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Observations of the Mindanao Current During the Western Equatorial Pacific Ocean Circulation Study

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The Western Equatorial Pacific Ocean Circulation Study (WEPOCS) III expedition was conducted from June 18 through July 31, 1988, in the far western equatorial Pacific Ocean to observe the low-latitude western boundary circulation there, with emphasis on the Mindanao Current. This survey provides the first quasi-synoptic set of current measurements which resolve all of the important upper-ocean currents in the western tropical Pacific. Observations were made of the temperature, salinity, dissolved oxygen, and current profiles with depth; of water mass properties including transient tracers; and of evolving surface flows with a dense array of Lagrangian drifters. This paper provides a summary of the measurements and a preliminary description of the results. The Mindanao Current was found to be a narrow, southward-flowing current along the eastward side of the southern Philippine Islands, extending from 14°N to the south end of Mindanao near 6°N, where it then separates from the coast and penetrates into the Celebes Sea. The current strengthens to the south and is narrowest at 10°N. Direct current measurements reveal transports in the upper 300 m increasing from 13 Sv to 33 Sv (1 Sverdrup = 1×10^6 m^3 s^{-1}) between 10°N and 5.5°N. A portion of the Mindanao Current appears to recurve cyclonically in the Celebes Sea to feed the North Equatorial Countercurrent, merging with waters from the South Equatorial Current and the New Guinea Coastal Undercurrent. Another portion of the Mindanao Current appears to flow directly into the NECC without entering the Celebes Sea. The turning of the currents into the NECC is associated with the Mindanao and Halmahera eddies.

1. INTRODUCTION

The western equatorial Pacific Ocean circulation and its variability is important to understand because it has potentially large impacts on the Earth's climate. In particular, the role of the interaction of the strong low-latitude western boundary currents with the equatorial circulation in the development of the El Niño/Southern Oscillation (ENSO) phenomenon is unknown, but there are hypotheses which suggest that these interactions are important [e.g., *White et al.*, 1985; *Wyrtki*, 1987]. Also, these boundary currents supply waters of the Pacific Ocean to the flow through the Indonesian Archipelago, which has been shown to play a large role in the basin-scale general circulation and heat and mass balances [*Godfrey and Golding*, 1981; *Piola and Gordon*, 1984; *Gordon*, 1986; *Godfrey*, 1989].

The data available until recently have been relatively sparse and ill suited for resolving the circulation and its variability; the historical hydrographic data do not provide good spatial coverage of these boundary currents and the equatorial circulation, both because of relatively large station spacing and because of coarse sampling in the vertical (see *Toole et al.* [1988] for a summary of these historical data). The historical current measurements consist of short-duration time series by Russian investigators and of low-resolution relative profiles obtained by Japanese investigators using current meters lowered from shipboard [*Montgomery*, 1962; *Guan*, 1986].

Some problems existed with the historical data sets that had been used to study the Mindanao Current prior to 1986. There had been no quasi-synoptic mapping of the currents along with the sampling of the water masses. The separation of the current from the coast had not been observed. The source water properties for the Indonesian throughflow were not well known, especially their transient tracer properties. The fate of the South Equatorial Current/New Guinea Coastal Undercurrent waters had not been determined.

In 1985, U.S. 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]). These cruises were designed to determine the source waters of the Equatorial Undercurrent and to study the ocean response to the monsoon in the region from 143°E to 155°E (Figure 1).

One of the major findings was the discovery of a shallow western boundary undercurrent (the New Guinea Coastal Undercurrent) which transports about 8 Sv (Sverdrup; 1 Sv = 1×10^6 m^3 s^{-1}) from the Solomon Sea through the Vitiaz Strait and into the Bismarck Sea [*Tsuchiya et al.*, 1989]. A portion of this current appears to peel off within the WEPOCS region into the eastward-flowing Equatorial Undercurrent (EUC), but at 143°E the major fraction was still flowing northwestward along the New Guinea coast.

In the third U.S. WEPOCS cruise, the focus of attention shifted farther west, to the region from 124°E to 143°E, and north to the Mindanao Current and the North Equatorial Countercurrent (NECC). The overall objective of the WEP-

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Takahashi [1959, p. 142] noted the existence of "a cold region of distorted elliptic form" east of Mindanao in observations made by Japanese researchers in the early 1950s and related this feature to the circulation inferred from dynamic topography. *Wyrtki* [1961] noted the existence of this quasi-permanent Mindanao eddy associated with the turning of NEC waters at the coast of the Philippines, and their subsequent flow to the east in the North Equatorial Countercurrent. Wyrtki also discusses the seasonal variation of the eddy in relation to the fluctuations of the currents surrounding it.

The dominant feature on the map of the dynamic height of the sea surface relative to 1000 dbar constructed by *Masuzawa* [1968] is the depression of the sea surface near 7°N, 130°E, which is the sea surface signature of the Mindanao eddy. The Mindanao Current flows between the center of this eddy and the coast of Mindanao Island, with speeds of 1 m s^{-1} or more, extending offshore about 100 km according to *Masuzawa* [1969]. *Wyrtki* [1961] shows that the current extends to a depth of about 600 m, relative to 1250 m. On the basis of isopycnal slopes near 600 m, *Masuzawa* [1969] suggests that the current may extend deeper.

A substantial fraction of the water flowing southward in the MC appears to follow the coast of Mindanao into the Celebes Sea, but much of it appears to return to the Pacific to the north of Halmahera, where it becomes the NECC. How much of this water is "lost" to the throughflow is unknown. How much this water is modified within the Celebes Sea as it mixes with other waters is also unknown, but it seems that the low salinity tongue on the 300 cL t^{-1} potential density surface shown by *Masuzawa* [1969] may be partly due to entrainment of low-salinity waters as the MC flows through the Celebes Sea and back into the Pacific.

2.2. *The New Guinea Coastal Currents*

The confluence of waters of northern and southern hemisphere origin which occurs in the far western equatorial Pacific between the islands of Mindanao and Halmahera was investigated by *Wyrtki* [1956]. Here upper thermocline waters in the Mindanao Current and the SEC meet and are deflected eastward, though some waters of southern origin appear to make their way into the Indonesian seas, primarily south of Halmahera Island, but occasionally north of Halmahera as well. The eastward turning of the current along the New Guinea coast appears to be associated with the existence of an anticyclonic eddy.

Russian data from R/V *Vitiaz* were analyzed by *Cannon* [1966], and his analysis on the 300 cL t^{-1} surface (in the center of the thermocline) shows the high-salinity, low-oxygen water mass along the northern coast of New Guinea which we now know to be a manifestation of the circulation associated with the New Guinea Coastal Undercurrent (NGCUC; *Tsuchiya et al.* [1989]). These waters can be distinguished from the high-salinity Tropical Waters (called Subtropical Lower Waters by *Wyrtki* [1956]) of northern hemisphere origin on the basis of their oxygen content, but only near this isopycnal surface. *Moiseyev* [1970] discusses the layers and lens found in R/V *Vitiaz* temperature data from this area. The geographic distribution suggests that these are related to mixing near the confluence of southern and northern waters in the far western equatorial Pacific.

The Japanese have made most of the direct current measurements near the New Guinea coast. The vertical section of currents along 133.5°E and 137°E during January–February presented by *Masuzawa* [1968] in his Figure 2 illustrates the existence of the shallow eastward and southeastward Northwest Monsoon Current, overlying the strong northwestward flow of what appears to be the NGCUC, though Masuzawa considers this flow part of the SEC. The NGCUC is found between 100 and 400 m in the 137°E section, with a maximum speed of 92 cm s^{-1} toward the WNW at 200 m depth. In the 133.5°E section, the flow is only 20 cm s^{-1} to the NW, and it is found between 200 and 300 m on the equator. The eastward flow of the NECC appears to extend south only to 2°N in these sections. This is consistent with the analysis of the NECC boundaries by *Tsuchiya* [1961].

The various WEPOCS observations clearly show the NGCUC at 143°E, with about 10 Sv continuing towards the west. This is just about equal to the eastward transport in the EUC at this longitude so it is tempting to suggest that all of the water of the NGCUC returns to the east, but water mass properties indicate that about one-third of the water in the EUC at this longitude derives from northern hemisphere sources. Thus it appears that about 3 Sv from the NGCUC does not return in the EUC [*Tsuchiya et al.*, 1989]. The fate of this water is not yet known.

3. WEPOCS III OBSERVATIONS

The WEPOCS III Expedition took place from June 18 to July 31, 1988. Leg 1 began in Guam and ended in Palau on July 2. Leg 2 departed Palau on July 5 and ended in Manila. The cruise track is shown in Figure 1.

3.1. *Drifter Launches*

Thirty-five surface drifters were deployed during WEPOCS III [*Wooding et al.*, 1990]; they had small surface floats, drogues centered at 15 m, and drogue sensors. The drag area ratio of the drogues to tether plus surface float was around 50/1. All buoys measured sea surface temperature at a depth of a few centimeters below the surface. Buoy positions were calculated by Service Argos in France from the Doppler shift of the transmitted signal as it was received by polar-orbiting satellites. Each buoy transmitted continuously for its first 90 days at sea which resulted in approximately six fixes per day. After that the buoys transmitted every other day to reduce tracking costs. Data processing was performed at Woods Hole as described by *Richardson and Wooding* [1985].

3.2. *ADCP Observations*

Throughout the cruise an RD Instruments 150-kHz acoustic Doppler current profiler measured velocity structure from 20 m to a typical maximum depth of 350 m. Profiles measured nearly once per second were vector averaged over 5-min intervals in geographical coordinates. Dual-channel Transit and Global Position System (GPS) position fixes were recorded from a Magnavox 1157 integrated satellite navigation system. A rubidium clock was used to extend GPS coverage to 12 h/d.

Problems discussed by *Chereskin et al.* [1989] were minimized by overriding default operating parameters, so that the profiles are expected to be accurate to better than 5 cm s^{-1} as relative profiles. Because of the strong currents in the

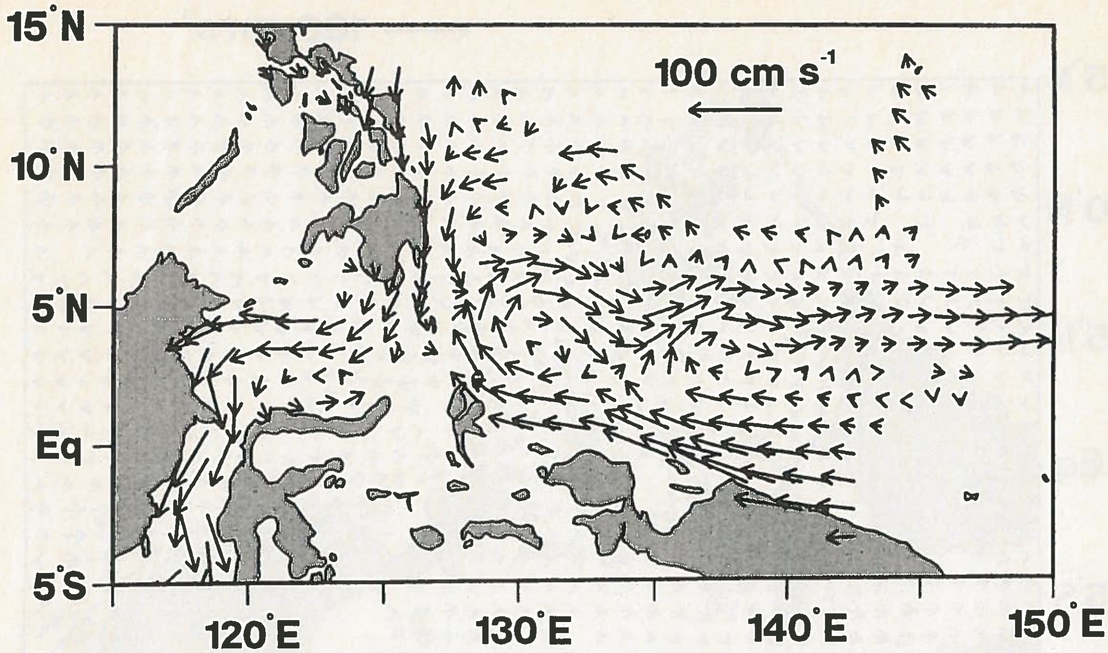

Fig. 3. Drifter velocity vectors averaged by 1° squares, July–September 1988. ADCP current observations are included. Gridded data have been smoothed (see text).

From the drifter array we observed the component currents and associated eddies of the far western equatorial Pacific circulation, including the Mindanao Current (MC), the Mindanao Eddy (near 7°N, 128°E), the South Equatorial Current (SEC), the Halmahera Eddy (near 4°N, 130°E), the origin of the North Equatorial Countercurrent (NECC), the flows in the Celebes Sea, and the flow in the Makassar Strait (Figure 2).

The Mindanao Current had near-surface speeds over 1 m s^{-1} and a width of about 100 km in the area south of Mindanao. Of 11 drifters seeded in the MC, three were advected directly into the NECC, two moved into the Celebes Sea and out again into the NECC, and six drifters entered the Celebes Sea without returning; two of these grounded, two failed or were stolen, and two continued through Makassar Strait with speeds of about 80 cm s^{-1}.

The drifters launched in the Mindanao Eddy described closed loops with a diameter of about 250 km. The circulation in this eddy seemed weaker than in the Halmahera Eddy (see below) and appeared to weaken further over the succeeding months.

Buoys were launched in the SEC as it accelerated to its maximum flow. Five buoys launched north of New Guinea between 1°N and 3°S converged into a narrow, swift current near 136°E. The fastest buoy was that launched closest to the New Guinea coast, moving westward at over 1 m s^{-1}. Three buoys drifted into and around the Halmahera Eddy, one grounded on Halmahera Island, and three retroflected near 135°E before reaching the Halmahera Eddy.

The Halmahera Eddy was revealed by closed loops of about 300 km diameter; the overall size appeared to be about 470 km. Four drifters looped around the eddy, and one slowed near the center. The speed of the drifters in the eddy was about 50 cm s^{-1}, and the period of drifter circuits in the loops was about 20 days.

The NECC was clearly present during the expedition, with buoys from both the MC and SEC traveling eastward in it. The drifters described a meandering path upon entering the NECC near its origin; the meander peaks were separated zonally by 700–800 km, and the meridional displacement of the drifters was about 400 km. There was no zonal displacement of the meander pattern with time which would be characteristic of phase propagation. Over a period of about 1 month, the range of the meanders decayed from 400 km to 200 km. Average drifter speed was about 80 cm s^{-1} with some buoys moving at over 1 m s^{-1}. Highest speeds were found near the origin of the NECC in the west (near 130°E), and slowest speeds of less than 20 cm s^{-1} in the east (145°E to 150°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 eight 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 and the ship drifts. 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].

4.2. *ADCP*

The dominant features in the map of upper-ocean ADCP currents are the MC and the Halmahera Eddy (Figure 5).

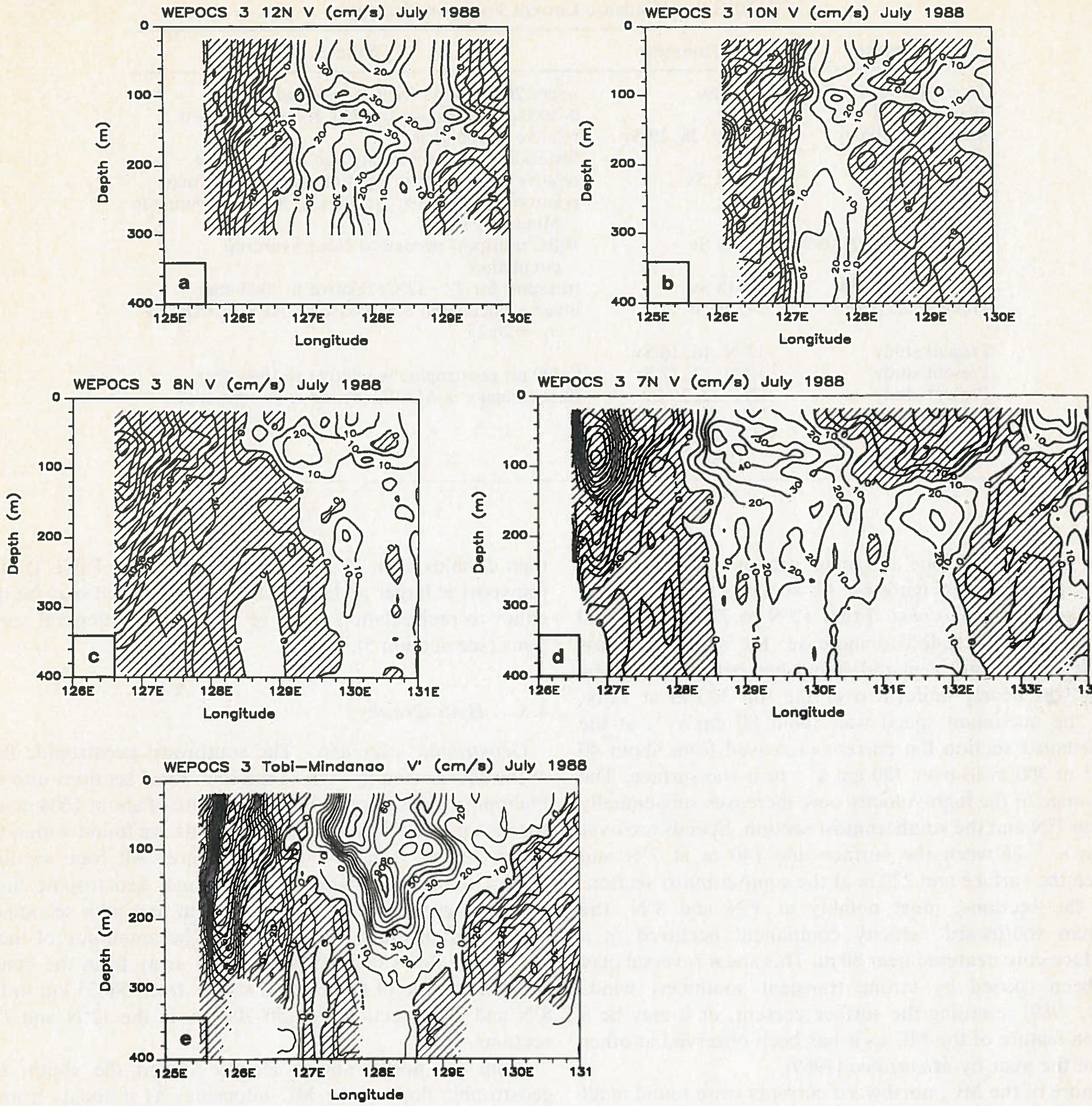

Fig. 6. Meridional component of ADCP-measured current along (*a*) 12°N, (*b*) 10°N, (*c*) 8°N, and (*d*) 7°N, averaged horizontally over 10 km. (*e*) The velocity component normal to the southernmost section which runs southeast from the southern tip of Mindanao at 5.5°N to the island of Tobi at 2.5°N. Because of poor navigational resolution near the coast at 7°N, the peak southward velocity of the Mindanao Current may be underestimated, and the northward flow at 400 m, 126.8°E, may be overestimated. Southward flow is hatched.

(Figure 2), is evident only as a weak feature in the ADCP measurements made in July.

Southeast of Mindanao and 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 four possible sources (the SEC, directly from the MC, the MC via the Celebes Sea, and from the Molucca Strait) is not at all clear from the ADCP currents and the drifter tracks, and remains to be studied through a complete isopycnal analysis.

In the midthermocline (200–250 m; Figure 5) the MC looks much as it does near the surface apart from a reduction in speed by roughly half. Elsewhere the midthermocline 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 Eddy. The field of motion may include several unresolved eddies; if so, it appears that the surface eddies and the subsurface eddies are not vertically aligned.

The downstream changes in the MC can be seen more

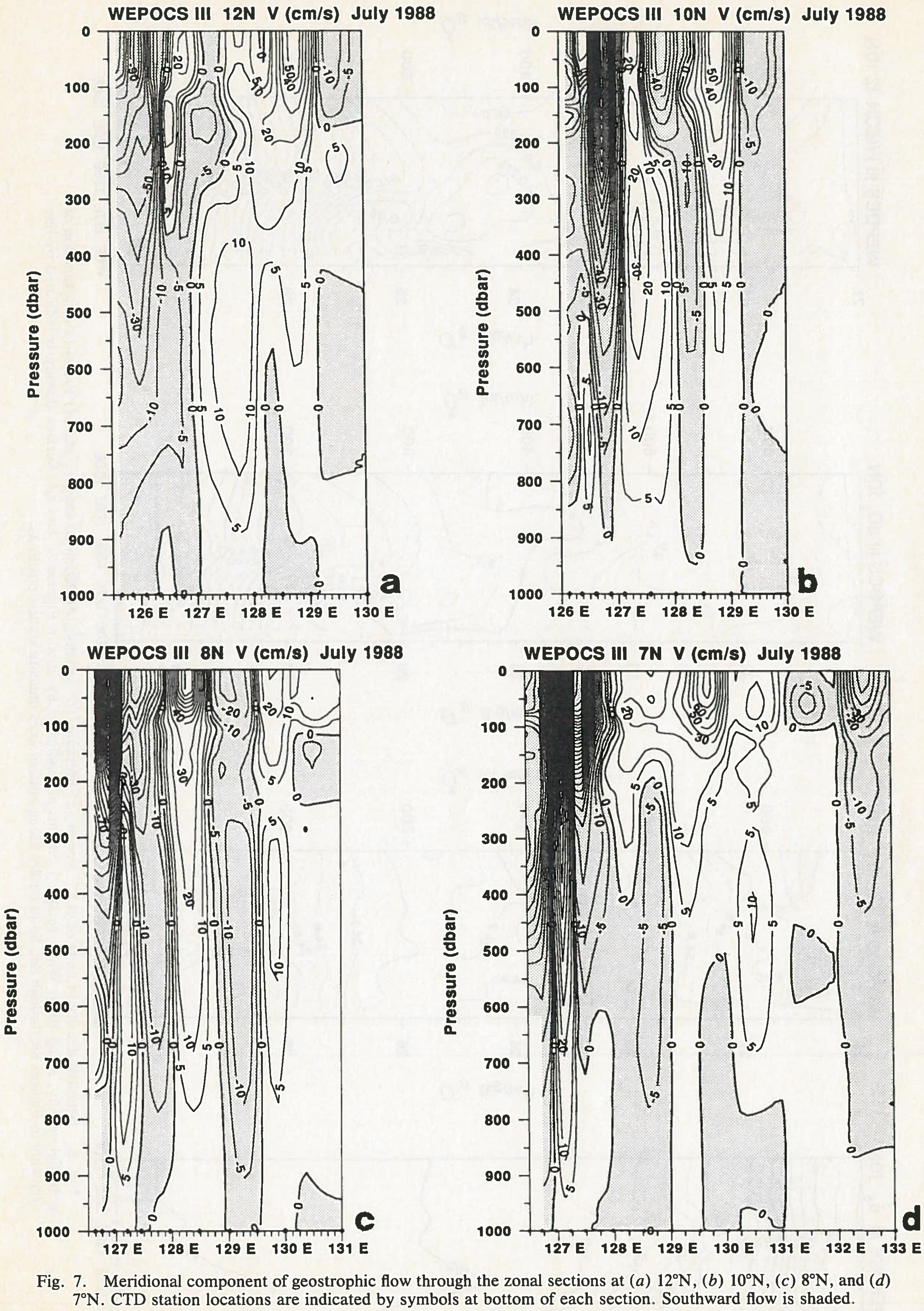

Fig. 7. Meridional component of geostrophic flow through the zonal sections at (*a*) 12°N, (*b*) 10°N, (*c*) 8°N, and (*d*) 7°N. CTD station locations are indicated by symbols at bottom of each section. Southward flow is shaded.

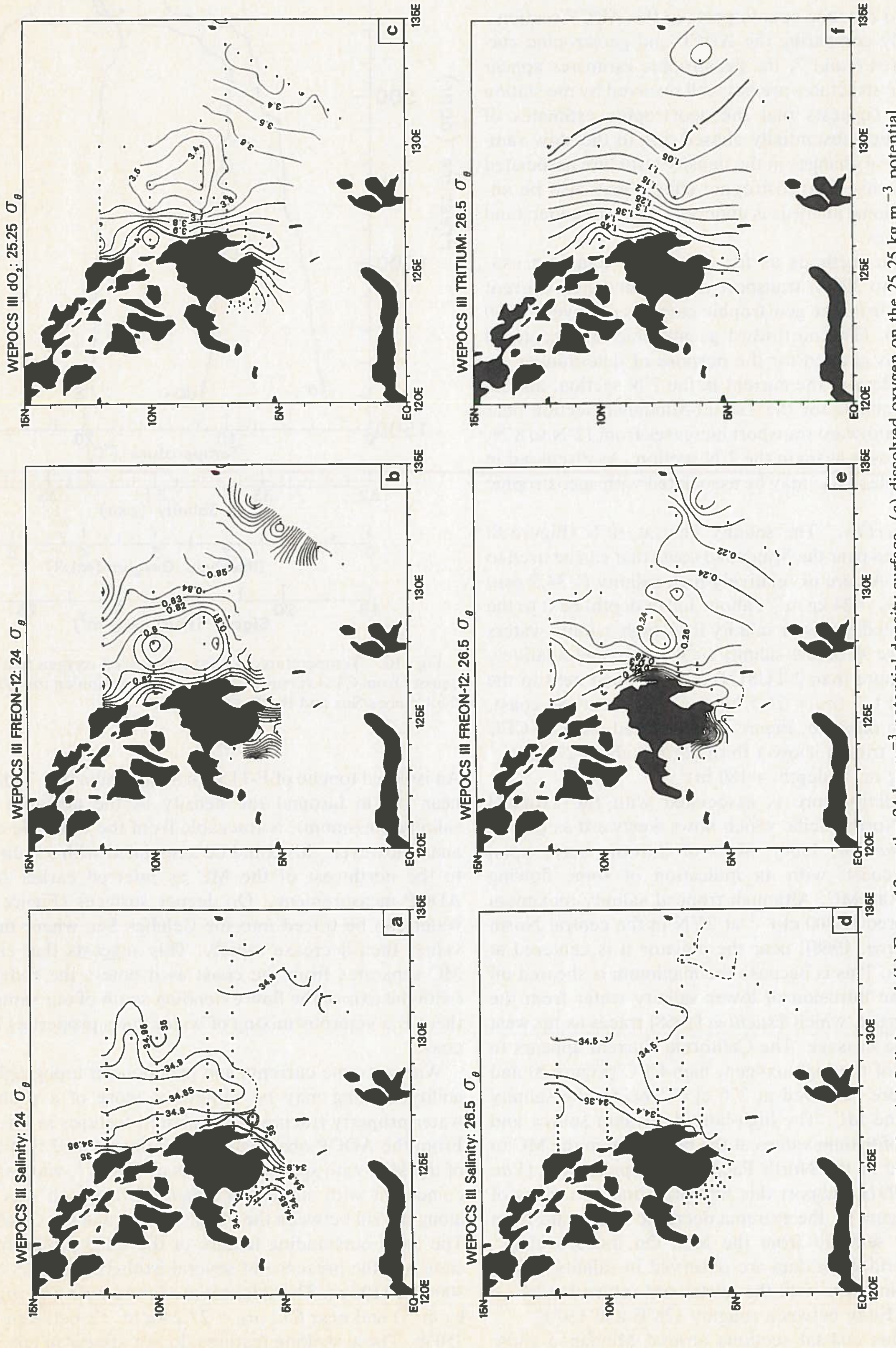

Fig. 9. (*a*) Salinity and (*b*) Freon-12 on the 24 kg m^{-3} potential density surface, (*c*) dissolved oxygen on the 25.25 kg m^{-3} potential density surface, (*d*) salinity, (*e*) Freon-12, and (*f*) tritium on the 26.5 kg m^{-3} potential density surface.

within the MC as it passes over the sill. The O_2 maximum near 8°C that is found in the current outside the sill is apparently wiped out by this intense mixing as the current continues into the Celebes Sea. Similarly, a deep salinity maximum between 8°C and 9°C is strongly modified as the current passes over the sill.

In the MC at 10°N, the low-salinity, high-tritium core has the TS characteristics of North Pacific Intermediate Water (NPIW). *Reid*'s [1965] map of NPIW on the 125-cl t^{-1} surface shows the low-salinity (less than 34.4 psu) water extending southward along the Mindanao coast to 8°N. The low-salinity core in the MC is centered above 125 cl t^{-1}, because at these low latitudes the deeper component of NPIW has been sheared off by intrusion of the relatively higher salinity of Antarctic Intermediate Water (AAIW; [e.g., *Wyrtki*, 1961; *Toole et al.*, 1988]). On maps of 150 cl t^{-1} (Figure 9) the tracer extrema in the NEC observed on shallower surfaces are not evident because of the poleward contraction of the subtropical gyre on denser surfaces. At this density the Mindanao Eddy appears as a salinity minimum. Furthermore, some NPIW, evidenced by a tritium maximum, can be traced to the Halmahera Eddy. Similar to the distributions observed on shallower levels, the tracer values on the 150-cL t^{-1} surface decrease sharply with distance into the Celebes Sea.

There is no maximum in F-12 on 150 cL t^{-1} corresponding to the tritium maximum near Halmahera, due to the different spatial and temporal dependence of the source functions for the CFCs compared to tritium. The absence of a CFC maximum on this density surface is due to the comparable CFC levels in the intermediate waters of southern (AAIW) and northern (NPIW) origin; given the meridional uniformity of the CFC forcing at the sea surface, this implies similar ventilation rates and transit times from temperate latitude source regions in each hemisphere to the western equatorial Pacific. The steep latitudinal gradient in the tritium source function selectively tags the NPIW component, clearly distinguished against the background of underlying AAIW of very low tritium content. Offshore the tritium values are only half of those near the coast. The high tritium values in the MC are similar to those observed in the North Pacific subtropical gyre [*Van Scoy et al.*, 1991], and show that the water is of northern hemisphere origin.

An important aspect of the CFC transient tracers is the possibility of assigning apparent ventilation ages to the deeper density layers. The use of F-11 and F-12 for this purpose is limited to ventilation processes which occurred before about 1976. The precision of the WEPOCS III CFC data was substandard; however, ventilation ages to the nearest decade for broad density intervals can still be assigned with good reliability. All waters sampled in the WEPOCS III study area with density $\sigma_\theta < 25.7$ are "modern" (their F-11/F-12 apparent ventilation age is less than 10–15 years). Water masses of intermediate density ($25.7 < \sigma_\theta < 26.5$) have apparent ventilation ages in the range of 15–20 years. Subpycnocline waters in the density range $26.5 < \sigma_\theta < 27.0$ have apparent ventilation ages of 20–25 years. Although waters below $\sigma_\theta = 27.0$ have measurable CFC tracer burdens (CFC-free waters are found below about $\sigma_\theta = 27.3$), these values lie too close to the blank for reliable dating by the F-11/F-12 ratio method.

The prominent near-surface features of the equatorial current system such as the MC, NGCUC, and the EUC have all been ventilated in the last 10–15 years. The salinity minimum (oxygen and tritium maximum) of the modified NPIW at $\sigma_\theta = 26.5$ (Figure 9) is estimated to have been ventilated approximately two decades earlier, probably in the subarctic frontal region northeast of Japan [cf. *Reid*, 1965]. The apparent CFC ventilation ages of 15–20 years for pycnocline waters in the density range $25.7 < \sigma_\theta < 26.5$ are consistent with the 14-year time scale estimated from tritium penetration on $\sigma_\theta = 26.2$ by *Fine et al.* [1987].

5. DISCUSSION

As discussed by *Lukas* [1988], earlier estimates of Mindanao Current transport have ranged from 8 to 40 Sv (Table 1). Our estimates of 0–300 m from WEPOCS III, 13-33 Sv, are well within this historical range. The various estimates of Mindanao Current transport include both temporal and

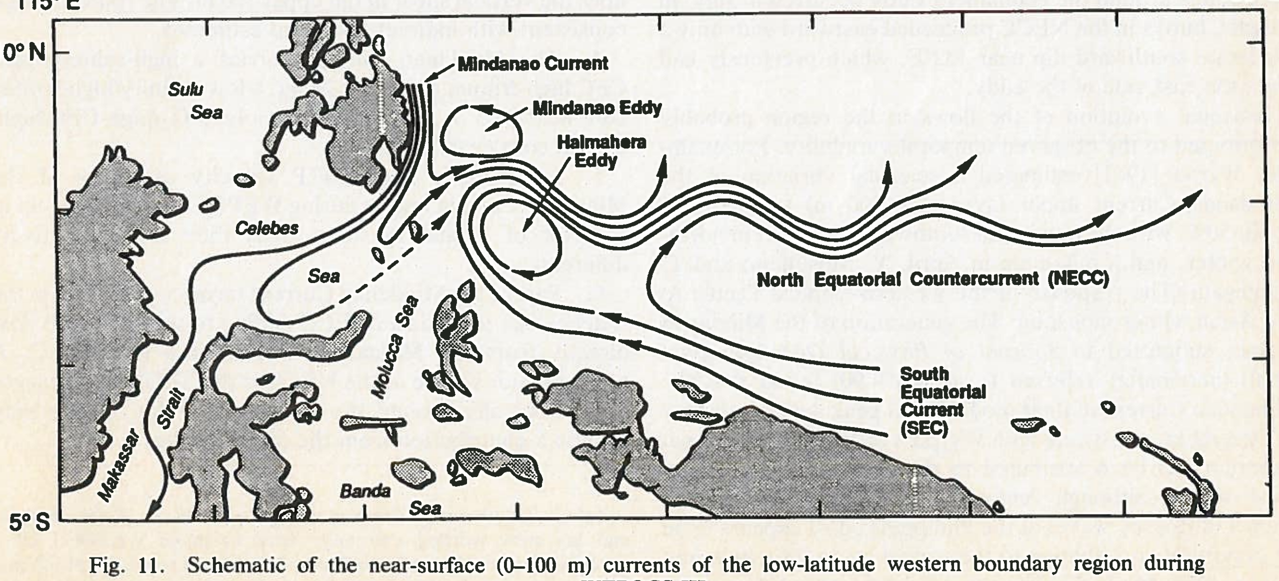

Fig. 11. Schematic of the near-surface (0–100 m) currents of the low-latitude western boundary region during WEPOCS III.

long hours overcoming the problems. The high-quality observations reported here would not have been possible without the expertise of Dave Muus, Art Hester, Marie Beaupre, Dave Bos, Doug Masten, and Carl Mattson of the Scripps Oceanographic Data Facility; the careful freon analyses of Dave Wisegarver, Fred Menzia, and Kevin Sullivan; the assistance of Jefrey Snyder, Gary Arakaki, and Steve Poulos for Doppler current profiling and navigation; and the enthusiasm and help of Mimi Baker, Dave Fratantoni, Ross Gushi, Kathy Prunier, and Janet Sprintall. Sharon DeCarlo, Willa Zhu, and Frank Bahr were instrumental in processing portions of the data and provided the graphics for this paper. We thank H. Gote Ostlund of the Tritium Laboratory for providing the tritium measurements. JIMAR contribution 90-221, SOEST contribution 2448, WHOI contribution 7371. The support of the National Science Foundation under grants OCE-8716509 and OCE-8716510 is gratefully acknowledged. The assistance provided by Richard Lambert to the WEPOCS program is particularly appreciated.

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