The Delineation of Dynamical Characteristics of Circulations and Their Changes in the Surface, Subsurface, Mid-Depth and Deep Layers of the Westernmost Part of the North Pacific*

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Configurational structure of ocean circulation in the westernmost part of the North Pacific and its time-varying processes are revealed through the combination of various means of measurements, that is, the measurements of cross-channel voltage, velocity profile, deep-water velocity, water characteristics together with hydrographic observations. The layered structure of circulation and current bursts of 10 to 20 days are clearly shown as well as the departure of the Kuroshio velocity-field from geostrophy. As a major process which modify the density structure of circulation, an intensified generation of internal tides over the Izu Ridge is also treated.

1. Introduction

This paper comprises a review of studies by the author starting with cross-channel voltage measurements for monitoring time-varying processes of the Kuroshio and its branch currents around Japan (Fig. 1(a)). The studies have then been directed to dig in problems on the detailed characteristics of Kuroshio velocity field, which is in departure from baroclinic geostrophy, problems on the configurational structure of circulation in the subsurface, mid-depth and deep layers and problems on the intensified generation of internal tides over the Izu Ridge, which modulate the density structure of circulations. All these problems were encountered by the author during the cross-channel voltage measurements. The final aim of these studies is to make clear the dynamical processes and mechanisms of ocean circulations. For this purpose, measurements have widely been carried out by many means as described in the following sections.

In the following treatments, the rectangular coordinate axes $x, y, z$ are set in the cross-stream, downstream and vertically upward directions, respectively.

2. Time-Varying Processes of the Kuroshio and Its Branch Currents Revealed through Cross-Channel Voltage Measurements in the Izu Island Region, the Straits of Tsugaru and the Straits of Oki around Japan

2.1 Cross-channel voltage measurements

The author, initiated by C. S. Cox, started the cross-channel voltage measurements by the use of the submarine telephone cables in the Izu Island region off the Bay of Tokyo (Fig. 1(b)). A cable was laid across the Oshima-West Channel from Kawazuhama (KH), Izu Peninsula to

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Fig. 1. (a) Map of regions of voltage measurements around Japan. (b) Map of the Izu Island region, which involves the Oshima-West Channel and Oshima-South Channel. (c) Map of the Straits of Tsugaru. (d) Map of the Straits of Oki.

Oshima (OS) and another cable across the Oshima-South Channel from Oshima to Miyakejima (MJ) on the Izu Ridge (Fig. 1(b)). The Kuroshio flowed across the cables and was expected to be monitored through voltage measurements on the cables. The southern edge of the Kuroshio usually passes over the ridge in the vicinity of Hachijojima (HJ) (Fig. 1(b)), which is about 100
km to the south of Miyakejima. Fortunately, however, during 1958 to 1961, throughout which the voltage measurement was carried out, the Kuroshio was in the meander condition to the west of the Izu Ridge and the most part of Kuroshio passed over the ridge to the north of Miyakejima as inferred from isotherm distribution (Kaiyosokuho, H.D.) on the basis of thermal-wind approximation.

With an aim to monitor the Tsugaru Current and Tsushima Current in parallel to the monitoring of the Kuroshio, voltage measurements were extended to be made between Tobetsu (TB) and Ishizaki (IZ) in the Straits of Tsugaru (Fig. 1(c)) and between Dogoshima (DG) and Chikumi (CK) in the Straits of Oki (Fig. 1(d)). These currents form branches of the Kuroshio (Fig. 1(a)).

In the period around 1960, observations of ocean current were generally made through measurements with GEK and BT and through hydrographic sampling from vessels, and could not be made continuously in time. Contrary to this, cross-channel voltage measurements could easily provide information continuous in time and were expected to reveal the new aspect of time-varying processes of the channels in detail.

2.2 Voltage noises and their elimination

Cross-channel voltages $\Delta \phi$ generally involve noise $\Delta \phi_G$ which is induced in association with ionospheric and magnetospheric fluctuations in addition to another noise $\Delta \phi_N$ which is due to contact potential difference between electrode and the sea water (Larsen, 1992). In measurements by the author, $\Delta \phi_N$ was minimized by using a non-polarized electrode and by connecting it directly to core conductor of submarine cable. The contact potential difference has the temperature and salinity dependencies, but its variations were kept within $\pm 2.5$ mV in amplitude by burying electrodes into beach sand close to the shore line, where temperature and salinity changes were kept within $\pm 5^\circ$C and 0.05%, respectively. Thus, $\Delta \phi_N$ can be ignored because of the magnitude being less than 5% of that of averaged cross-channel voltages.

For the purpose of surveying $\Delta \phi_G$, hourly records of cross-channel voltages, $\phi_{TB} - \phi_{IZ}$, $\phi_{KH} - \phi_{OS}$ and $\phi_{DG} - \phi_{CK}$ are subjected to spectral analysis with the frequency resolution of 0.01 cph in reference to those of geomagnetic fields, $H_{OG}$ and $D_{OG}$ (OG: Onagawa), $H_{KO}$ and $D_{KO}$ (KO: Kakioka), and $H_{KY}$ and $D_{KY}$ (KY: Kanoya), in the period from Sep. 5 to 25 in 1960. These three sites of geomagnetic-field observation are selected in the northern, central and southern part of Japan (Fig. 1(a)), respectively. Frequency distributions of spectral density for these records have uniformly frequency dependency of the form $10^{-0.81f}$ ($f$: frequency) in the frequency range from 0.04 to 0.2 cph, upon which spectral peaks at tidal frequencies are superposed as indicated in the coming paper (Teramoto and Yoshizawa). Variations of geomagnetic field $H$ in time and space are not so simple and consequently, their spectral density function $Z(w,k)$ can not readily be specified in frequency and wave number domain. Moreover, coherences of voltage records to geomagnetic field are generally high in the frequency range from about 0.04 to 0.15 cph. This frequency range involves frequencies of major tidal constituents such as K1, O1, M2 and S2. The separation of these variations of the two different origins, one from ocean tides and the other from ionospheric and magnetospheric variation, is quite difficult. Thus, the author made up his mind to eliminate components of frequency higher than the diurnal cycle from the original voltage records through low-pass filtering. In the range of frequency lower than the diurnal cycle, cross-channel voltages are not significantly coherent to geomagnetic field fluctuations (Teramoto and Yoshizawa) and are worthwhile to be analysed from oceanographical standpoint.
2.3 Establishment of the relation to estimate transports of channels from motionally-induced cross-channel voltages

A motionally-induced voltage, which is obtained from a measured voltage after eliminating voltage noises, is considered to be associated with a transport of the channel (Longuet-Higgins et al., 1954) even though modulated with the along-shore electric field when the channel is not uniform in the downchannel direction as in the author’s case. In order to form the relation of the voltage $\phi_O - \phi_A$ to the transport $Q$, an objective method of actual transport measurement is essentially important to provide the reference for comparison. But, unfortunately, there was no means to measure actual transports.

Under such a circumstance, the author should build the relation by the help of a simple electro-hydrodynamic model constructed with a channel water flowing and a sea bed at rest. The application of the model needs the sea-bed resistivity as indicated in the following formula.

$$Q = \frac{h}{Hz} \left(1 + \frac{rD}{Re h}\right)(\phi_O - \phi_A),$$

where, $h$, $r$ are the depth and resistivity of sea water averaged over the cross section of the channel and $D$ the width of the channel, $Hz$ vertical component of the geomagnetic field and $Re$ the resistivity of the sea bed averaged to the depth of the order of $D$. The resistivity is estimated by using cross-channel measurement of voltage in parallel to surface electric current in addition to measurement of vertical profile of velocity (Teramoto, 1971). The especially low resistivity for the Straits of Tsugaru was noticed in the paper cited.

Equation (1) are specified for four channels under consideration as below. For the Oshima-West channel,

$$Q_{OW} = 1.4 \times 10^4 (\phi_{KH} - \phi_{OM}) \text{ m}^3\text{s}^{-1}$$

for the Oshima-South channel,

$$Q_{OS} = 2.0 \times 10^4 (\phi_{OS} - \phi_{MJ}) \text{ m}^3\text{s}^{-1}$$

for the straits of Tsugaru,

$$Q_{ST} = 3.0 \times 10^4 (\phi_{TB} - \phi_{IZ}) \text{ m}^3\text{s}^{-1}$$

and for the Straits of Oki,

$$Q_{SO} = 2.1 \times 10^4 (\phi_{DG} - \phi_{CK}) \text{ m}^3\text{s}^{-1}.$$

The judgement for the appropriateness of the transport estimation are made through whether or not the analysis on the basis of these estimations bring reasonable results in reference to independent physical quantities.
2.4 Comparison of transports \( Q_{OS} \) with reference to baroclinic, geostrophic transport \( Q_G \) from hydrographic observations

The comparison was made by the author in the preceding paper (Teramoto and Kojima, 1994). The \( Q_G \) were obtained 7 times between Stas. D2 and D3 or between D51 and D52 (Fig. 1(b)) for about one year of the voltage measurements. The ratios of \( Q_G \) to \( Q_{OS} \) together with the ratios of \( Q_G \) to running-averaged \( Q_{OS} \) over 5, 11, 21 and 31 days for seven cases are estimated. These periods for averaging are decided to eliminate variations of time scales of 7 and 25 days involved in the record of \( Q_{OS} \). The former is wind-induced, non-geostrophic variations and the latter is supposed to be associated with barotropic oscillations of the Shikoku-Philippine Basins. In the first 4 cases, the running averaging does not almost change ratio values. But in the rest, the running averaging especially over more than 21 days clearly brings better results in the sense that the ratio values approaches to unity. This means that in the later half period of voltage measurement variations which are not in baroclinic, geostrophic balance were in high energy level.

Through the comparison the transport estimated from motionally-induced voltage is verified to be of the reasonable order of magnitude.

2.5 Noticeable time-varying processes revealed through measurements of motionally-induced voltages

2.5.1 The negative current burst and the successive recovery in the Oshima-West Channel

The transport \( Q_{OW} \) is usually positive (northwards) at Kawazuham-Oshima section. A negative current burst in typical form happened toward the end of March, 1961 in \( Q_{OW} \) (Fig. 2(a)).

![Fig. 2.](image-url)
Total processes involving synchronously-occurred temporal-variations in the Kuroshio configuration are treated in the preceding paper (Teramoto and Kojima, 1994), in detail. The close relation of the negative transport burst to the formation of cold water mass off the Suruga Bay, which is associated with the folding back in the Kuroshio path, is clearly seen.

Through this study, the cross-channel voltage measurements are verified to be very helpful for making clear time-varying processes, in detail. According to the frequency distributions of spectral density of $Q_{OW}$ and $Q_{OS}$, both of which are seriously affected by Kuroshio behaviours, variations of the time scale of 10 to 20 days such as the negative current burst form dominant spectral peaks as will be shown in Fig. 4.

2.5.2 Typhoon-associated changes of the Tsugaru Current and the estimation of bottom-frictional stress-coefficient of the current during the period between passages of two typhoons

The transport $Q_{ST}$ shows an abrupt increase and successive decrease (Fig. 3) which occurred in close association with the passage of a typhoon to the west of the Straits on Sep. 18, 1959 and the other to the east on Sep. 27, 1959. The process is treated in the succeeding paper (Teramoto and Yoshizawa) in detail. The changes in $Q_{ST}$ during the 10 days reach as much as $6 \times 10^6$ m$^3$s$^{-1}$. This amount is larger than the magnitude of long-term averaged transport of $5 \times 10^6$ m$^3$s$^{-1}$. The abrupt changes in transport are in time delay of about 7 to 8 hrs relative to changes in $\partial(\zeta - \zeta^*)/\partial t$ estimated from sea-level difference $\zeta_{IS} - \zeta_{HH}$ (IS: Iwasaki on the Japan Sea coast, HH: Hachinohe on the Pacific coast, Fig. 1(c)) as can be visually estimated in Fig. 3. The fundamental equation for the process in the form integrated over the cross section is represented in the following form by the use of frictional stresses $\tau_{sy}$ and $\tau_{by}$ at the surface and the bottom.

\[
\frac{\rho \partial Q}{D \partial t} = -\frac{\rho gh}{l} \Delta (\zeta - \zeta^*) + \rho (\tau_{sy} - \tau_{by}),
\]

(6)
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where $\zeta^*$ is sea-level changes in balance with atmospheric-pressure changes. When we assume that the inertial terms are negligibly small and frictional forces are proportional to the transport $Q = Q_{ST}$, the fundamental equation is analogous to that for electric current in the circuit made of a capacity and resistance. The time delay mentioned can readily be explained on the equation.

From the equation $\tau_{by}$ is estimated by giving $\tau_y$ on the basis of the bulk formula from wind data and other terms from the simultaneous records.

The instantaneous bottom stress $\tau_{by}$ is empirically known to be represented as

$$\tau_{by} = -k\rho v_b v_b'$$  \hspace{1cm} (7)

where $v_b$ is the water velocity at the certain distance from the bottom and $k$ the fractional stress coefficient.

$v_b$ can be expressed as

$$v_b = V + v'$$  \hspace{1cm} (8)

where $V$ is the 25 hr-running average of $v_b$ after subtracting the annual mean and $v'$ the deviation from the average. According to the study in the past (Unoki, 1993), the major components of $v'$ in the straits are of $K_1$ and $M_2$ periods. On taking the average velocity $v$ over the cross section as $v_b$, the frictional stress coefficient $k$ is estimated and is also plotted in Fig. 3 (Teramoto and Yoshizawa).

There is an empirical evidence that the coefficient of bottom stress $k$ between the flowing water and sea bottom is around $2.5 \times 10^{-3}$ as well as that of wind stress between the sea and air (Bowden, 1956). It is seen in Fig. 3 that $k$ value are in the vicinity of this value during the period in which the pressure gradient force is almost in the balance with the bottom fractional force.

2.5.3 Evidence of shelf waves along the coast of Izumo in the Straits of Oki

In Fig. 2(d), the record of $\phi_{DG} - \phi_{CK}$ during the period from Sep. 9, 1960 to Feb. 28, 1961 is plotted. From the visual inspection of $\phi_{DG} - \phi_{CK}$, it is seen that there exist dominant, pulsive variations of the time scales of several days. Furthermore, these pulsive variations are found to be in close correspondence to those in $\tau$, as well as those in $\zeta_{SK} - \zeta_{SG}$ as treated in more detail in the coming paper (Teramoto and Yoshizawa). These results suggest that the frequent occurrence of pulsive variations in $\phi_{DG} - \phi_{CK}$ is due to shelf waves generated in association with pulsive variations in wind field in the straits.

2.6 Comparison between averages and between spectral characteristics of transports estimated from motionally-induced voltages across the two channels and straits

Depending upon the geographical situations of channels and straits, the averages and spectral characteristics of transport estimated from the motionally-induced voltages are different from each other as described below. The transport of $Q_{OW}$ varies from the maximum value of $7.2 \times 10^6$ m$^3$s$^{-1}$ (SV) to the minimum value of $-0.84$ SV with the average of 2.7 SV during the period of 26 months from June 1959 to August 1961 (Fig. 2(a)). The transport of $Q_{OS}$ varies from the maximum value of 10 SV to the minimum value of $-0.12$ SV with the average of 4.2 SV during the period of 12 months from May 1959 to April 1960 (Fig. 2(b)). The transport of $Q_{ST}$ varies from the maximum value of 15.8 SV to the minimum value of $-0.71$ SV with the average of 5.0 SV during 37 months from October 1959 to November 1962 (Fig. 2(c)). The transport of $Q_{SO}$ varies
Fig. 4. (a) The frequency distribution of spectral density for $\phi_{KH} - \phi_{OS}$ across the Oshima-West Channel, that for $\phi_{OS} - \phi_{MJ}$ across the Oshima-South Channel, that for $\phi_{TB} - \phi_{IZ}$ across the Straits of Tsugaru and that for $\phi_{DG} - \phi_{CK}$ across the Straits of Oki. (b) Percentage distributions of the frequency-integrated spectral density of motionally-induced voltages $\phi_{DG} - \phi_{CK}$, $\phi_{OS} - \phi_{MJ}$, $\phi_{KH} - \phi_{OS}$ and $\phi_{TB} - \phi_{IZ}$.

from the maximum value of 4.5 SV to the minimum value of –2 SV with the average of 0.5 SV during the period of 9 months from September 1960 to May 1961 (Fig. 2(d)). $Q_{OW}$ becomes a little greater in the period of Kuroshio meandering as in the period under consideration than in the period of Kuroshio straight path. Hence, the maximum transport mentioned above is considered to represent the actual maximum of the channel transport, in general. $Q_{OS}$ decreases when the Kuroshio displays the meandering feature to the west of the Izu Ridge. The minimum transport described above indicates that there are chances in which the Kuroshio does not pass over the ridge through the Oshima-South Channel and passes over through the channel further south. The average transport in the period in question should be 1/4 to 1/5 times as small as that in the period of the Kuroshio straight path (Taft and Freitag, 1978). $Q_{SO}$ is very small in its averaged value. This indicates that the 1st branch of the Tsushima Current, which is considered to go up northwards along the Japanese coast from the Tsushima Straits, usually flows mainly offshore beyond the Oki Islands. The transport of every channel does not present the seasonal variability and the year to year variations seem to be more dominant.

These records of motionally-induced voltage are subjected to the spectral analysis with the frequency resolution of 0.005 (=1/200) cpd. Frequency distributions of spectral densities are presented in Fig. 4(a). The percentage distributions of frequency-integrated spectral density for these records are plotted in Fig. 4(b). Generally speaking, such a figure indicates the relative significance of high-frequency components in these records. In the Straits of Oki and Oshima-South Channel, variations of the time scales of up to 20 days are relatively intense compared to those in the Straits of Tsugaru and in the Oshima-West Channel, which are both regions of more near-shore characteristics.
3. The Examination into the Detailed Structure of Actual Velocity Field of the Kuroshio with Relation to the Distribution of Shearing Stress

Studies of oceanic processes through motionally-induced voltage measurements across ocean currents intensely requested measurements of actual transports of the currents. The integration of vertical profile of actual velocity across the current was considered to be the most practical means for obtaining the actual transports. Thus, the author intended to develop the methods for measuring actual velocity profile in two ways, one of which is by the use of accelerometer-type profiler and the other is by sonic-wave type profiler. These were naturally very helpful for the study of the actual velocity structure of the Kuroshio, which had still remained uncertain.

The Kuroshio is characterized by strong shears of velocity in the cross-stream direction as well as in the vertical direction. In association with these shears, significant frictional forces are acting on the current. This fact indicates that the Kuroshio is necessarily in departure from geostrophy.

Until the recent time, in which ADCP has been developed and used on the routine basis, information on kinematical properties of ocean currents such as velocity and transport, especially below surface layer were mainly obtained through dynamic computations based on observations of temperature and salinity fields. The computation stands on the assumption of baroclinic geostrophy. The author has kept much interest in examining the departure of the Kuroshio as a boundary current from baroclinic geostrophy and has made experiments for this purpose as described below.

3.1 Structure of the baroclinic, geostrophic velocity-field of the Kuroshio

According to measurements of surface velocity $v_0$ by means of towed electrodes, the surface-velocity field of the Kuroshio has a cross-stream structure as shown typically in Figs. 5(a) and (b) which are for the sections of the Kuroshio and its Extension, respectively. These figures

Fig. 5. (a), (b) Cross-stream distributions of surface velocity $v_0$ (upper panel) and vertical profile of baroclinic, geostrophic velocity $V_C$ (a) and $V_G$ (b) (lower panel). (c) An example of velocity profile measured in the area of Tsugaru Current Extension.
indicate an existence of intense shear in a boundary area to the left of the surface-velocity maximum on facing towards the downstream direction. In addition, lower panels of these figures indicate that in this left-hand area, a vertical profile of geostrophic velocity $V_G$ has a convex feature vertically downwards in the subsurface with respect to $Z-V_G$ coordinates and a concave feature in the right-hand area of the surface-velocity maximum.

Another characteristics possessed by the vertical profile of geostrophic velocity in the right-hand area is the presence of the maximum velocity at a subsurface layer such as 200 to 300 m in depth. Thus, it is recognized that the stream axis exists in the subsurface. Whether or not such characteristics are possessed by the actual velocity field is a problem to be digged in.

3.2 Development of a velocity profiler of accelerometer type and a measured velocity profile of the Tsugaru Current Extension

When we provide a buoy, which can freely descend down to the sea bottom and can freely ascend up to the sea surface after releasing a weight at the bottom, the vertical profile of absolute velocity $V$ against the depth is available from continuous measurements of horizontal acceleration $\alpha$ of the buoy with time (Teramoto, 1972).

The determination of $V$ is requested to be made with an accuracy better than 1 cm s$^{-1}$ under the actual condition that $V$ is of the order of 100 cm$^{-1}$ at most. In the actual operation of profiler in the open ocean of several thousands meters in depth, the time $T$ necessary for the descending or ascending is of the order of 1000 s in operation. Thus, measurements of $\alpha$ is necessary to be made with the accuracy better than $10^{-3}$ cm s$^{-2}$. The author made such a kind of up and down buoy involving an accelerometer of this accuracy and has conducted operations a few times in 1968 and 1969 (Teramoto, 1972).

Figure 5(c) illustrates an example of actual velocity profile measured by the use of the velocity profiler in the extension of the Tsugaru Current, off Onagawa (Fig. 1(a)) in Sep., 1969. The profile (E-W component) indicates the convex feature vertically downwards even though modulated with undulations of small amplitude and wave length. The undulations were due to undesirable oscillations of the profiler around its center of gravity and can be stopped by lowering the position of the center of gravity within the profiler. The profiler of this type is now evaluated to be used effectively as a necessary auxiliary to ship-born ADCP, which can present an actual velocity profile only for the upper several hundreds meters of the ocean.

3.3 Development of a velocity profiler of sonic-wave type and measurements of actual velocity profile across the Kuroshio with the profiler

A current meter using sonic sing-around method was developed around 1965 and was connected to the conductor of a cable reeled on a winch drum of the R/V Hakuhomaru to measure a vertical profile of velocity. By stopping the current meter at desired depths in its lowering process, velocity measurements were made. A vertical profile of water velocity relative to the drifting vessel was obtained. The correction of the ship’s drift was made on board by supplying signals on vessel’s drift from an auto-Loran, which provides a necessary part of the profiler system.

Six stations 2 (33°30’ N), 3 (33°20’ N), 4 (33°10’ N), 5(33°00’ N), 6 (32°50’ N) and 7 (32°40’ N) were selected in the Kuroshio along 135°20’ E off the Kii Peninsula (Fig. 1(a)) and were occupied once every day during Oct. 15 to 19 in 1967 for conducting measurements of vertical profile of actual velocity by the use of the profiler. The measurements should be terminated soon after the above 5-day operations to avoid the attack of a typhoon. The profiles
at every station are averaged over the above five days and the average is illustrated in Fig. 6 (upper panel). The measurements were limited to the upper 600 m due to the malfunction of the connector beyond this depth. The presented velocities are those relative to velocity at 600 m for every station.

The surface velocity maximum exists around Sta. 4. To the left of this station on facing the downstream direction, velocity profiles are of the concave feature downwards in the subsurface and to the right the convex on downwards. And at any station velocity profile does not have the velocity maximum in the subsurface, on being clearly different from the case of the geostrophic velocity profiles, already mentioned and also to be described below.

3.4 Departure of the Kuroshio velocity-field from baroclinic geostrophy

During the above-stated measurements of actual velocity profiles, observations of density field are carried out by means of CTD in succession to the profile measurements at every station. The cross-stream distribution of vertical profiles of baroclinic, geostrophic velocity averaged over the five days is shown with black curves in Fig. 6 (lower panel). Every geostrophic velocity profile is considered to represent the averaged one between the two neighbouring stations. For comparison, profiles of actual velocity are averaged over two neighbouring stations and are illustrated with dotted curves in the lower panel of Fig. 6. These two kinds of velocity profile are in very good agreement everywhere on the Kuroshio section except for the upper 200 m. Thus, it can be concluded that in this upper layer of the Kuroshio, the additional velocity field is superimposed upon the baroclinic, geostrophic velocity field to form the actual velocity field. This additional field is considered to be due to barotropic, geostrophic and/or non-geostrophic velocity components and their magnitudes reach as much as 30 cm s⁻¹ as a total sum at the surface, where the actual velocity is of the order of 50 to 100 cm s⁻¹.

Figure 7(a) indicates the iso-vel distributions on the vertical section along 135°20′ E for the

![Fig. 6. Cross-stream distribution of vertical profiles of actual velocity along 135°20′ E averaged over 5 days (upper panel). That of baroclinic geostrophic velocity is also illustrated (lower panel), upon which cross-stream distribution of vertical profile of actual velocity averaged over two neighbouring stations (dotted curve) are drawn.](image)
actual velocity field. This is analogous to that drawn by Kaneko et al. (1992) on the basis of recent measurements of the Kuroshio velocity profiles with ADCP.

3.5 Distribution of velocity shear in the Kuroshio

The structure of velocity field of the Kuroshio in the idealized form is delineated in Fig. 7(b), which is characterized by the strained distribution of velocity on a cross section. At the surface, the velocity field of the Kuroshio has a strong shear in the cross-stream direction and therefore, has the positive vertical vorticity on the left-hand side of the surface velocity maximum on facing the downstream direction and negative one on the right-hand side. The velocity shear is, on the other hand, associated deeply with a shearing stress and a resultant frictional force. In the subsurface, the breadth of the current shrinks and the magnitude of the velocity maximum decreases rapidly with the increase of depth. Thus, the velocity shear varies with depth, producing changes in distributions of vorticity and frictional forces. The Kuroshio also has a strong velocity shear in the vertical direction as shown in Fig. 7.

The distribution of vorticity and these frictional forces should be taken into consideration in the treatment of behaviours of the current. The meandering and non-meandering of the Kuroshio, for instance, should be studied from this standpoint on the basis of accumulating information on the detailed structure of velocity field from direct current measurements. Then, the more accurate discussion on the dynamics of the behaviours would become possible.

3.6 Determination of reference level of no motion in Kuroshio off Cape Shionomisaki

Fukasawa together with Teramoto and Taira (1995) made the determination of the reference level at the layer around 2500 m in depth in the Kuroshio off the cape Shionomisaki (Fig. 1(a)), through the comparison of the baroclinic, geostrophic velocity field from CTD observations to
the actual velocity field measured with moored current-meter array. The determination is very helpful for interpreting hydrographic observations in the past.

4. Delineation of Ocean Circulations in the Subsurface, Mid-Depth and Deep Layers of the Philippine Sea, the Westernmost Part of the North Pacific

The fact that the Kuroshio transport estimated from the motionally-induced voltage over the Izu Ridge is constantly less than that from hydrographic observations at the section off the Kii Peninsula by 20 to 30 × 10^6 m^3 s^-1 (Teramoto and Kojima, 1994) has given the insight to the author of recirculation at the subsurface layer in the Shikoku Basin to the west of the ridge. While, there is a fact that the age determination for the sea water by the use of ^14C indicated the deep water of the Philippine Sea being younger by about 200 years than that of the major part of the North Pacific to the east of the ridge (Gamo, personal communication). This fact gives the insight of the deep current to be flowing northwards along the deep western boundary of the South Pacific and then flowing into the North Pacific on pouring its branch into the Philippine Sea. These insights requested the further inquiry to elucidate the detailed configuration of ocean circulation together with water-mass distribution in the Philippine Sea. In such a circumstance, the author organized and promoted the project research titled “Dynamics of the deep ocean circulation” under the philosophy to coordinate studies on open ocean physics with those on ocean chemistry. In the project, measurements of velocity by mooring current meters, trackings of circulation by means of SOFAR floats and numerical modelling of circulation are carried out as well as water-characteristics analysis on the basis of water-property distribution.

4.1 Delineation of water-mass distribution, especially of its layered structure in the Philippine Sea

Through the water-characteristics analysis, the configurational structure of water-mass distribution is delineated, and processes to give rise to such a structure are deduced as summarised in the following (Kaneko and Teramoto, 1985). The water of the South Philippine Sea is in the sharp contrast to that of the Northwest Pacific in water characteristics in a sense that the former is of higher salinity (S), higher concentration in dissolved oxygen (DO) and lower concentration in dissolved Silica (DSi) compared to the latter between the surface of \(\sigma_\theta = 26.8\) (about 800 m in depth) and that of \(\sigma_\theta = 27.75\) (about 3000 m in depth). These two kinds of water are specified as water masses, that is, South Philippine Sea Water (SPSW) and Northwest Pacific Water (NwPW). The sea water filling a layer between the isopycnal surface of \(\sigma_\theta = 26.8\) and that of \(\sigma_\theta = 27.75\) in the Shikoku Basin has specific characteristics different from those of the surrounding waters such as NwPW and SPSW. Hence, this water is specified to be the third watermass, Shikoku Basin Water (SBW). The mass is confined within the basin as typically illustrated in Fig. 8 for \(\sigma_\theta = 27.70\) (about 2000 m in depth). The upper portion of this watermass in a layer between the surface of \(\sigma_\theta = 26.8\) and that of \(\sigma_\theta = 27.55\) (about 1500 m in depth) is considered to have been formed through the horizontal mixing of NwPW flowed into the basin passing over the ridge with the water of higher salinity and higher oxyty existing in the east of Taiwan. The lower portion of SBW in a layer between the surface of around \(\sigma_\theta = 27.70\) and that of \(\sigma_\theta = 27.75\) can be formed through the vertical mixing of the upper SBW \((\sigma_\theta \leq 27.30, \text{ about } 1000 \text{ m})\) with the deep water below SBW. This deep water filling a layer below the mass of SBW has characteristics similar to those of SPBW. Thus, the sea water of the Shikoku Basin is recognized to have four-layer structure; namely, the surface layer from the sea surface to the surface of \(\sigma_\theta = 26.8\) (about 800 m), the subsurface layer from the surface of \(\sigma_\theta = 26.8\) to that of
Fig. 8. (a) Distribution of water mass NW PW, SPBW and SBW on $\sigma_\theta = 27.70$ (about 2000 m) surface (Kaneko and Teramoto, 1985). (b), (c) iso-geopotential (dynamic height) lines on the isobaric surfaces of 1000 db (b) and 3000 db (c) estimated on assuming the isobaric surface of 2000 db being the level of no motion. (d) Total ocean circulation model for the Philippine Sea.

$\sigma_\theta = 27.55$ (about 1500 m), the mid-depth layer from the surface of around $\sigma_\theta = 27.70$ (about 2000 m) to that of $\sigma_\theta = 27.75$ (about 3000 m), and the deep layer from the surface of $\sigma_\theta = 27.75$ to the sea bottom.

As for the deep water, the question arises on where its origin is. For inquiring this question, the water-characteristics analysis was made in the preceding paper (Teramoto, 1993) on the basis of water-property data from the Ryofumaru Cruise along 137°E in the Philippine Sea, the Hakuhomaru Cruise along 158°E in the western North Pacific and GEOSECS Expedition along 180° in the equatorial area in the northern and southern hemispheres. S-DO and DSi-DO diagrams for the surfaces of $\sigma_\theta = 27.55$, 27.7 (1500, 2000 db) and 27.77 (3000 db) were used. The
The delineation of dynamical characteristics of circulations and their changes diagrams for $\sigma_\theta = 27.77$ indicates that the deep equatorial water at around 10°S of GEOSECS Expedition is traced to branch into the South Philippine Sea through the Yap and Palau Trench to continue to the water observed during Ryofumaru Cruise along 137°E. While, the deep water near 5°N of the GEOSECS Expedition is traced to flow northward into the North Pacific and continue to the water observed during Hakuhomaru Cruise along 158°E. In a summary, it can be concluded that the deep boundary current flowing northwards along the deep western boundary of the South Pacific flows into the North Pacific through the Samoan Passage as Stommel and Arons (1960) delineated, and then branches a part of it into the Philippine Sea through the Yap-Palau Trough, leaving the rest of it in the state of going further northwards along the Mariana-Ogasawara-Izu Ridge. On the other hand, the water-characteristics analysis suggested that the deep SPSW expands northwards along the deep western boundary. On the basis of this result, the deep circulation of the Philippine Sea is delineated as shown at the bottom of Fig. 8(d), which consists of the deep western boundary current and deep interior current with upwelling, as is similar to those presented by Stommel and Arons (1960) for the major oceans.

4.2 Delineation of ocean circulation of the Philippine Sea on the basis of dynamic computation of geopotential

The geostrophic circulations on isobaric surfaces of 1000 db and 3000 db of the basin are delineated as shown in Figs. 8(b) and (c) on setting the reference level at the isobaric surface of 2000 db. The most striking feature of the figure is that the circulations are both confined in the area occupied by SBW and are opposite in direction of circulation. The layered structure of the circulation is in the close correspondence to the layered structure of the water masses filling the subsurface and mid-depth layers.

4.3 Delineation of subsurface and mid-depth circulations of the Shikoku Basin on the basis of SOFAR float tracking

For the purpose of confirming further the configuration of subsurface and mid-depth circulations of the basin, the tracking of SOFAR floats deployed in the basin was carried out (Taira and Yanagimoto, 1993). The access to this technology was made by the group organized by the author in 1980 in the financial support of Ministry of Education, Science and Culture. The results of tracking carried out under the leadership of Taira during 1988 to 1991 can be summarized as below. The trajectories of floats are subjected to the deformation due to disturbances such as meso-scale eddies encountered during their drifting. Consequently, the elimination of the influence of the disturbances through running averaging of trajectory over about 100 days, for instance, is needed for delineating the configuration of ocean circulations. Most trajectories of float draw clockwise circulations in the subsurface layer as shown in Fig. 9(a) and anticlockwise circulation in the mid-depth layer as shown in Fig. 9(a) after the elimination of disturbances. Such a feature is manifested in the northern boundary area, but in the interior area the trajectories seem contaminated more heavily with meso-scale eddies, which are of the order of 100 km in spatial scale and of 100 to 200 days in time scale.

4.4 Delineation of deep circulation of the Philippine Sea on the basis of long-term current-meter mooring

With an aim to confirm the structure of deep circulation shown in Fig. 8(d) as well as to reveal kinematic properties of velocity field in the deep northern boundary of the Shikoku Basin, long-term measurements of velocity were carried out by mooring current meters (Chaen et al., 1993).
This work has also been conducted as a part of project research “Dynamics of the deep ocean circulation” as mentioned above.

Velocity vectors averaged over 200 to 550 days for Stas. CS, CA, KP, CT, RT and BC are in the westward or southwestward directions (Fig. 9(c)), which are almost parallel to the local contour lines of bottom topography in the northern boundary of the Shikoku Basin, except for KP, where the velocity field is affected by the local topography characterized by the trench (Chaen et al., 1993). These features indicate the existence of the deep northern boundary current in the Shikoku Basin. The very small magnitude of average velocity at BC may indicate that this point is the stagnant point formed by the deep western boundary current with the northwestern boundary current. The existence of the deep northern boundary current supports the deep circulation model of the Philippine Sea presented in Fig. 8(d).

4.5 Full delineation of configurational structure of ocean circulations in the surface, subsurface, mid-depth and deep layers of the Philippine Sea

On summarizing the above treatments, the total circulation model for the Philippine Sea is delineated in Fig. 8(d). The sufficient explanation for the dynamical mechanism to form the subsurface and mid-depth circulations in the Shikoku Basin has remained unpresentable.

5. Mechanism of Intensified Generation of Semi-Diurnal Internal Tides over the Izu Ridge, which Modulate the Density Field of Ocean Circulations

In relation to the Space Robot Experiment made in Uchiura Bay, which is at the bottom of Suruga Bay (Fig. 1(b)), the author together with Matsuyama had much interest in the internal tides, which were the dominant processes of the bay steadily existing. The numerical experiment suggested the possibility of amplification by resonance of the internal tides intruded into the bay from the outside (Matsuyama and Teramoto, 1978). We had an idea that the internal tides were generated over the Izu Ridge, which lies long like a barrier in the direction normal to the incidence of surface tides in the area south of Japan. For verifying the idea, the author has promoted the study in cooperation with Hamatani (1989) as described below.
5.1 Spatial distribution of phase angle of tide waves in the direction normal to the Izu Ridge line

Long-term measurements of velocity were made by the Physical Oceanography Division (managed by the author), Ocean Research Institute with the use of current meters moored at about 500 m from the bottom at stations distributed in the Kuroshio area in the Shikoku Basin, in the area over the Izu Ridge and in the Kuroshio Extension area in the western part of the North Pacific. The similar measurements were also made by the Hydrographic Office at stations over the ridge. These stations are situated at 30° to 34°N in latitude. Four major constituents \( K_1, O_1, M_2 \) and \( S_2 \) of tidal current are extracted from these velocity records over 150-day period. The major axes of the tidal ellipse at these stations are almost in the westward directions, which are in good agreement with those of tide wave incidence. Phase angles of four major constituents referring to the direction of the major axes of tidal ellipse are plotted against the longitude of station (Fig. 10). The specially large error-bar for the phase of \( K_1 \) constituent (Fig. 10(c)) is due to the inertial motions. On these figures, it is noticed that for the semi-diurnal constituents \( M_2 \) and \( S_2 \) the phase angles are almost uniformly constant at any stations from 135° to 138° in longitude, which are involved in the Shikoku Basin. This feature is in contrast to that of the phase angles for the diurnal constituents \( K_1 \) and \( O_1 \), which are in gradual increase with decrease in longitude of station. The constant phase angles suggest that the semi-diurnal tides behave as standing waves in the Shikoku Basin, while the diurnal tides behave as progressive waves travelling westwards. Phase angles at stations from 138° to 142° in longitude, which are over the Izu Ridge, vary very irregularly with regard to longitude irrespective of constituents being diurnal or semi-diurnal. This irregularity can be understood when we assume the occurrence of internal tides over the ridge. For the diurnal constituents \( K_1 \) and \( O_1 \), all the phase-angle data except for those over the ridge are connected with a smooth curve indicated as a dotted line in Figs. 10(a) and (b), although

![Fig. 10.](image-url)
the line slightly bends at longitude over the ridge depending upon the difference in water depth between the Shikoku Basin (typically 4000 m) and the western part of the North Pacific Basin (typically 6000 m). On the other hand, as shown in Figs. 10(c) and (d) for the semi-diurnal constituents M₂ and S₂, a dotted line connecting the phase-angle data clearly bends around the longitude of 140°E, which is at the eastern edge of the ridge.

5.2 Spatial distribution of harmonic constants of tidal elevation in the Philippine Sea—Evidence for resonance of semi-diurnal surface tides in the sea

Amplitudes and phases from harmonic analysis of sea-surface elevations at tide stations distributed in the Philippine Sea to the west of the Izu-Ogasawara-Maliana Ridge were studies (Teramoto and Hamatani, 1985). An amplitude of each diurnal constituent is almost constant throughout the sea and phase increases almost linearly westwards. These features suggest the diurnal surface tides to behave as travelling waves in the sea. On the other hand, an amplitude of each semi-diurnal constituent decreases rapidly eastwards reaching to almost zero at the line a little outside the ridge and that the iso-line for amplitude runs almost in parallel to the longitudinal line. In addition, the phase of each semi-diurnal constituent is almost uniformly constant throughout the sea. These features clearly suggest the occurrence of resonance for semi-diurnal surface tides with the node at the ridge line and loop at the western boundary of the sea. The suggestion can be verified when we estimate the wave length of the semi-diurnal tides to be about 8000 km in this sea of 4000 m in water depth, which is 4 times as large as east-west scale of 2000 km of the sea. Amplitudes of tidal current are their maxima at the node, which may provide the good condition for intensified generation of semi-diurnal internal tides over the ridge.

5.3 Measurements of vertical profile of tidal current with moored current meters and simultaneous measurements of tidal undulations of isopycnals with CTD over the Izu Ridge

The topographical features characterized by the Izu Ridge, which stands as a barrier against the tide-wave incidence, seem to present the good condition appropriate for generating internal tides in this area. Especially for the semi-diurnal tides, the water motion there is so violent, because of the ridge line forming the nodal line of tidal resonance, that internal tides with noticeable amplitude are thought to be generated. For verifying this thought, long-term measurements of velocity were made by mooring current meter in four layers at the two stations Hₓ₁ (33°06.0′ N, 139°06.5′ E) and Hₓ₂ (33°05.8′ N, 138°52.8′ E) near Hachijojima over the Izu Ridge for about 6 months from May 23 to Nov. 24, 1985. The two stations (Fig. 1(b)) were selected on a line of surface-tide incidence with a distance of about 20 km, which is about a quarter of wave length of semi-diurnal internal tides expected. Vertical distributions of tidal ellipses for K₁ and M₂ constituents obtained from harmonic analysis of the current records are illustrated in Figs. 11(a) and (b). Recordings in the 2nd layer at Hₓ₁ and 3rd layer at Hₓ₂ were in failure.

The vertical distribution of K₁ tidal ellipse is almost common in feature to both stations. Namely, the length and direction of major axis as well as ellipticity are uniform irrespective of positions and depths of stations. Actually, upon this velocity field represented by the tidal ellipse, the supplementary velocity field, which is small in magnitude and variable in direction with depth, are superposed. The field would be due to the internal tides. The vertical distribution of M₂ tidal ellipse presents the feature quite different from that of K₁. That is, the tidal ellipse varies from depth to depth and from one station to another in amplitude and direction of major axis as well as the ellipticity. These features suggest that semi-diurnal internal tides are of various vertical modes.
Fig. 11. (a) Vertical distribution of tidal ellipses for $O_1$ constituents at Hx1 and Hx2 obtained from harmonic analysis of current records (Hamatani, 1989). (b) Vertical distribution of tidal ellipses for $M_2$ constituents at Hx1 and Hx2 obtained from harmonic analysis of current records (Hamatani, 1989). (c) Time sequence of changes in depth of isopycnals, $\sigma_\theta = 24.0$ to 27.5.
By the courtesy of J. Yoshida and his colleagues of the Tokyo University of Fisheries, CTD observations were carried out from the surface to the bottom at a station near Hx 1 with the time interval of 1.5 hrs during 25 hrs from 13:00 on Oct. 13 to 14:00 on Oct. 14 in 1985. Time sequence of changes in depth of isopycnals from $\sigma_\theta = 24.0$ to 27.5 are plotted in Fig. 11(c). This figure clearly shows the undulation of isopycnal layer at semi-diurnal cycle with the amplitude maximum of 50 m at the layer of 900 m in depth, which verify the existence of internal waves of that period.

Through the above-mentioned observations, the steady generation of internal tides, especially the intensified generation of semi-diurnal internal tides is verified to take place over the ridge. Matsuyama and his colleagues has treated that the internal tides of the diurnal periods behaved as internal Kelvin waves travelling anticlockwise into the Suruga Bay along the western wall of the ridge and on the other hand, internal tides of the semi-diurnal periods behaved as inertia-gravity waves travelling both into the Sagami and Suruga Bays (Ohwaki et al., 1994). Semi-diurnal internal tides, though generated intensely over the ridge under the influence of configurational resonance of incident surface tides, diverse their energy in every direction. Thus, amplitudes of major axes of internal tidal ellipse for $M_2$ and $S_2$ are around 10 and 5 cm s$^{-1}$, which are almost similar to those for $K_1$ and $O_1$.

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