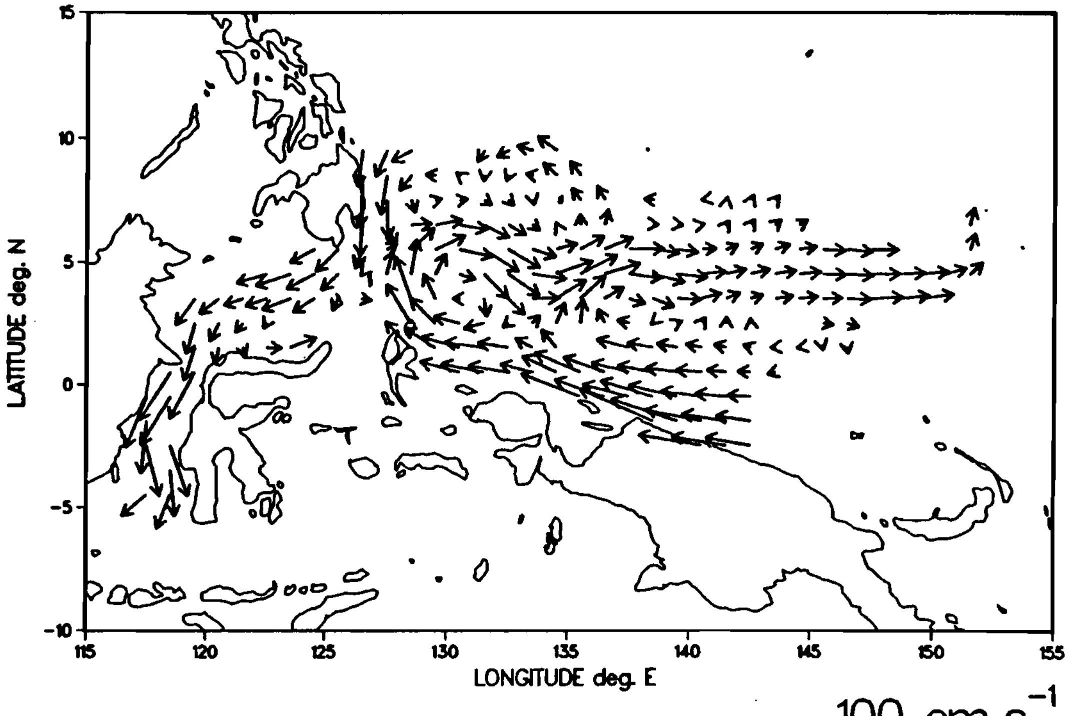

Figure 3: Drifter velocity vectors averaged by 1° squares, July–September 1988. Gridded data have been smoothed (see text).

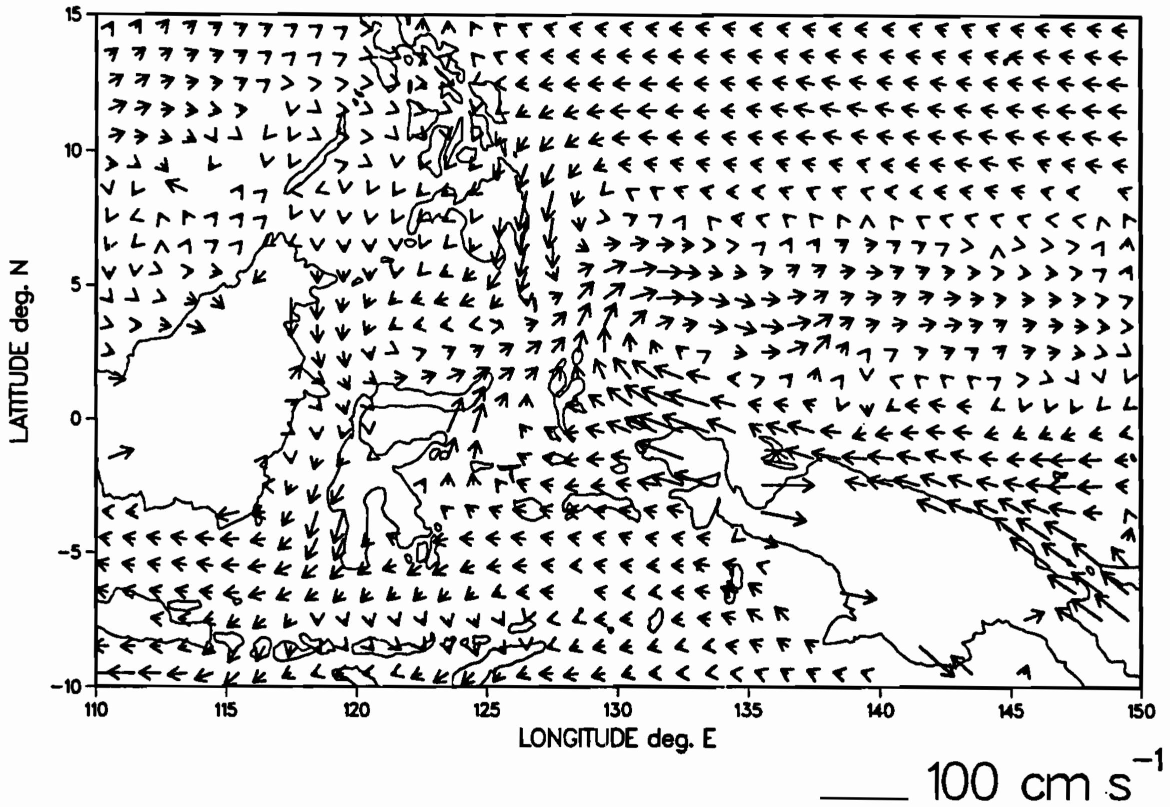

Figure 4: Historical monthly-mean ship-drift observations averaged from May through November in 1° squares and smoothed (see text).

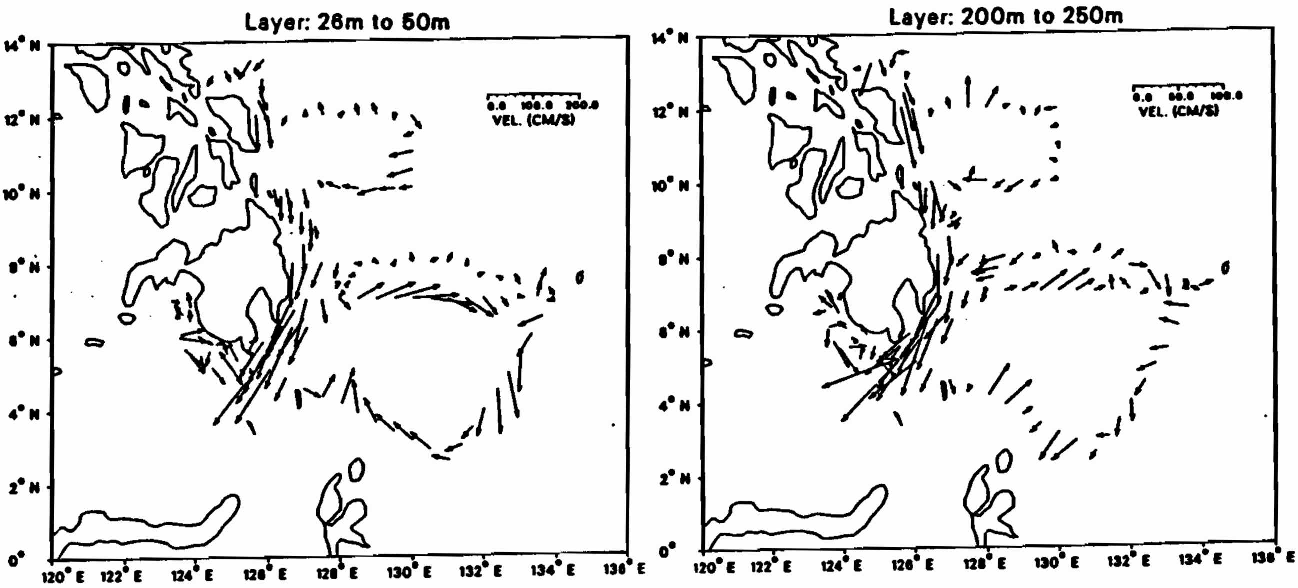

Figure 5: Currents measured by the ADCP, averaged from 25–50 m (left) and from 200–250 m (right). Note the change in velocity scale.

Eddy. The field of motion may include several unresolved eddies; if so, it appears that the surface eddies and the subsurface eddies are not coincident.

The downstream changes in the Mindanao Current can be seen more clearly in the sequence of zonal sections of meridional velocity component (Figure 6). All sections begin within 1 km of the Philippine coast. From 12°N to the southernmost section (Tobi–Mindanao), the vertical shear in the Mindanao Current tended to increase, and the current became increasingly intensified near the surface. The current was nearly uniform over the top 300 m at 12°N, where the maximum speed was about 80 cm/s; at the southernmost section the current increased from 30 cm/s at 300 m to 110 cm/s near the surface. In some of the sections, most notably at 7°N and 8°N, the maximum southward velocity component occurred in a subsurface core near 80 m. This shear reversal may have been caused by strong transient southwest winds retarding the surface current (Lukas, 1989). Offshore of the Mindanao Current, northward currents were found in all sections. The structure of the northward flow varied from section to section, but there appear to be two components: a near-surface current, and a deeper one, with its core near or below the maximum depth range of the ADCP (about 400 m). This subsurface northward current has been identified also in geostrophic sections by Hu and Cui (1989), who have named it the Mindanao Undercurrent.

Geostrophic currents and tracers

The geostrophic current section at 10°N (Figure 7) shows that the Mindanao Undercurrent there has a core depth of about 350 m, and a speed (relative to 1000 dbar) exceeding 20 cm/s, in agreement with the ADCP (absolute) velocity measurement. The undercurrent appears to extend over a large depth range; its full extent cannot be determined from these geostrophic calculations.

The geostrophic current section also agrees with the ADCP section in that both show a strong Mindanao Current, but otherwise the two estimates of current are surprisingly different. The geostrophic estimate of maximum southward component in the Mindanao Current is 165 cm/s, compared with only 60 cm/s from the ADCP. The northward surface current found above the Mindanao Undercurrent in the ADCP section is nearly absent in the geostrophic section. The geostrophic section shows two surface currents with speeds exceeding 40 cm/s—a southward current near 128°E and a northward current near 129°E—which have no obvious counterparts in the ADCP section. These differences between the geostrophic and ADCP current estimates appear to be real, not due to any deficiencies in the measurements, but they are not yet understood.

The salinity field at 10°N (Figure 7) shows two cores near the Mindanao coast that can be used to trace the Mindanao Current. A high-salinity core (>34.9 psu) at 390 cl/ton (about 100 m depth) next to the coast is separated by lower salinity from a second high-salinity core offshore. A low-salinity core (<34.4 psu) is found next to the coast at 150 cl/ton (about 300 m). Both of these cores can be traced along the Mindanao coast from 14°N to the southernmost section (Figure 8).

Transport

Estimates of Mindanao Current transport have ranged from 8 to 40 Sv (Table 1; Lukas, 1988), with the highest resulting from a calculation of Sverdrup transport (Kessler and Taft, 1987). Our estimates for 0–300 m from WEPOCS III, 10–24 Sv, are well within this historical range. Although ADCP and geostrophic transport estimates both increase downstream, the geostrophic estimates are systematically higher than the ADCP integrals on this cruise. The reasons for this difference, and whether it occurs in other observations such as those of the US/PRC Bilateral Air-Sea Interaction Program, remain to be investigated.

Conclusions

Although our analysis of the WEPOCS III data is at an early stage, we can draw some qualitative conclusions:

- Currents during the cruise, June–July 1988, appear to have been normal in spite of the ongoing cold event.

- A strong, narrow Mindanao Current flows southward very close to the coast as far as the southern tip of Mindanao, where it separates and continues as a jet into the Celebes Sea.

- Part of the Mindanao Current turns in the Celebes Sea to feed the NECC. A second major source of the NECC is the SEC, which curves around the Halmahera Eddy. There may also be a contribution from the Molucca Sea, which may in turn receive water from the Mindanao Current

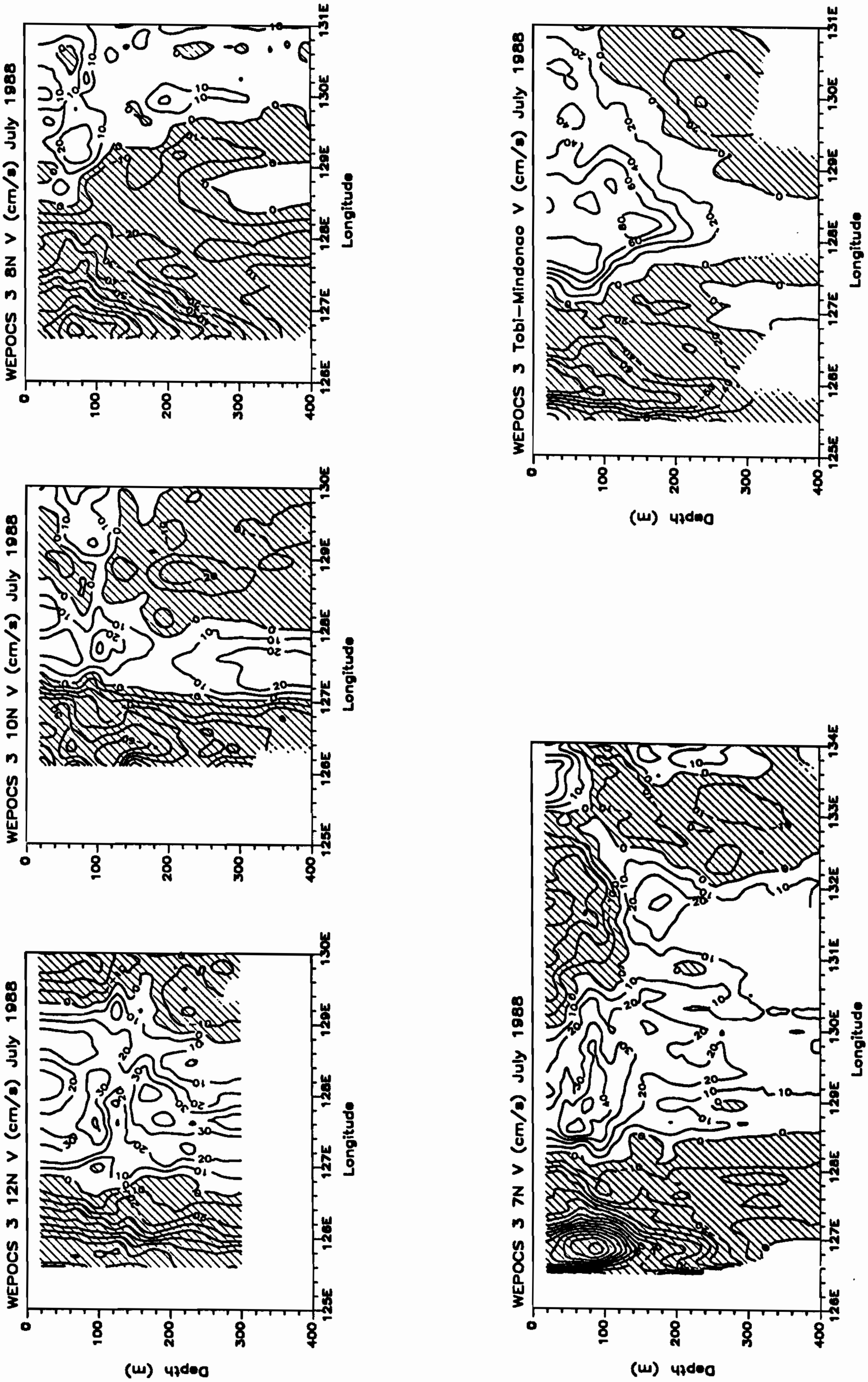

Figure 6: Meridional component of the Mindanao Current from 12°N to the southernmost section, which runs east-southeast from the southern tip of Mindanao at 5.5°N to the small island of Tobi at 2.5°N.

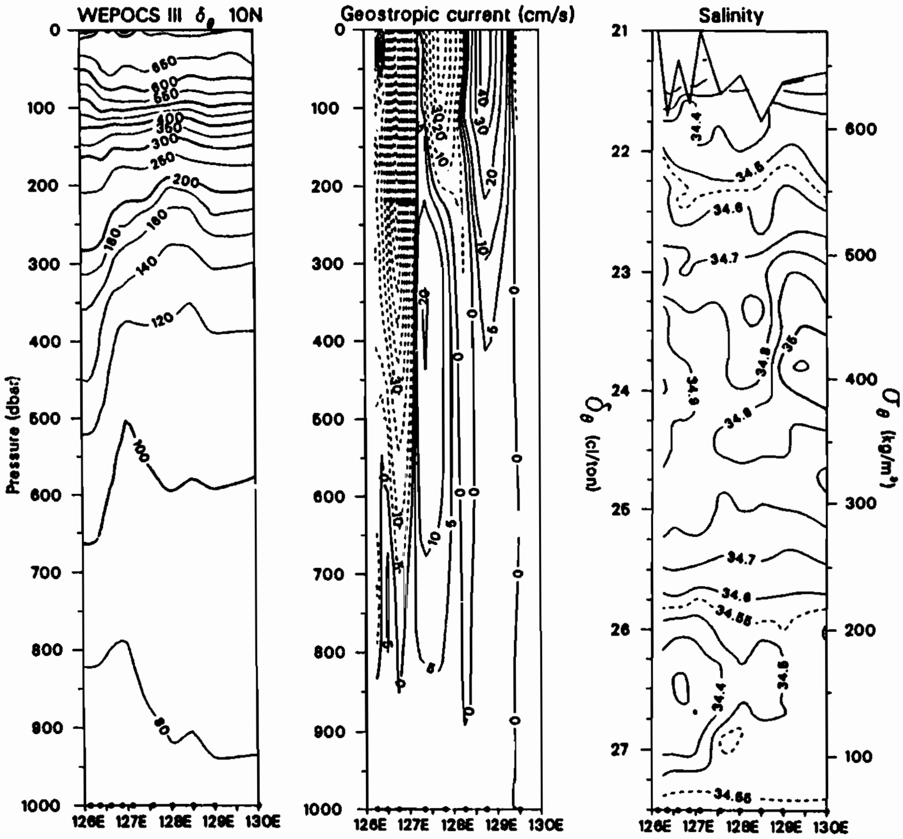

Figure 7: Isopycnals (left) and meridional component of geostrophic velocity (middle) as functions of depth along 10°N; and salinity (right) as a function of δ_θ. Note the high-salinity core next to the Mindanao Coast at 390 cl/ton, and the low-salinity core at 150 cl/ton.

Table 1: Mindanao Current Transport Estimates

Source	Transport	Notes
Wyrtki (1956, 1961)	8–12 Sv	upper 200 m only, friction included
Wyrtki (1961)	25 Sv	0–1000 dbar, relative to 1250, friction included
Masuzawa (1969)	13, 19, 26, 29 Sv	relative to 600 dbar
Kendall (1969)	24 Sv	historical data, geostrophy and mass balance
Cannon (1970)	18, 31 Sv	relative to 1000 dbar; rapid change in space/time
Nitani (1972)	24 Sv	relative to 1200 dbar; plus 15 Sv recirculating in Mindanao Eddy
Kessler and Taft (1987)	24–40 Sv	WBC transport needed to close Sverdrup circulation
Toole *et al.* (1988)	17–18 Sv	transport for T>12°C, relative to 1000 dbar
WEPOCS III	10 Sv at 10°N	ADCP, upper 300 m
	22 Sv at 5°N	
	18 Sv at 10°N	geostrophy, upper 300 m relative to 1000 dbar
	24 Sv at 7°N	

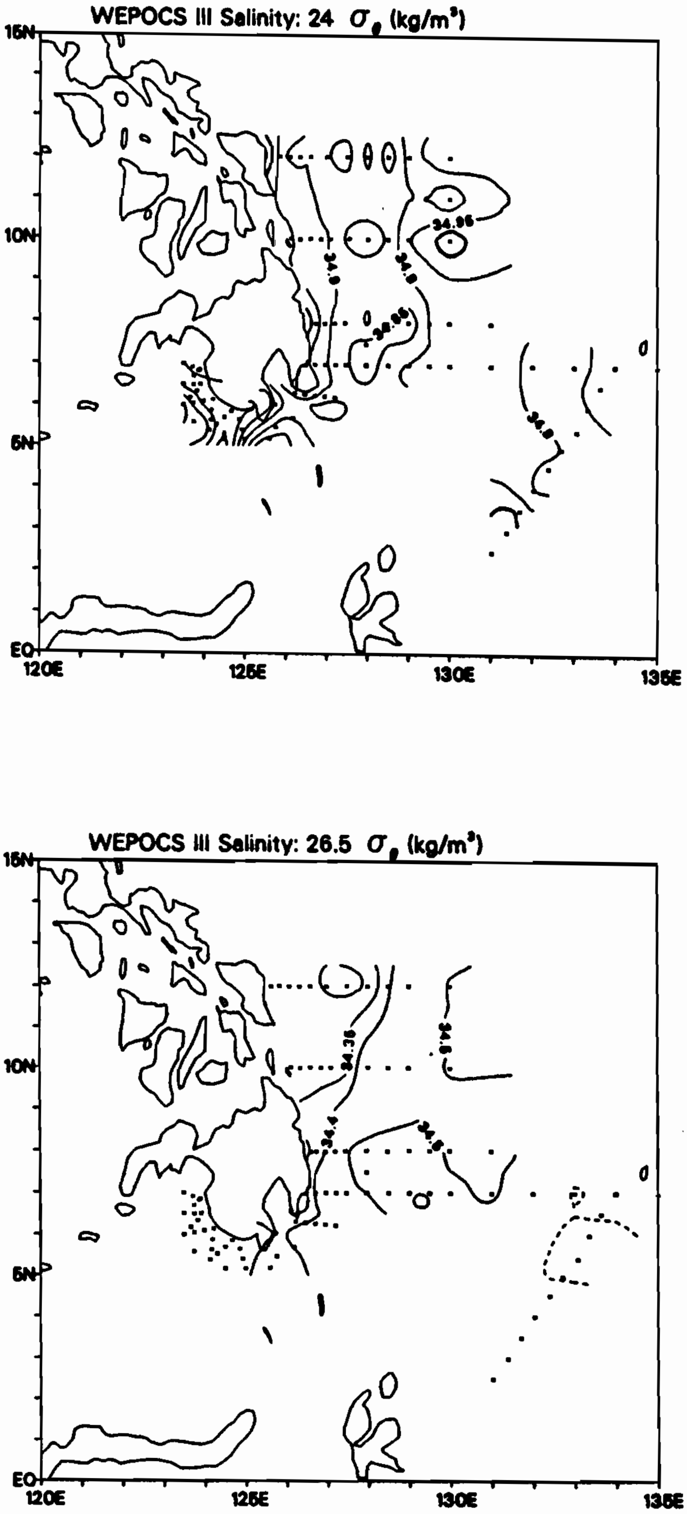

Figure 8: Salinity on the 24 (390 cl/ton; top) and 26.5 (150 cl/ton; bottom) σ_t surfaces. The Mindanao Current carries southward a high salinity core at 24 σ_t and a low salinity core at 26.5 σ_t.

via the Makassar Strait, but this is not resolved by the direct current measurements alone.

- The transport of the Mindanao Current increases rapidly downstream from 10°N to 6°N, as does the vertical shear in the upper 300 m.
- The Mindanao Current carries a high salinity core at 24 σ_t and a low salinity core at 26.5 σ_t.
- Geostrophic and ADCP current estimates in the Mindanao Current can differ by a factor of two.

More detailed analysis of the WEPOCS III data set is planned. In particular, we expect that the combination of isopycnal analysis with the direct current measurements and geostrophic calculations will clarify our picture of the circulation.

Acknowledgements

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