Journal of the Oceanographical Society of Japan
Vol. 34, pp. 160 to 172, 1978

Splitting of the Subtropical Gyre in the Western North Pacific*

Keiichi HASUNUMA and Kozo YOSHIDA**

Abstract: Examined here is a hypothetical idea of the splitting of the subtropical gyre in the western North Pacific on the basis of two independent sources of data, *i.e.*, the long-term mean geopotential-anomaly data compiled by the Japanese Oceanographic Data Center and the synoptic hydrographic (STD) data taken by the Hakuho Maru in the source region of the Kuroshio and the Subtropical Countercurrent in the period February and March 1974. Both of the synoptic and the long-term mean dynamic-topographic maps reveal three major ridges, which indicate that the western subtropical gyre is split into three subgyres. Each subgyre is made up of the pair of currents, the Kuroshio and the Kuroshio Countercurrent, the Subtropical Countercurrent and a westward flow lying just south of the Countercurrent (18°N-21°N), and the northern part of the North Fquatorial Current and an eastward flow at around 18°N. The subgyres are more or less composed of a train of anticyclonic eddies with meridional scales of between 300 and 600 km, so that the volume transport of the subgyres varies by a factor of two or more from section to section. The upper-water characteristics also support the splitting of the subtropical gyre; the water characteristics are fairly uniform within each subgyre, but markedly different between them. The northern rim of each subgyre appears as a sharp density front accompanied by an eastward flow. The bifurcations of the sharp density fronts across the western boundary current indicate that the major part of the surface waters in the North Equatorial Countercurrent is not brought into the Kuroshio. The western boundary current appears as a continuous feature of high speed, but the waters transported change discontinuously at some places.

1. Introduction

The most pronounced feature of the general circulation of the ocean is the subtropical gyre, the western margin of which is composed of an intensified current such as the Kuroshio or the Gulf Stream. The general motion over the interior of the gyre has long been thought to be slow and changeless. Besides the recent discoveries of the energetic meso-scale eddies in the interior oceans, which should certainly be of first-rank importance in oceanography, we may point out another type of fundamental departure from the quasi-permanent structure of the interior subtropical gyre hitherto believed. This feature had been entirely overlooked before YOSHIDA and KIDOKORO (1967a, b) pointed its possibility. They predicted the presence of an eastward current, the Subtropical Countercurrent, in the midst of the interior region of the subtropical gyres in various oceans. The important points in their predictions are the possibility that the subtropical gyre could be split into two gyres, north and south, and the suggestion that we might have to reexamine the interior structure of the gyre which could differ fundamentally from that hitherto considered.

Various papers supporting the existence of the Subtropical Countercurrent and consequently of the splitting of the subtropical gyre have appeared since around 1969. UDA and HASUNUMA (1969) presented evidences for the countercurrent to be persistent throughout the year from hydrographic and ship-log data. A thermocline-depth topography computed from bathythermograph (BT) data (ROBINSON, 1969) reveals a steep southward deepening at around 20°N. Indications of the eastward counter-

---

* Received Oct. 17, 1977, revised Aug. 15 and accepted Sept. 11, 1978.

** Ocean Research Institute, University of Tokyo, Minamidai 1-15-1, Nakano-ku, Tokyo 164, Japan

*** Geophysical Institute, University of Tokyo, Yayoi 2-11-16, Bunkyo-ku, Tokyo 113, Japan

current are clearly seen on the synoptic maps of dynamic topography obtained during the Cooperative Study of the Kuroshio (CSK) Program (Japanese Oceanographic Data Center, 1967, 1968, 1969, 1970). WYRTKI (1974a, 1975) mapped the dynamic topographies relative to 500 db and 1,000 db for the entire Pacific Ocean using all available hydrographic data. Although the gross feature of his dynamic topography is similar to those presented by REID (1961) and REID and ARTHUR (1975), a notable difference has revealed in the interior of subtropical gyre. The map of the annual mean dynamic height, as well as the bimonthly mean, shows a well-defined topographic feature, the north equatorial ridge (WYRTKI, 1974b), which extends east at about 20°N from just east of Taiwan and forms the U-shaped ridge together with the ridge associated with the Kuroshio. The northern slope of the north equatorial ridge gives a sound evidence of the Subtropical Countercurrent.

Later findings of YOSHIDA (1970) based on the CSK data indicated that eastward currents appeared at various latitudes and revealed a banded structure with somewhat regular intervals of about 300 km over the latitudes between 20°N and 30°N. This new feature has even suggested multi-gyre splitting rather than the two-gyre hypothesis. RODEN (1977) prepared long meridional dynamic-height sections of closely spaced stations in the North Pacific Ocean and found that wave-like disturbances of dynamic height with length scale between 400 and 600 km are common over the North Pacific and particularly pronounced in the west. The baroclinic currents associated with the disturbances are often an order of magnitude faster than the mean flow.

Concerning the splitting of the gyre, a further analysis of the CSK data as well as the past data was undertaken by the present authors. The authors made dynamic height maps of the western subtropical North Pacific for winter and summer seasons. Their maps indicated the presence of two separated regions of high dynamic topography rather than a continuous U-shaped ridge shown by WYRTKI (1975) for the both seasons. The two ridges, the north equatorial ridge and the ridge associated with the Kuroshio (Kuroshio ridge), seemed to be disconnected from each other because the water characteristics forming the ridges are considerably different.

Most of hydrographic sections made in the past were terminated at a latitude of 20°N, covering either to the north or to the south of this arbitrary-boundary latitude, where the north equatorial ridge is centered. For example, the data from the NORPAC and the CSK programs are distributed north of 20°N and that from the EQUAPAC and the IGY covers south of the latitude. Therefore, further analysis of existing data should not allow us to derive a firm evidence of the splitting of the subtropical gyre. A carefully designed field experiment was needed in order to make clear whether or not the splitting of the subtropical gyre in the western North Pacific is a real feature. Thus, we made a special cruise (ship time was shortened from the original plan by two weeks because of the 1973 oil crisis) with the R.V. Hakuho Maru during February 6 to March 22, 1974 over the area between 15°N and 26°N, and west of 134°E. A major point of the present article is to show that the western subtropical gyre of the North Pacific is not formed by single gyre but by several subgyres on the basis of the two different kind of data, the synoptic data from the Hakuho Maru cruise and the long-term mean data compiled by the Japanese Oceanographic Data Center.

2. Data

The primary objective of the Hakuho Maru cruise was to make a synoptic observation of the western North Pacific subtropical region in order to test the idea concerning the possible splitting of the subtropical gyre and to examine the features of the Subtropical Countercurrent. In this first stage of the investigation, we confined the focus of our observational plan into one of many aspects of possibly desirable approach. We, therefore, attempted to examine more or less simultaneous (or instantaneous) pictures of the thermohaline structure of this rather broad region, to see whether or not the thermohaline structure associated with the Subtropical Countercurrent could be verified, and perhaps more curiously to see if the western edge of the subtropical gyre could be found to reveal double-gyre or multi-gyre structure with two or more distinguished ridges (or peaks) in the surface dynamic topography. We chose this type of simple approach first.

The existing data suggest that the Subtropical Countercurrent is a relatively shallow phenomenon and that the appreciable changes in the thermohaline structures are confined to the depths of the thermocline or to the surface layers above 1,000 m. Because the dynamic-topographic features in the region of present interest are determined by the density distribution in the shallow surface layer, the vertical thermohaline structure must be observed densely. Thus the vertical distributions of temperature and salinity were measured with a continuous salinity-temperature depth recorder (STD, Plessy model 9006).

The STD was lowered at a speed of 0.5 m s^{-1} down to 1,000 m. The output was recorded in both digital and analog forms, and the digitized data were taken every one second. Seven meridional sections were made at the longitudes 134°E, 131°30′E, 129°E, 127°E, 125°30′E, 124°E and 122°45′E between the latitudes 15°N and 26°N. The STD stations were taken at intervals of 40 nautical miles on all sections. On the eastern three sections, expendable bathythermographs (XBT probes) were launched between the STD stations to back up the coarse spacing of STD stations.

Also used in the present paper is another source of data to be compared with the results of the Hakuho Maru cruise. This is a long-term mean (LTM) data of geopotential anomaly provided by the Japanese Oceanographic Data Center (JODC). In view of most of recent indications from various data source (JODC, 1966–1969; WYRTKI, 1975), it appears likely that the splitting of the gyre into two or more subgyres is the semi-permanent feature well recognizable even from the climatological mean pictures. To substantiate this further, we have constructed a map based on the data from finer grid.

3. Long-term mean field of geopotential anomaly

In order to seek the possibility of the double gyre structure for the subtropical gyre, various data have carefully been examined. The dynamic-height map constructed by REID (1961) did not clearly reveal these features because it was drawn on the basis of scarce data for this region. The CSK Atlases (JODC, 1966–1969) have provided some evidence of the features. Recent maps of LTM dynamic topography presented by WYRTKI (1975) and JODC (1975) gives further evidence for the splitting of the subtropical gyre. Wyrtki's map is based on the values averaged over areas of 2° of latitude and longitude.

For the discussions of the dynamic topography in the region of present interest, we would need the finer scale structure and believe it desirable to construct a map based on the data from finer grids. We present such a LTM data of geopotential anomaly provided by the JODC in Fig. 1, which gives the dynamic topography of the sea surface relative to the 1,000-db surface. This map is based on the same data used for the map prepared by JODC (1975), and drawn on the values averaged for the 1° mesh of latitude and longitude, and also on 21,055 observations. Because the JODC's map is drawn in a smoothed way, we redrew the contours so as to follow the original values as correct as possible.

In the area north of 20°N and west of 150°E each grid may have sufficient data to describe the LTM field of dynamic height, while the grids east of 155° have only limited numbers of data. In addition to the paucity of data, the map could be biased by the seasonal change because all the data in each grid are simply averaged without regard to the season when the data were collected. According to WHITE, HASUNUMA and SOLOMON (1978) the subtropical front shows a remarkable seasonal variability; it is twice as strong in spring as in fall, and its maximum north-south displacement reaches ±4° of latitude. The interpretation of the map, then, has its limitations on these points.

The topographic features would not be changed considerably with various choices of reference levels greater than 1,000 db, because the deep water in the North Pacific is so uniform in temperature and salinity that the resulting baroclinic structure is little below the level. The geopotential topography of the 1,000 db surface referred to 3,000 db ranges in a narrow values between 1.1 and 1.2 dynamic meter in the area of present interest (*e.g.*, see REED, 1970; REID and ARTHUR 1975), and yet, the values higher than 1.15 dynamic meter are

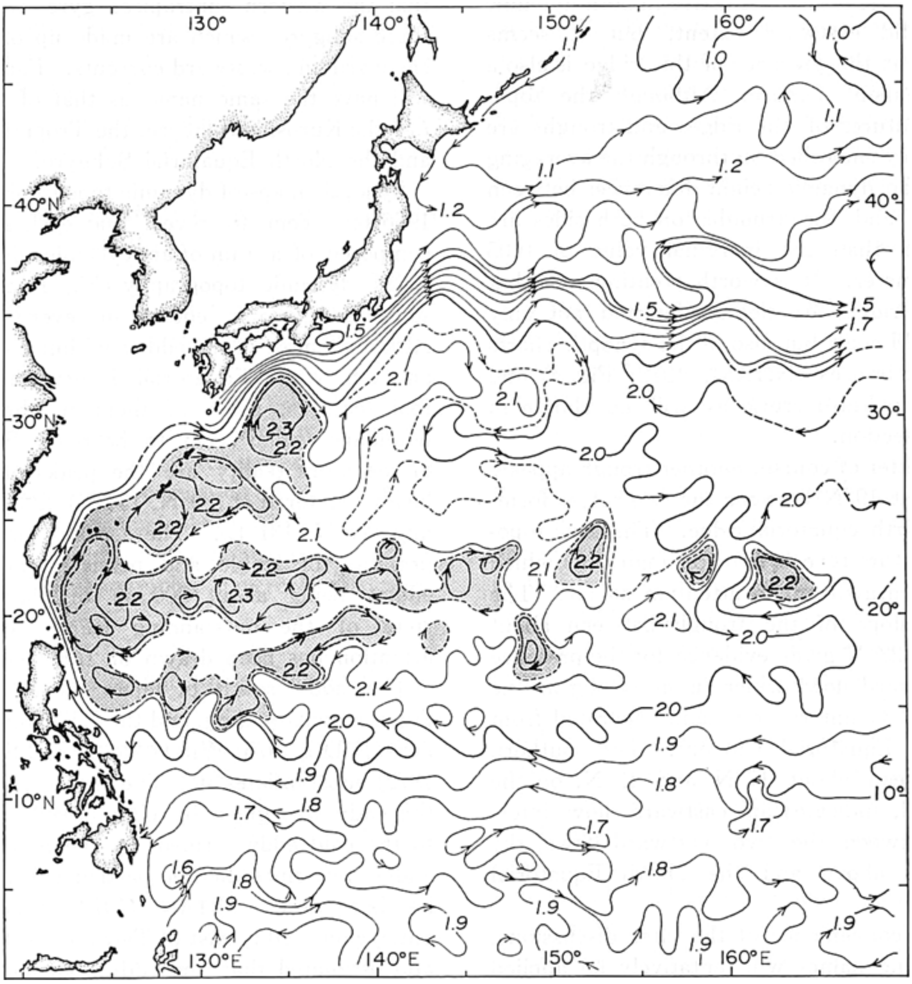


Fig. 1. Long-term mean geopotential anomaly at the sea-surface relative to the 1,000-db surface, in dynamic meters (10 j kg^{-1}). Based on 21,055 observations.

found only in a restricted region along the offshore side of the Kuroshio south of Japan. Therefore, the contours drawn at intervals of 0.05 dynamic meter may be meaningful.

The general feature of the dynamic height revealed on the new map is similar to that of Wyrtki's map (1975, Fig. 1). Our map also clearly reveals the presence of the two ridges, the Kuroshio ridge which appears along the right hand side of the Kuroshio and the north equatorial ridge which forms the northern boundary of the North Equatorial Current. There is no remarkable difference between the dynamic height values of the two ridges. In between the two ridges a well-defined trough deeply penetrates westward from 33°N, 155°E to very close to the western boundary. The northern slope of the trough indicates the Kuroshio Countercurrent, which flows southwestward intervening between the Kuroshio and the Subtropical Countercurrent.

Concerning the structure of the north equatorial ridge, the present map (Fig. 1) reveals a new feature which is not shown in Wyrtki's. According to our map, the north equatorial ridge appears to be composed of two zonal ridges of high geopotential anomaly in the western tropical region; one of the ridges appears slightly north of 20°N and the other extends eastward along around 17°N. It is indicated that the two ridges come in contact with each other at their western end. The southern ridge is less distinctive in both dynamic heights and eastward extent, but it seems evident that the presence of this ridge is also a semi-permanent feature. Although the topographic features of the ridges and troughs are considerably smoothed off through the averaging process, the dynamic height differences between the ridge and the troughs on both sides are still larger than the marginal value of 0.05 dynamic meter. It is worth pointing out that these two ridges are clearly depicted not only in the LTM chart but also in the synoptic charts from CSK cruises (NITANI, 1972, Fig. 4) and the Hakuho Maru cruise as will be shown in the next section.

As a matter of course, another trough appears along about 19°N between the two ridges forming the north equatorial ridge. This new topographic feature reveals two zonal currents which have not drawn much attention so far. The northern slope of the trough between about 19°N and 22°N gives evidence for the presence of a westward flow which is as strong as the Subtropical Countercurrent and separated from the North Equatorial Current. The southern slope between about 17°N and 19°N, on the other hand, indicates an eastward flow intervening between the two westward flows, the one stated above and the North Equatorial Current.

For the convenience of the later discussions, the following names will tentatively be applied to the topographic features. Because it is found that the north equatorial ridge is composed of two different ridges, the name of the North Equatorial Ridge will be applied only to the southernmost ridge. Actually it forms the northern limit of the North Equatorial Current in the western North Pacific (NITANI, 1972, p. 151). The northern ridge (centered at around 22°N) associated with the Subtropical Countercurrent will be referred to as the Tropical Ridge. The other ridge, the Kuroshio Ridge, spreads along the right hand side of the Kuroshio and merges into the southern two ridges east of Taiwan. The two troughs north and south of the Tropical Ridge will be named the Subtropical Trough (about 23°N at 130°E and 30°N at 155°E) and the Tropical Trough (centered at around 19°N).

These ridges in dynamic topography indicates that the western subtropical gyre is split into three subgyres which are made up of a pair of eastward and westward currents. Each subgyre will have the same name as that of the ridge, *i.e.*, the Kuroshio Subgyre, the Tropical Subgyre and the North Equatorial Subgyre.

Synoptic maps of dynamic topography (JODC, 1966-69) seem to reveal that each subgyre is composed of a train of anticyclonic eddies. Our LTM dynamic topography (Fig. 1) also shows some anticyclonic eddies in every subgyre. Although most of the eddies within the Tropical and the North Equatorial Ridges may not be real features, some of them in the western boundary region seem to be real. Such cases of the more reality are the peaks of dynamic height centered at (30°N, 134°E), (23°N, 125°E) and (27°N, 131°E). These peaks manifest the presence of stable and persistent anticyclonic eddies being about 500 km in diameter. In spite of the outstanding feature only little attention has been drawn on these eddies.

The eddy south of Japan (30°N, 134°E) is the most outstanding, and the LTM temperature field (JODC, 1975; WINTERFELT and STOMMEL, 1972) substantiates it. The first description on the eddy was given by UDA (1949) in relation to the cold eddy formed by the Kuroshio meander, but since then no particular investigation has been done. NITANI (1972) discussed the anticyclonic eddy east of Taiwan (23°N, 125°E), and estimated that the eddy transport amount to about $10\times10^6 \mathrm{m}^3\,\mathrm{s}^{-1}$. It is easily conjectured that the volume transport and the water characteristics of the Kuroshio change from place to place even at a given time because of these eddy activities.

The Kuroshio ridge rather abruptly loses its feature at around 155°E, while a well-defined trough appears south of the ridge and penetrates deeply westward. This change of dynamic topography indicates that the Kuroshio Countercurrent principally originates in this region. UDA and HASUNUMA (1969) presented four seasonal maps showing zonal components of the surface currents on the basis of ship-log data. These maps also indicate that the Kuroshio Countercurrent begins at around 155°E, and that the Countercurrent appears in a relatively small area west of 155°E and north of 20°N.

The dynamic height of the Kuroshio ridge sharply decreases at around 138°E. To the east of this longitude the variability of the dynamic height is so large (WYRTKI, 1975; JODC, 1975) that the topographic features may be flattened there through the averaging process.

4. The results of the Hakuho Maru cruise in February-March 1974

In the tropical region the dynamic topographic features are almost determined by the amount of low density water confined in the surface layer shallower than 200 m. Therefore, the currents associated with the Tropical and the North Equatorial Subgyres are relatively shallow phenomena. The midwinter season was chosen for the observation because in other seasons a well-developed seasonal thermocline may mask the essential features of the Subtropical Countercurrent and oceanographic structures associated with the current.

4.1. Geopotential topography

The obtained dynamic topography of the sea surface relative to the 1,000-db surface is shown in Fig. 2. Basic features revealed on the map are an outstanding peak just east of Taiwan, three zonal ridges and two troughs. The peak east of Taiwan exhibits a considerably high peak value exceeding 2.4 dynamic meter, demonstrating presence of an anticyclonic eddy. It seems to be identical with the eddy appeared east of Taiwan on the LTM map shown in Fig. 1.

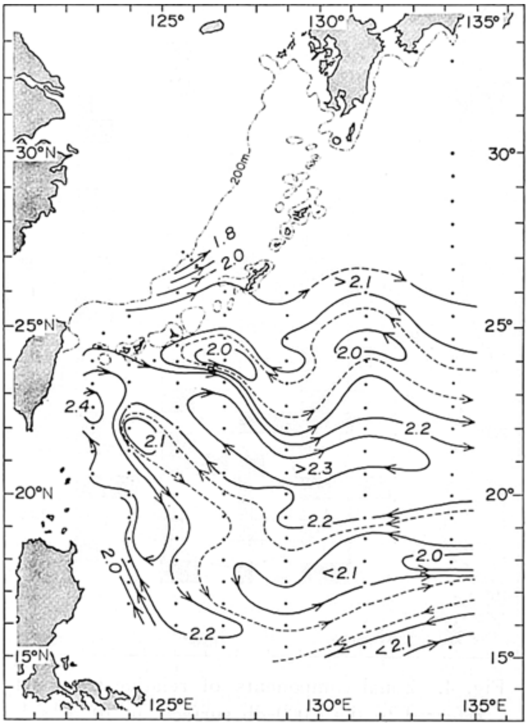


Fig. 2. Geopotential anomaly at the sea-surface relative to the 1,000-db surface, in dynamic meters (10 j kg^{-1}). Hakuho Maru, February-March 1974.

It appears from Fig. 2 that the zonal ridges spread from the peak. The southernmost ridge extends southeast and then east around 17°N east of 125°E, decreasing its dynamic height with increasing distance from the peak. This ridge seems to correspond to the North Equatorial Ridge which is the newly found feature on the LTM topography and defined in the previous section. The most outstanding ridge in Fig. 2 extends east also from the peak between 20°N and 23°N; this must be the Tropical Ridge in question. These features stated above show strong resemblance to the LTM dynamic topography in Fig. 1. There is the third ridge which is weakly developed but continuous between 24°N and 26°N.

It is of particular interest to point out that the Kuroshio Ridge, which should be the most pronounced ridge to be found around the Ryukyu Islands and south of Japan, was not clear at all in the area surveyed. It is indicated that the Kuroshio Ridge is not a continuous feature from the Tropical Ridge but a separated one by a trough of low geopotential. This new observed feature accords with the hypothesis of the splitting of subtropical gyre.

Between the three ridges stated above, we clearly recognize the presence of two distinct troughs within this survey area; one lies roughly between 23°N and 25°N, and the other around 18°N east of 127°E extending northwestward to 22°N around 124°E. As defined before, these seem to correspond to the Subtropical and the Tropical Troughs, respectively. The Tropical Trough indicates the presence of two zonal currents which have not drawn much attention. The northern slope of the Trough, *i.e.*, the southern slope of the Tropical Ridge between about 18°N and 22°N, indicates a westward flow as strong as the Subtropical Countercurrent. NITANI (1972, p. 153) found a continuous westward flow just south of the Subtropical Countercurrent. NAGASAKA and SAWARA (1972, Figs. 3 and 4) also found a concentrated occurrence of westward flux south of the eastward current. This current seems to form the counterpart of the Subtropical Countercurrent in the train of anticyclonic eddies which make the Tropical Ridge. On this westward flow, NITANI (1972, p. 154) gives a notable statement that it does not join the Kuroshio. The southern slope of the trough, on the other hand, indicates another eastward flow. YAMANAKA, ANRAKU and MORITA (1965) found frequent occurrence of an eastward current at around 18°N in the western North Pacific. NITANI (1972) detects the eastward flow on the CSK data, and described it as a current associated with the warm core to the north of the North Equatorial Current. The current system deduced from the dynamic topography in Figs. 1 and 2 shows a good agreement with Nitani's description (1972) except some minor features.

One can see from the map shown in Fig. 2 a "banded structure" of the geopotential topography with ridges and troughs. A remarkable feature revealed is the zonal continuity of the topographic features. The ridges and troughs continue more than 1,000 km. The troughs north and south of the Tropical Ridge penetrate well west and reach to the western boundary region. Both the distances between the two troughs or between the three ridges in Fig. 2 are 500 to 600 km. This meridional scale is the same as that of the perturbations of dynamic height recently found by RODEN (1977).

Although there may be several bands of topographic ridges in synoptic maps, the significant ones are Kuroshio Ridge, the Tropical Ridge, and the North Equatorial Ridge, which are identified even on the long-term mean basis as described in the preceding section. It should be noted that each of the ridges composes a

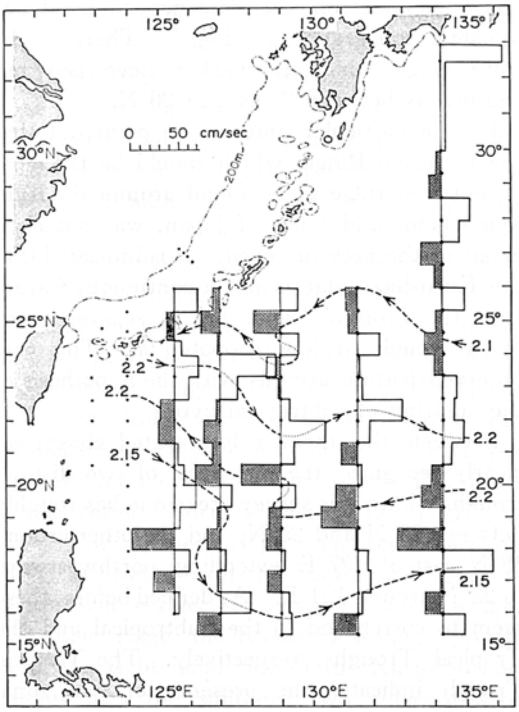


Fig. 3. Zonal components of geostrophic flow at the sea-surface relative to the 1,000-db surface in cm s^{-1}. Dashed lines indicate the geopotential anomaly contours shown in Fig. 2. Shaded part indicates westward component. Hakuho Maru, Ferbuary-March 1974.

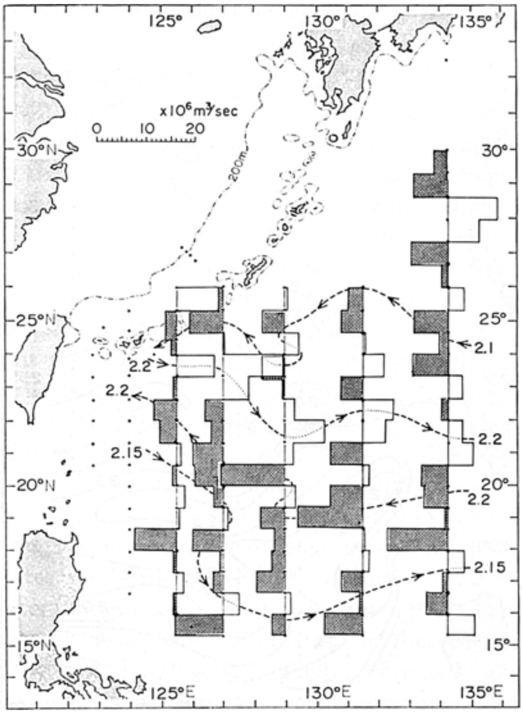


Fig. 4. Zonal components of relative transport referred to the 1,000-db surface, in 10^6 m^3 s^{-1}. Dashed lines indicate the geopotential anomaly contours shown in Fig. 2. Shaded part incicates westward transport. Hakuho Maru, February-March 1974.

subgyre in the western subtropical gyre. These subgyres are made up of the pairs of easterly and westerly currents, the Kuroshio and the Kuroshio Countercurrent, the Subtropical Countercurrent and the newly found westward flow lying south of the Countercurrent, and the easterly current associated with the northern slope of the North Equatorial Ridge and the northern part of the North Equatorial Current.

4.2. *Current speed and volume transport*

Zonal component of geostrophic flow and volume transport referred to the 1,000-db surface were calculated for all the sections. In this paper, however, most of the discussions will be limited to the eastern four sections to which currents cross nearly at right angles. The zonal components of geostrophic flow at the sea surface and the relative transport referred to the 1,000 db surface are shown in Figs. 3 and 4, respectively. There are four continuous zonal currents in relation to the dynamic topography. In order to identify the four currents at each section, dynamic-height contours in Fig. 2 are superposed on the figures.

We see, for every section, frequent change of zonal current direction. None of zonal current has a width exceeding 160 nautical miles, and yet each current is continuous over 1,000 km or more as is shown by the dynamic height contours. This feature indicates that the North Equatorial Current known as a stable westward current is limited south of 15°N in the western North Pacific. The Ryofu Maru sections at 137°E (MASUZAWA, 1967; NAGASAKA and SAWARA, 1972) also support that the North Equatorial Current is a narrow feature confined south of 15°N.

The clearest eastward flow takes place along the contour of 2.2 dynamic meter, and this may correspond to the principal stream of the Subtropical Countercurrent. At 125°30′E the eastward maximum speed of the Countercurrent is 25 cm s^{-1}, while at 127°E it accelerates as fast as 57 cm s^{-1} within the short distance. As we go further east, the maximum speed decreases to 23 cm s^{-1} at 134°E. The transport shows similar longitudinal variation; between the sections at 125°30′E and 127°E it increases suddenly from 7.5×10^6m^3 s^{-1} to 17.2×10^6m^3 s^{-1}, then decreases to 9.7×10^6m^3 s^{-1} at 134°E. This range of the transport shows a good agreement with the result, 8 to 18×10^6 m^3 s^{-1}, calculated by UDA and HASUNUMA (1969) for the summer of 1965, and suggest that its transport varies by a factor of two or more at various sections. These values of transport are considerably large in comparison with that of the equatorial currents. For the further measurement of the transport the station spacing should be closer than 40 miles because the eastward transport occurs in a narrow band of about 80 miles, although the eastward current appears in a slightly wider zone at the sea surface.

Just south of the Subtropical Countercurrent, there is a westward current which forms the counterpart of the Subtropical Countercurrent. The maximum speed of this current decreases westward, 44 cm s^{-1} at 134°E to 26 cm s^{-1} at 127°E. The transport is about 23×10^6m^3 s^{-1}, and does not show appreciable downstream change. As mentioned before this current is separated from the North Equatorial Current and has no name as yet. The large amount of the westward flux requires more attention to this current.

The eastward flow associated with the North Equatorial Ridge is relatively weak and minor though accompanied by a sharp density front. The transport is 3.3×10^6m^3 s^{-1} at most, and at some sections the relative transport over 1,000 m is westward because the current direction reverses below the main thermocline. In the low latitudes the main thermocline deepens toward north and the current field basically has westward components associated with the thermal structure. The main part of the eastward currents, which flows against the basic westward component, are limited upper 300 m (UDA and HASUNUMA, 1969). Fig. 5 shows vertical current structure at 131°30′E. Eastward currents at 17°N and 22.5°N are accompanied by a sharp density front (see Fig. 6).

4.3. *Water characteristic in the surface layer*

Each subgyre has its characteristic water in the surface layer. This feature can be clearly seen in the distribution of density or thermosteric anomaly. The thermosteric anomaly section at 131°30′E (Fig. 6) reveals two well-defined fronts at 17°N and 23°N, which are located near the northern rims of the subgyres. The waters south of 17°N and between the two fronts belong to the North Equatorial

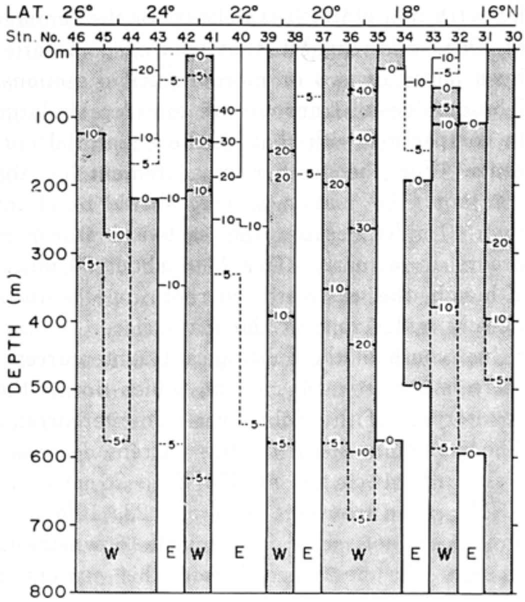


Fig. 5. Vertical section of zonal geostrophic flow ($cm\ s^{-1}$) at 131°30′E. Shaded zone shows westward flow. Hakuho Maru, February 1974.

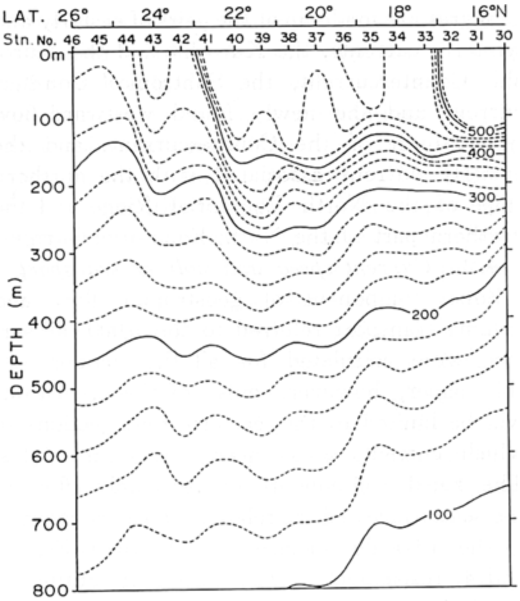
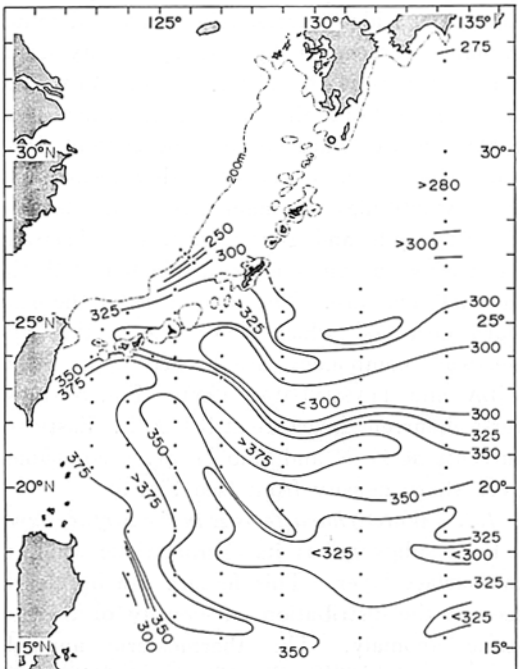


Fig. 6. Vertical section of thermosteric anomaly ($cl\ t^{-1}$) at 131°30′E. Hakuho Maru, February 1974.



Fig' 7. Thermosteric anomaly ($cl\ t^{-1}$) at a depth of 200 m. Hakuho Maru, February-March 1974.

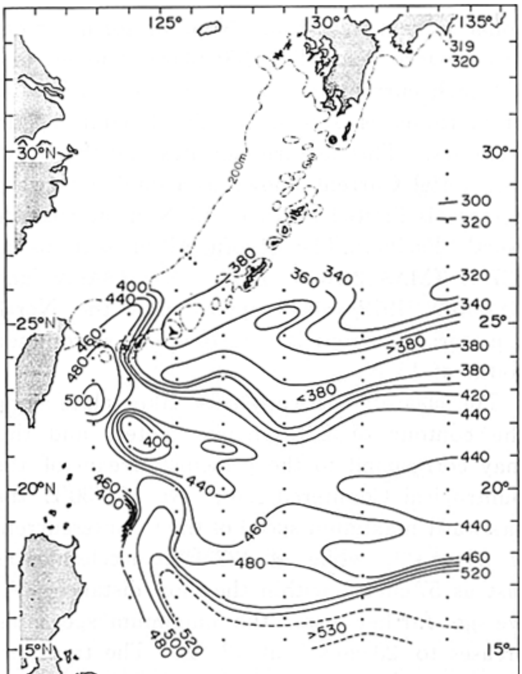


Fig. 8. Thermosteric anomaly ($cl\ t^{-1}$) at a depth of 80 m. Hakuho Maru, February-March 1974.

and the Tropical Gyre, respectively. In each subgyre temperature and salinity of the surface mixed water varies a little, but its thermosteric anomaly is kept uniform; thermosteric anomalies of the surface waters are slightly higher than 520 cl t^{-1} in the North Equatorial Gyre and about 450 cl t^{-1} for the Tropical Gyre. These low density waters concentrated in the upper 200 m are essential to form these ridges in dynamic topography, so that the pattern of the thermosteric-anomaly distribution at 200 m (Fig. 7) shows a good resemblance to that of dynamic height. The winter-surface water of the Kuroshio Gyre is known by its uniformity and referred to as the Subtropical Mode Water (MASUZAWA, 1969), thermosteric anomaly of which is about 290 cl t^{-1}.

The two density fronts in Fig. 6 are continuous features over the area observed. In order to show the continuity of the fronts the thermosteric-anomaly distribution at 80 m, near the bottom of the surface mixed layer, is shown in Fig. 8. The northern density front associated with the Subtropical Countercurrent seems to be a continuous feature across the entire North Pacific Ocean. The sea-surface density map in winter (REID, 1969, Fig. 6) reveals a front crossing the North Pacific Ocean at slightly north of 20°N. The characteristic density of the front, centered at about 24.0 g l^{-1} in sigma-t (392 cl t^{-1}), is in good agreement with that of the front associated with the Subtropical Countercurrent. As is evident from Figs. 5 and 6, the major part of eastward transports occurs just south of the density fronts.

The bifurcation of the sharp density fronts from the western boundary region (see Fig. 8) implies that the water transported by the western boundary current suddenly changes at some places. The northern part of the North Equatorial Current turns its course northward off the Philippine Islands to form the western boundary current. The low density water, higher than 480 cl t^{-1} in thermosteric anomaly, in the North Equatorial Current is transported northward as a part of the western boundary current as far north as 20°N, but most of the low density water turns its course there and flows eastward along the southern density front. The same situation also takes place on the western boundary current after passing through the Ryukyu submarine ridge east of Taiwan. The high thermosteric-anomaly water higher than 400 cl t^{-1} are carried into the southern tip of the East China Sea by the western boundary current, but immediately turns its course southward. A part of the water may recirculate into the anticyclonic eddy east of Taiwan, but the major part of the water seems to join the Subtropical Countercurrent. Only a little of the low-density water is entrained into the Kuroshio forming the narrow warm core on the right hand side of the Kuroshio. Across the front the thermosteric anomaly changes from higher than 460 cl t^{-1} to lower than 390 cl t^{-1}. These branchings of density fronts across the western boundary current indicate that the water characteristics change discontinuously at the place.

Geostrophic fluxes by water characteristics have been calculated by MASUZAWA (1964, 1965, 1967, 1972) and NITANI (1972) at various sections. The mode of geostrophic flux on the T-S diagram change in accordance with the present discussion. The thermosteric anomalies of the surface water transported by the North Equatorial Current is higher than 500 cl t^{-1} throughout the year and forms a significant mode on the geostrophic fluxes (MASUZAWA, 1964, 1967). In the east of Taiwan the mode appears in evidently low thermosteric anomaly about 450 cl t^{-1} even in summer (NITANI, 1972). In the Kuroshio south of Japan the surface-water flux mode appears between 300 cl t^{-1} and 350 cl t^{-1} (MASUZAWA, 1965, 1967).

Although the western boundary current may appear as a continuous feature, the waters transported by the current are not continuous.

5. Discussion

The synoptic dynamic height chart from the Hakuho Maru cruise as well as the long-term mean chart are shown to substantiate our more or less hypothetical idea of the splitting of the subtropical gyre. There is a strong possibility that the western subtropical gyre is split into several, most likely three, subgyres; the three dynamic topographic ridges manifest them. The structure of the subtropical gyre in the North Pacific is dramatically different from that hitherto believed. The splitting of the subtropical gyre should lead to the necessity of a fundamental reexamination of the dynamics of the ocean circulation, in particular, of the Kuroshio. The present analysis indicates that the Kuroshio is not fed by the North Equatorial Current, but rather by the Kuroshio Countercurrent.

It is suggested that there is little exchange of surface water between the subgyres because each gyre has its own particular surface water. In winter, there are striking differences between the characteristics of the surface waters transported by the North Equatorial Current (higher than 500 cl t^{-1}), the Subtropical Countercurrent (400-450 cl t^{-1}) and the Kuroshio (about 300 cl t^{-1}); the major part of surface water transported by the North Equatorial Current cannot be found in the Kuroshio nor in the Subtropical Countercurrent.

Because each subgyre is formed more or less by a train of anticyclonic eddies, the transport of the current changes by about a factor of two in a short time or in a short distance. On the basis of 32 hydrographic sections of the Kuroshio made at 135°E in the period from December 1951 to November 1953, MASUZAWA (1954) presented a time sequence of the transport referred to the 1,000-db surface. According to it, the transport changes between about 30 and $60\times10^6 m^3 s^{-1}$ within two or three months. In addition, the subgyres or the eddies are subject to change by local disturbances because they cover only small areas compared with the whole subtropical gyre. The current systems might be more variable than we considered before.

The splitting of the subtropical gyre presents interesting problems that how the subgyres are linked up and how oceanographic variations propagate from one subgyre to the others. According to the present analysis it is questionable that the variations in the North Equatorial Current propagate directly into the Kuroshio. The region east of Taiwan is considered to be crucial to understand these problems because all the western ends of the subgyres together there. In addition to the mutual relationships, the time dependent features of the subgyres and individual persistent eddies have to be investigated. Under the monsoon regime they may show remarkable seasonal changes in their location, spatial extent, current speed and volume transport. Although it had been postulated that the central part of the subtropical gyre is quiet and stable, WHITE *et al.* (1978) has found a large seasonal change in the location and the intensity of the Subtropical Countercurrent.

In this paper only shallow features are described concerning the split of the subtropical gyre, but the split is still discernible at greater depths, about 1,000 m. A dynamic topographic map at the 1,000 db surface referred to 3,500 db (REID and MANTYLA, 1978) shows up two ridges extending eastward along about 20°N and 35°N all across the Pacific Ocean from the western boundary. The large-scale oxygen distribution can be explained better with the current pattern deduced from the dynamic topography (REID and MANTYLA, 1978).

Acknowledgements

This paper represents one of the results from the R.V. Hakuho Maru cruise, KH-74-1. The authors wish to express their hearty thanks to Prof. Toshihiko TERAMOTO, the director of the cruise, and to the members of the scientific party, officers and crew aboard the Hakuho Maru. Our success at the field measurements derived from their cooperation and careful work at the rough sea.

References

Japanese Oceanographic Data Center (1966, 1967, 1968, 1969): CSK Atlases, Vols. 1-4, Tokyo.

Japanese Oceanographic Data Center (1975): Maritime Environmental Atlas—Status of the oceanographic elements. Japan Hydrographic Association, Tokyo, 164 pp.

MASUZAWA, J. (1954): On the Kuroshio south off Shiono-misaki of Japan. Oceanogr. Mag., **6**, 25-33.

MASUZAWA, J. (1964): Flux and water characteristics of the Pacific North Equatorial Current. *In*, Studies on Oceanography, Prof. Hidaka's Commemorative Volume, Tokyo, pp. 121-128.

MASUZAWA, J. (1965): Water characteristics of the Kuroshio. Oceanogr. Mag., **17**, 37-47.

MASUZAWA, J. (1967): An oceanographic section from Japan to New Guinea at 137°E in January 1967. Oceanogr. Mag., **19**, 95-118.

MASUZAWA, J. (1969): Subtropical Mode Water. Deep-Sea Res., **16**, 463-472.

MASUZAWA, J. (1972): Water characteristics of the North Pacific central region. *In*, Kuroshio, Its Physical Aspects, ed. by H. STOMMEL and K. YOSHIDA, University of Tokyo Press, Tokyo, pp. 95-127.

NAGASAKA, K. and T. SAWARA (1972): A preliminary report of the cruise of the R.V. Ryofumaru in January-March 1971. Oceanogr. Mag., **24**, 25-38.

NITANI, H. (1972): Beginning of the Kuroshio. *In*, Kuroshio, Its Physical Aspects, ed. by H. STOMMEL and K. YOSHIDA, University of Tokyo Press, Tokyo, pp. 129-163.

REED, R. K. (1970): Geopotential topography of deep levels in the Pacific Ocean. J. Oceanogr. Soc. Japan, **26**, 331-339.

REID, J. L., (1961): On the geostrophic flow atthe surface of the Pacific Ocean with respect to the 1,000-db surface. Tellus, **13**, 489-502.

REID, J. L. (1969): Sea-surface temperature, salinity, and density of the Pacific Ocean in summer and in winter. Deep-Sea Res., Supplement, **16**, 215-224.

REID, J. L. and R. S. ARTHUR (1975): Interpretation of maps of geopotential anomaly for the deep Pacific Ocean. J. Mar. Res., Supplement, **33**, 37-52.

REID, J. L. and A. W. MANTYLA (1978): On the mid-depth circulation of the North Pacific Ocean. J. Phys. Oceanogr., (in press).

RODEN, G. I. (1977): On long-wave disturbances of dynamic height in the North Pacific. J. Phys. Oceanogr., **7**, 41-49.

ROBINSON, M. K. (1969): Theoretical predictions of subtropical countercurrent confirmed by bathythermograph (BT) data. Bull. Jap. Soc. Fisheries Oceanogr., Special number, Prof. Uda's Commemorative Papers, 115-121.

UDA, M. (1949): On the correlated fluctuation of the Kuroshio Current and the cold water mass. Oceanogr. Mag., **1**, 1-12.

UDA, M. and K. HASUNUMA (1969): The eastward Subtropical Countercurrent in the western North Pacific Ocean. J. Oceanogr. Soc. Japan, **25**, 201-210.

WHITE, W. B., K. HASUNUMA and H. SOLOMON (1978): Large-scale seasonal and secular variability of the Subtropical Front in the western North Pacific. J. Geophys. Res., (in press).

WINTERFELD, T. and H. STOMMEL (1972): Distribution of stations, and properties at standard depths in Kuroshio Area. *In*, Kuroshio, Its Physical Aspects, ed. by H. STOMMEL and K. YOSHIDA, University of Tokyo Press, Tokyo, pp. 81-93.

WYRTKI, K. (1974a): The dynamic topography of the Pacific Ocean and its fluctuations. Hawaii Institute of Geophysics HIG-74-5, 19 pp.+37 figs.

WYRTKI, K. (1974b): Sea level and the seasonal fluctuations of the Equatorial Currents in the western Pacific Ocean. J. Phys. Oceanogr., **4**, 91-103.

WYRTKI, K. (1975): Fluctuations of the dynamic topography in the Pacific Ocean. J. Phys. Oceanogr., **5**, 450-459.

YAMANAKA, H., N. ANRAKU and J. MORITA (1965): Seasonal and long-term variations in oceanographic conditions in the western North Pacific Ocean. Rep. Nankai Fish. Res. Lab., **22**, 35-70 and appendix table, (text in Japanese, abstract and legends in English).

YOSHIDA, K. and T. KIDOKORO (1967a): A subtropical countercurrent in the North Pacific—An eastward flow near the Subtropical Convergence. J. Oceanogr. Soc. Japan, **23**, 88-91.

YOSHIDA, K. and T. KIDOKORO (1967b): A subtropical countercurrent (II).—A prediction of eastward flows at lower subtropical latitudes. J. Oceanogr. Soc. Japan, **23**, 231-246.

YOSHIDA, K. (1970): Subtropical Countercurrents: Band structures revealed from CSK data. *In*, The Kuroshio, East-West Center Press, Honolulu, Hawaii, pp. 197-204.

西部北太平洋における亜熱帯環流の分裂

蓮沼啓一*，吉田耕造**

要旨: 亜熱帯反流の存在は，単に一つの東向流が回帰線域にあることを示しているだけでなく，亜熱帯環流がいくつかの，少なくとも二つの，副環流系からできていることを示しているのだとする我々の仮説を二つの独立した資料にもとづいて調べた．一つの資料は海洋資料センターで集められたジオポテンシャル・アノマリーの長期間平均であり，他は1974年の2月から3月にかけて，134°E 以西の15°N と26°N の間で行なわれた白鳳丸による SDT の観測結果である．

総観的観測結果および長期間平均の双方の場から三つのジオポテンシャル・アノマリーの嶺が認められた．これら三つの嶺は西部北太平洋の亜熱帯環流が，三つの副環流系からできていることを示唆している．各副環流系は二つの流れが一組となって構成され，黒潮と黒潮反流が一つの副環流系を作り，亜熱帯反流とそのすぐ南にある西向流（18°N-21°N)，また北赤道海流の北縁部と18°N 付近に見られる東向流がそれぞれ一組となって別の副環流系を構成している．各副環流系は，緯度方向のスケールが300-600 km の高気圧性の渦によって構成され，副環流系を作る流れの流量は場所によって2倍ないしはそれ以上の変化を示す．

表層水の特性分布もまた亜熱帯環流の分裂を支持しており，各環流系内ではほぼ一様の特性を持っているのに対し，環流間では明らかに異なった特性値を示す．各副環流系の北縁部には西端境界域から分離してきた密度前線が見られ，これには東向流が伴なっている．西端境界流を横断して亜熱帯環流内部領域に達する密度前線の存在は北赤道海流によって運ばれている表層水の主要部分が黒潮中には運び込まれていないことを示唆している．西端境界流は一連の強流帯を形成してはいるものの，それによって運ばれている水はある場所によって不連続的に変化している．

---

* 東京大学海洋研究所
〒164 東京都中野区南台 1-15-1
** 東京大学理学部地球物理学教室
〒113 東京都文京区弥生 2-11-16