The Western Boundary Current in the Far-Western Pacific Ocean

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1. Introduction

The Western Boundary Current (WBC) is well known, not only because of its being one of the strongest currents in the world ocean, but also its extremely important role in the global transport and redistribution of heat. The WBC in the North Atlantic (the Gulf Stream) is quite well understood by long period of various investigations. However, the WBC in the North Pacific (PWBC), especially east of the Philippines is relatively poorly understood, except the Kuroshio south of Japan, although much work has been done during CSK (Cooperative Study of the Kuroshio, 1965-1977). The PWBC is different from the WBC in the North Atlantic, where only exists a northward current in the Gulf Stream. Here, PWBC consists of two currents east of the Philippines : the Kuroshio a northward current, and the Mindanao Current towards the south. The latter is poorly understood.

From 1986 through 1988 about 70 CTD stations (Fig. 1) were occupied by R/V Science 1 of Academia Sinica Institute of Oceanology in each October. In the present paper some features of the PWBC are extracted from the CTD data by inversion manipulation.

2. Method

Since all the CTD casts did not reach the bottom, instead, just 1500 m, Wunsch's inverse method (1978) should be modified for calculation. In consideration of the fact that the velocity field should be of potential with f-plane approximation, we add one more equation

$$\int V X d s = 0$$

to

$$A b = - \Gamma$$

where V is the velocity vector, ds the tangential element vector, c the closed cruise track (loop). A is an m x n matrix, b a column vector consisting of n components, velocities at reference level, Γ a column vector of residual term, as described by Wunsch (1978).
Then we have :

$$\Sigma \delta_j \rho r_j \Delta \chi_j b_j = 0$$

for reference level, say, 1500 m, where δ_j is +1 or -1 depending on whether the water flows into or out of the box, ρr_j the density at the reference level at the j-th station pair, $\Delta \chi_j$ the separation of the j-th station pair, and b_j the reference velocity at the j-th station pair at reference level.

As 1500 m is quite shallow and geostrophy is not quite valid in the upper layer, we divided the water column into two layers by σ_t = 27 or 27.5, which has been tested being the optimal, for every box, in which mass is conserved. Then some features are realized as follows.

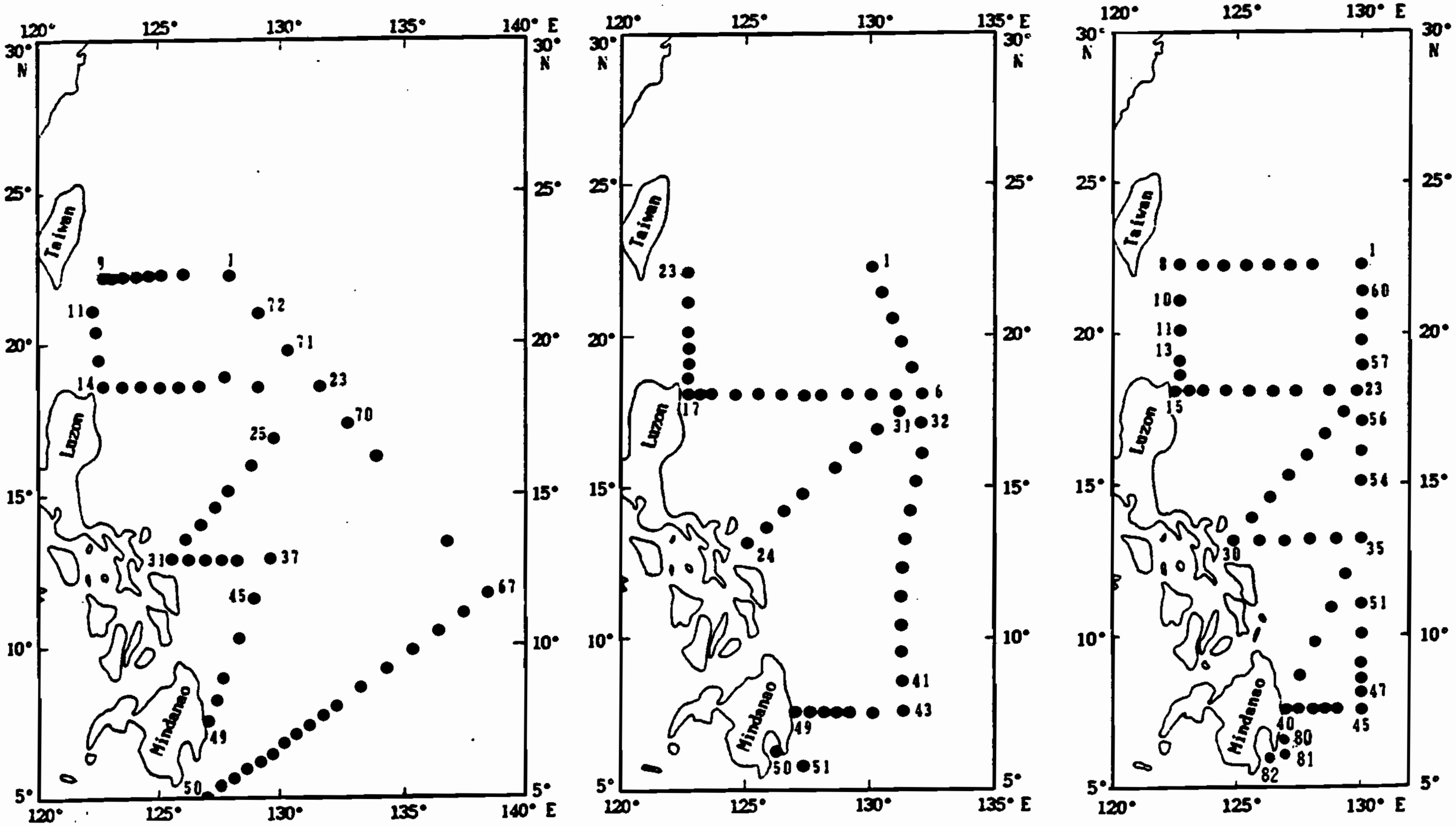

FIG.1. Cruise tracks in October 1986 (left), October 1987 (middle), and October 1988 (right).

3. Some Features of the PWBC

3.1. The Kuroshio at its origin

The Kuroshio is defined differently by different oceanographers (Kishindo, 1931; Sverdrup et al., 1942; Wyrtki, 1961; Nitani, 1972). Nitani (1972) stated that the current from just north of the place where the North Equatorial Current is separated into two branches offshore east of the Philippines to the east of Japan where the current veers away from land can be called the Kuroshio in a broad sense. At least, the beginning of the Kuroshio is in the region off the east coast of Luzon.

In order to detect the Kuroshio three sections east of northern Luzon and Taiwan were designed (Fig. 1). However, the latitude of the section east of the north end of Luzon for 1986 is half degree different (more) than 1987 and 1988. A summary can be made about the Kuroshio as follows from the inversion-calculated results.

a) Volume transport of the Kuroshio in its origin area

October 1986. The strength of the Kuroshio can be examined by westward volume transport through the meridional section east of Luzon Strait (approximately 122°20'E) and northward through the zonal sections (18°30'N and 22°10'N). It is seen from Fig. 2 that the main flows are concentrated in the upper 600m layer. A very narrow northward flow between st. 7 and 9 is more than 19.10^6 $m^3.s^{-1}$ in transport (Fig.2a). There are two westward flows between st. 9 and 11 (east of Taiwan) with 11.10^6 $m^3.s^{-1}$ in transport and between st. 12 and 14 (north of Luzon) with 19.10^6 $m^3.s^{-1}$ (Fig. 2b). A narrow eastward flow of $3.10^6 m^3.s^{-1}$ in transport gets through the meridional section (Fig. 2b). So if we use the northwestward flow from st. 7 and 14 to indicate the Kuroshio, the transport is about 46.10^6 $m^3.s^{-1}$ without the leakage in between st. 14 and Luzon coast (they are about 46 km apart. The velocity near st. 14 is more than 30 $cm.s^{-1}$. Suppose the average velocity in the upper 600 m is 18 $cm.s^{-1}$ southeast of st. 14, then the transport leaked is about $6.10^6 m^3.s^{-1}$. Therefore, the volume transport of the Kuroshio east of Luzon and Taiwan is about 52.10^6 $m^3.s^{-1}$ which is about 1.5 times of the normal transport (Hu, 1989). This can be circumstantially verified by the σ_t = 26 topography (Fig. 5a).

October 1987. Through 122°40'E section (Fig. 3a) gets a westward flow between st. 18 and 21 with a volume transport of 18.10^6 $m^3.s^{-1}$, and eastward flow with $18.7.10^6 m^3.s^{-1}$ in transport including a narrow eastward flow between st. 17 and 18 with 1.5 X $10^6 m^3.s^{-1}$. Through 18°N section (Fig. 3b) take place a northward flow between st. 17 and 14 (transport is about 15.10^6 $m^3.s^{-1}$), and two bands of southward flow offshore with transport of 19.10^6 $m^3.s^{-}$ between st. 14 and 13 and 5.10^6 $m^3.s^{-1}$ between st. 9 and 8 in the upper layer. In consideration of the fact that st. 17 is about 50 km away from land, northwestward leakage between st.17 and Luzon might be about 5.10^6 $m^3.s^{-1}$. And then the transport of the Kuroshio is only about 20.10^6 $m^3.s^{-1}$, which is only half of the normal (Hu, 1989). Obviously, the Kuroshio is weaker during this time. A great deal of water getting through the section of 132°E (Fig. 3d-st. 5 to 1) turns right to the north in the place east of st. 1. This also can be verified by the σ_t = 26 topography (Fig. 5b).

October 1988. An obvious westward flow through the 122°40'E section (Fig. 4a) is between st. 10 and 15 mainly in the upper 600 m layer with a volume transport of about $30.10^6 m^3.s^{-1}$ and a return (eastward) flow in the upper 300 m layer exists between st. 8 and 10 with 7.10^6 $m^3.s^{-1}$ in transport. The section along 18°N (Fig. 4b) shows a strong $28.10^6 m^3.s^{-1}$ in transport and wide (about 300 km in width) northward flow, in the upper 600 m layer between st. 15 and 18 and a return flow, which is 300 km wide and with volume transport of 10.10^6 $m^3.s^{-1}$ in the upper 500 m layer in between st. 18 and 21. This year the volume transport of the Kuroshio here is about 33.10^6 $m^3.s^{-1}$ with the same estimate as above since the distance between st. 15 and Luzon is about 33 km. This tendency can be verified from figure 5c.

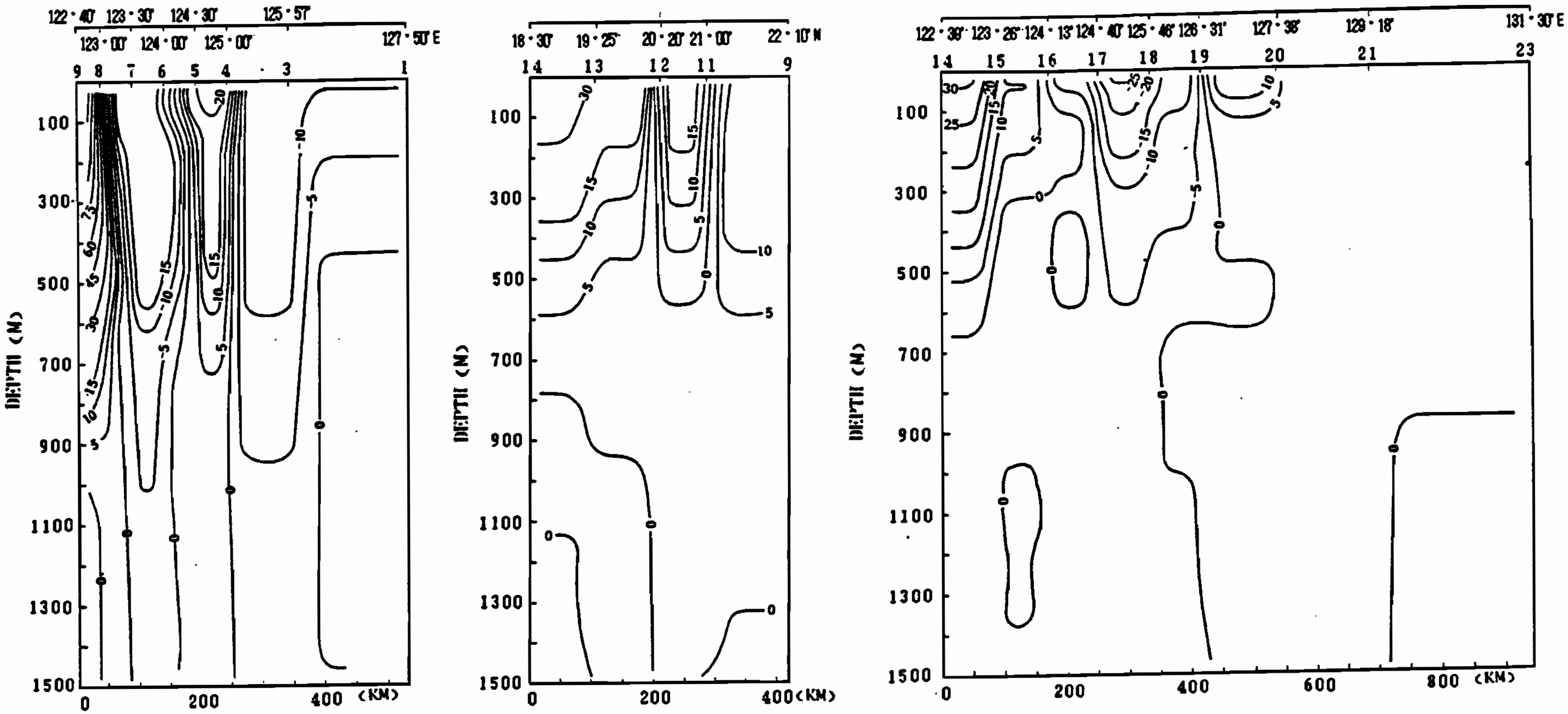

FIG.2. Velocity distribution in October 1986 along 22°10'N (left), 122°20'E (middle), and 18°30'N (right). Positive (negative) flow into (out of) the paper.

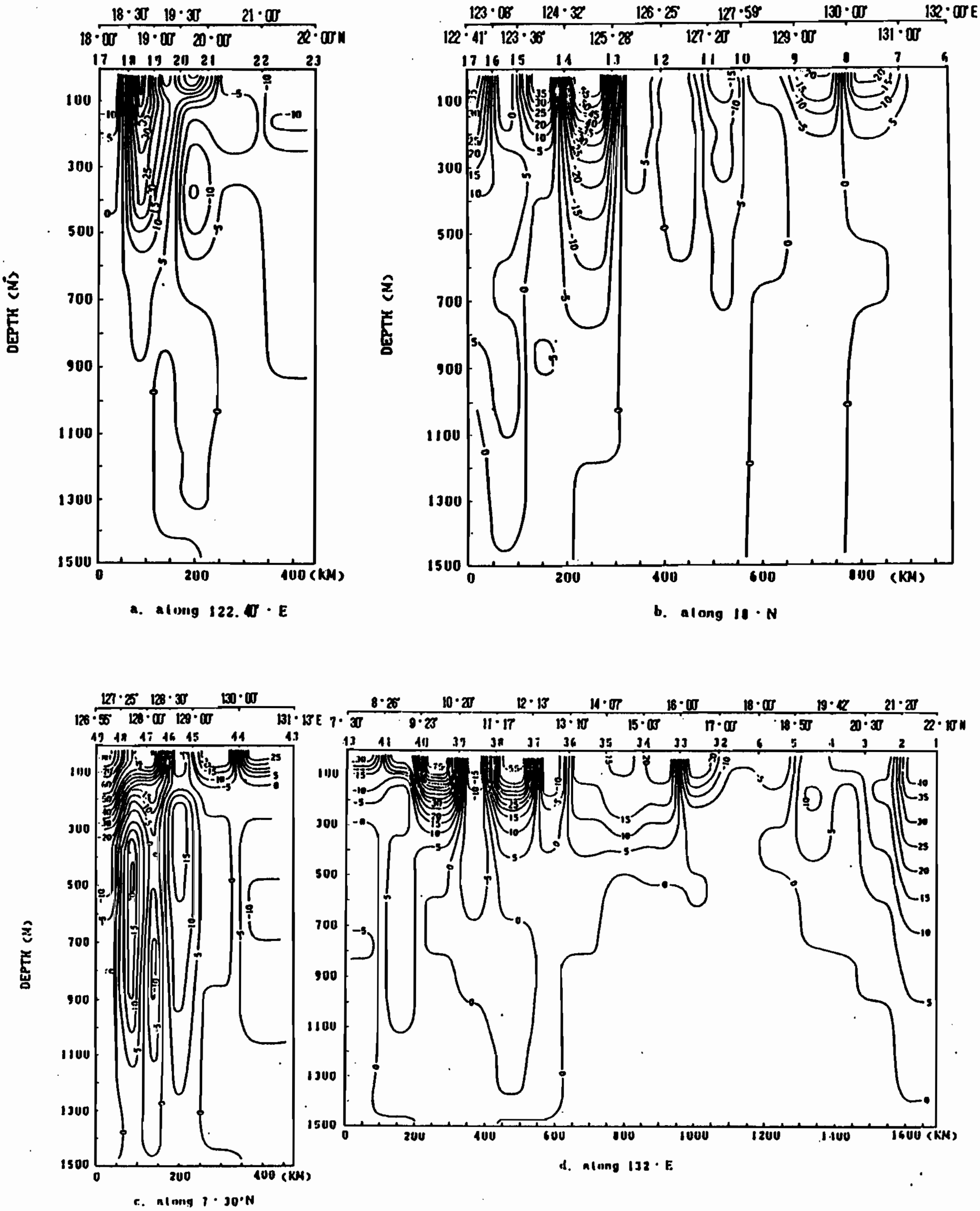

FIG.3. Velocity distribution in October 1987, determined by inverse method. Positive (negative) flow into (out of) the paper.

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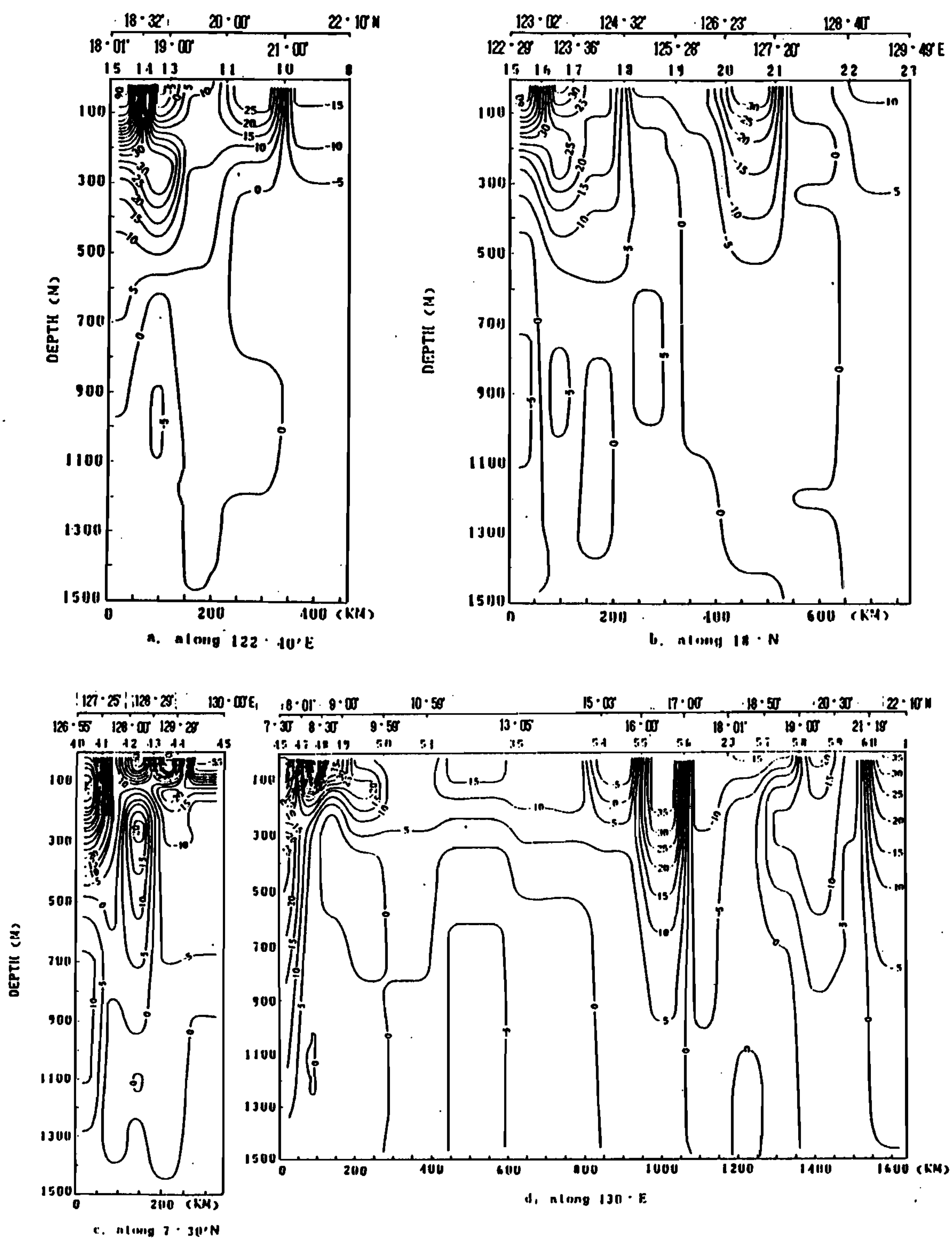

FIG.4. Velocity distribution in October 1988, detremined by inverse method. Positive (negative) flow into (out of) the paper.

In sum, the transport of the Kuroshio east of Luzon Strait is about 52, 20 and $33.10^6 m^3.s^{-1}$ for October of 1986, 1987 and 1988, respectively. Besides the difference in transport, there are still some differences from year to year. For 1986, more than half ($30.10^6 m^3.s^{-1}$) of the transport of the Kuroshio comes from offshore east of Taiwan directly and about 24.10^6 $m^3.s^{-1}$ from the northeast of Luzon. For 1987 the main feature is westward flow near Luzon and eastward flow near Taiwan and the net flux through the meridional section approaches to zero. For 1988, westward flow near Luzon is dominant through 122°40' section and a weak flow returns towards the east.

b. Velocities

1986. The maximum velocity occurs between st. 8 and 9 of about 107 $cm.s^{-1}$ (Fig. 2a). The maximum velocity near the north end of Luzon is about 37 $cm.s^{-1}$ between st. 13 and 14 (Fig. 2b). Flow with velocity greater than 5 $cm.s^{-1}$ appears in the upper 600 m layer on 122°40' section (Fig. 2b) and in the upper 900 m layer on the 22°10' section (Fig. 2a).

1987. The maximum velocity of 54 $cm.s^{-1}$ takes place between st. 19 and 18 north of Luzon (Fig. 3a). Velocity greater than 5 $cm.s^{-1}$ occurs mainly in the upper 800 m layer, which is deeper than 1986.

1988. Velocity takes its maximum of 96 $cm.s^{-1}$ is between st. 14 and 15 (Fig. 4a). Main (greater than 5 $cm.s^{-1}$) flow is concentrated in the upper 600 m layer. A striking feature different from 1986 and 1987 is the fact that there appears an undercurrent north of Luzon (Fig. 4a, b) below 500 m and centered at 900-1000 m with maximum velocity of 6-7 $cm.s^{-1}$ and transport of about 2.10^6 $m^3.s^{-1}$.

c. Eddies surrounding the Kuroshio

It is easily seen from various sections that a quite number of eddies (cyclonic and anticyclonic) take place, for instance, between st. 3 and 4, 5 and 6, 7 and 8, around st. 12, 11, 17, 19 for 1986 (Fig. 2); around st. 8, 11-12, 13, 14, 18, 20-21 for 1987 (Fig. 3); around st. 10, 18, 21 for 1988 (Fig. 4);

3.2. The Mindanao Current (MC) and the Mindanao Undercurrent (MUC)

a. The Mindanao Current

The Mindanao Current is a distinguished branch of the Western Boundary Current east of the Philippines. According to Nitani (1970) the MC east of Mindanao is stronger than the Kuroshio east of Luzon, and its volume transport is about 40.10^6 $m^3.s^{-1}$, while the Kuroshio is only 30.10^6 $m^3.s^{-1}$.

In the present study the MC is examined with a section along 7°30' from a station (126°55'E), which is about 37 km away from Mindanao coast, to a station (130°E) (Figs. 3c and 4c). This section was occupied in October of 1987 and 1988. In what follows, for convenience, it is described yearly first.

1987 (Fig. 3c). The MC is restricted within about 200 km from the coast of Mindanao in the upper 600 m layer (velocity greater than 5 $cm.s^{-1}$). There are two cores between st. 48 and 49 (maximum velocity-about 77 $cm.s^{-1}$) and between st. 44 and 45 (maximum velocity about 25 $cm.s^{-1}$). The calculated southward volume transport from st. 49 to 44 is about 28.10^6 $m^3.s^{-1}$. Suppose the leakage between st. 49 and land can be estimated with average southward velocity of 30 $cm.s^{-1}$, judging from Fig. 3c, in the upper 500 m layer, which accounts for about 6.10^6 $m^3.s^{-1}$. So the total volume transport of the MC in a broad sense should be abut 34.10^6 $m^3.s^{-1}$.

1988 (Fig. 4c). As Cui and Hu (1989) stated, the MC is mainly in the upper 600 m layer with three cores: (1) The strongest is near the coast in the upper 500 m layer with maximum velocity of about 80 $cm.s^{-1}$ located at 120 m. Its transport is approximately 15.10^6 m^3s^{-1}. (2) Adjacent to the above is a shallow one in the upper 150 m with 4.10^6 $m^3.s^{-1}$ in transport and 50 $cm.s^{-1}$ in maximum velocity in between st. 41 and 43 (127°45'

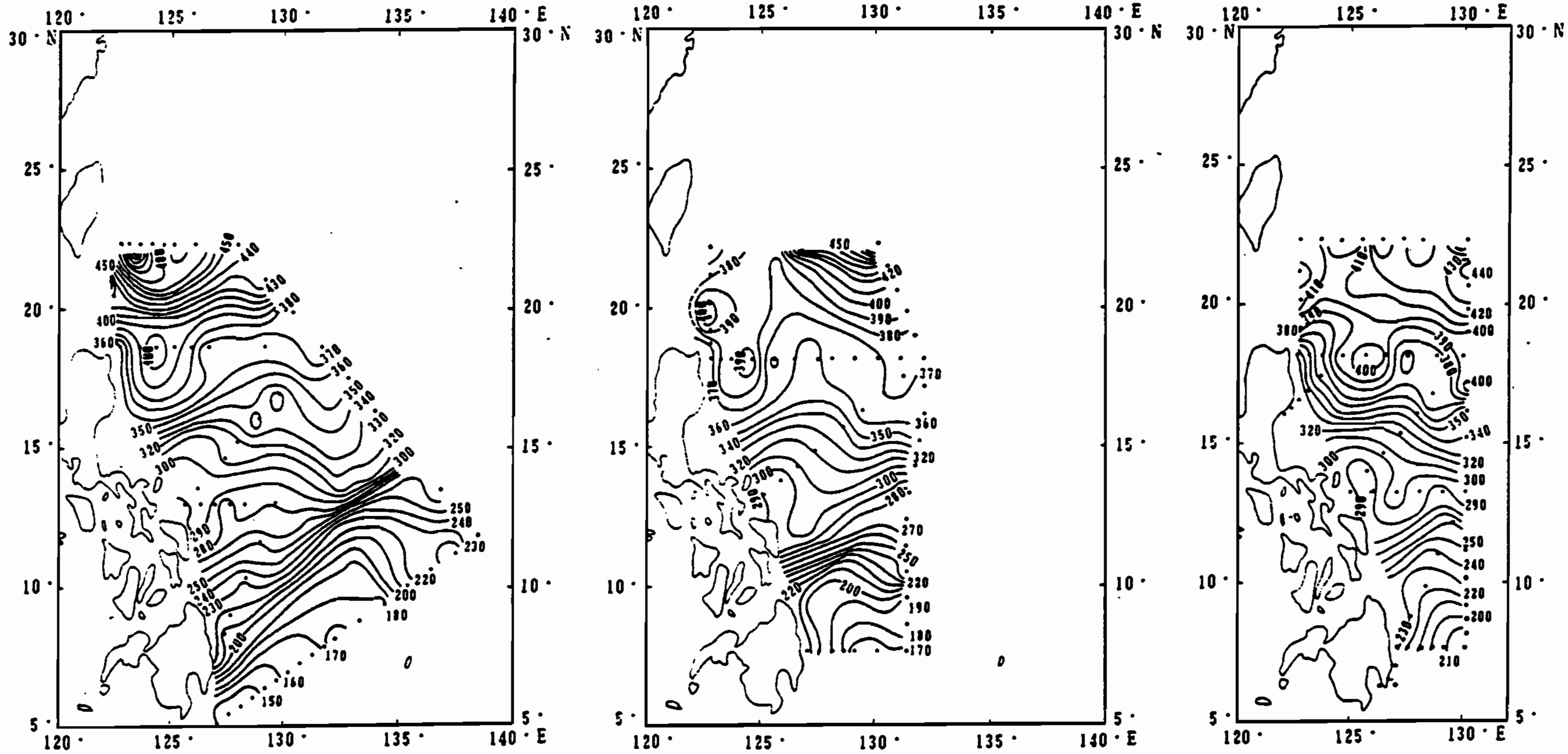

FIG.5. Sigma-t topography in October 1986 (left), October 1987 (middle), and October 1988 (right).

- 128°30'E). (3) Separated by a surface northward flow between st. 43 and 44 (128°30' - 129°E), is a thicker one reaching 1000 m in between st. 43 and 45 (128°30' - 130°E). Its transport is about 12.10^6 $m^3.s^{-1}$ with maximum velocity of about 56 $cm.s^{-1}$. We also calculated the leakage between st. 40 and land with a box consisting of st. 40, 80, 81 and 82, which should be about 5.10^6 $m^3.s^{-1}$. So the total MC volume transport is approximately 36.10^6 $m^3.s^{-1}$.

b. The Mindanao Undercurrent (MUC)

The MUC is definitely revealed on the section of 7°30'N (Figs. 3c and 4c). It seems multicore, penetrating into the MC, which should be considered as a wide flow spanning from the coast of Mindanao to about 130°E since generally the Mindanao eddy is centered at about 130°E.

1987 (Fig.3c). There are two northward quasi-subsurface flow cores, which are separated by an extremely narrow southward flow. The two subsurface flows look like twin with almost the same transport of 9.10^6 $m^3.s^{-1}$ extending from about 200 m to 1200 m with main core from 300 to 1000 m. However, the one closer to the coast is centered at about 500 m with 75 km in width mainly between 127°25' to 128°05'E and another is centered at about 350 m, occupying the whole column with main core from 200 to 900 m and 175 km wide. It seems that the northward flow between st. 43 and 44 (130°-131°E) and the southward flow between 129° and 130° E form an eddy and upwelling around st. 44 (130°E).

1988 (Fig. 4c). There are three northward cores. (1) A protruding northward subsurface current, about 85 km wide is in between 127°45' to 128°30'E with maximum velocity of 22 $cm.s^{-1}$ at 300 m level and thickness of about 650 m (150-800 m) and volume transport of about 5.10^6 $m^3.s^{-1}$. (2) Connected with the above is the nearshore subsurface northward flow below 500 m within less than 100 km from the coast of Mindanao. The core is located at 750 m with velocity of 12 $cm.s^{-1}$ and volume transport of approximately 3.10^6 $m^3.s^{-1}$. (3) A surface northward flow between st. 43 and 44 in the upper 100 m layer with maximum velocity of 39 $cm.s^{-1}$ and a little transport of $1.5.10^6$ $m^3.s^{-1}$.

It seems that the MUC in 1987 is different from and stronger than 1988. But it any case there are some things in common, for example, northward current (MUC) does exist and the three cores look like in somewhat connected.

3.3. The North Equatorial Current (NEC)

a. Volume transport

For 1986 dynamical method is used to estimate transport between st. 56 and 71, which is about 41.10^6 $m^3.s^{-1}$, and then plus 17.10^6 $m^3.s^{-1}$ from inversion for st. 1-72 (Fig. 1a), we have 58.10^6 $m^3.s^{-1}$ for NEC transport through around 130°E from 7°30' to 22°10'N. For 1987 the transport of the NEC, calculated from inversion, is 61.10^6 $m^3.s^{-1}$, and about half of which is transported to the north, west of st. 1 (Fig. 3d). For 1988, $45.10^6 m^3.s^{-1}$ is transported westward through section of 130° E from 7°30' to 22° 10'N (Fig. 4d) with almost no northward transport through section of 22° 10'N.

b. Flow pattern

Since there is no meridional section for 1986 around 130° E, comparison is meaningless. For 1987 there are three strong westward flows between st. 40 and 39, 38 and 37, 3 and 1, which constitute the main body of the NEC. And also there are a few bands of eastward flow (Fig.3d): (1) between st. 43 and 41 (7°30'-8°27'N) below 300 m; (2) 7.10^6 $m^3.s^{-1}$ mainly between st. 39 and 38 (10°20'-11°17'N) with maximum velocity 23 $cm.s^{-1}$; (3) 3.10^6 $m^3.s^{-1}$ between st 37 to 36 (12°13'-13°10'N) in the upper 400 m with maximum velocity 14 $cm.s^{-1}$; and (4) 16.10^6 $m^3.s^{-1}$ between st. 33 to 5 (16°-18°50'N) in the upper 500 m and between st. 36 to 3 (13°10'-20°30'N) below 500 m. It seems there are three swift eastward flows near 11°, 12°30' and 16°30'N in the upper 400 m layer. In the lower layer below 600 m there exists wide sluggish eastward flow. In sum, in the upper layer (0-600 m) transport is $69.10^6 m^3.s^{-1}$ westward; in the lower layer (600-1500 m-) transport is 7.10^6 $m^3.s^{-1}$ eastward.

For 1988, westward and eastward flows are alternate (Fig. 4d). There are two swift westward flows : one near 8°N with maximum velocity of about 122 cm/s and another near 16°30'N with maximum velocity of 37 $cm.s^{-1}$. Also there appear a few bands of eastward flow : one from 10° to 15°N in the lower layer (500-1500m) with transport of about 16.10^6 $m^3.s^{-1}$, the second from 17° - 20°N from surface to 1500 m with volume transport of 15.10^6 $m^3.s^{-1}$ and maximum velocity of about 16 $cm.s^{-1}$ at surface near 18°30'/N. As a whole, transport in the upper layer (0-600 m) is - 49.10^6 $m^3.s^{-1}$ westward and in the lower layer (600x1500m) is - 5.10^6 $m^3.s^{-1}$ eastward.

Summarizing, the NEC consists of a quite number of zonal flows, which are alternate and, as far as volume transport is concerned in the upper layer (0-600 m), it is westward and in the lower layer (600-1500 m) is eastward, which implies the undercurrents take place.

3.4. Dynamical aspects of the PWBC

a. Dynamical structure of the circulation in the far-western Pacific

As is know, the NEC is divided into two branches offshore east of the Philippines: the Kuroshio and the Mindanao Current. That is true for the surface layer. What happens for the lower layer?

From the velocity section along 7°30'N of 1987 and 1988 (figs. 3c and 4c) prominent northward undercurrent (MUC) takes place with considerable transport. Again, from the meridional section of 132°E (1987) or 130°E (1988), eastward flow in the lower layer is obvious.

Now, let us examine the situation off Luzon coast. First of all, from the section of 122°40'E of 1988 (Fig. 3a) an eastward subsurface flow can be seen near the coast centered at 1000 m with 2.10^6 $m^3.s^{-1}$ in transport and 6 $cm.s^{-1}$ in maximum velocity. From the section of 18°N a southward subsurface flow can be found centered at 900 m with volume transport of $2.5.10^6$ $m^3.s^{-1}$ and a maximum velocity of 7 $cm.s^{-1}$.

Judging from the above, the dynamical structure of the circulation in the far-Pacific seems the following. In the surface layer, the NEC is divided into the Kuroshio and the Mindanao Current (MC) . In the lower layer, the Mindanao Undercurrent (MUC) flowing towards the north and the subsurface flow from the north to the south converge somewhere around 15°N east of Luzon and Samar causing eastward flow through 130°E section, which is consistent with the calculated transport through the section of 130°E or 132°E.

b. Possible role of the PWBC in climate

* The role of the Kuroshio in climate of southeast China.

The ocean plays a central role in the variability of global climate and appears to be as important as the atmosphere in the global transport and redistribution of heat. Poleward heat transport of the PWBC in a narrow band is the main channel of heat transport in the world ocean. On the other hand, the effect of the ocean on climate can be classified into two categories : remote effect and local effect. The first means that the ocean affects general atmospheric circulation, which furthermore makes effect upon climate in some area. The second means that the effect is more direct, for example, the area near coastal upwelling or cold currents will be colder than other places at the same latitudes. In terms of local response, East Asia, especially southeast China should be heavily influenced by the northward - flowing PWBC (Hu, 1989).

* Possible role of the Mindanao Current in formation and maintenance of the warm pool in the western Pacific

Surface warm water is driven by the trade wind to the west and piled up in the equatorial western Pacific. Since the western boundary near the equator, such as the Papua New Guinea and Indonesia coast is more zonal (of acute angle with the equator) rather than meridional, the following question will naturally turn out. How can the warm water stay near the equator of how can the warm pool be maintained? It is speculated that the Mindanao Current and continuous North Equatorial Countercurrent (NECC) play an important role as if they acted as solid boundary preventing the warm water to extend to the north. So MC and NECC are important for study of the warm pool.

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