Eduction of Hydrodynamical Processes from Cross-Channel Electric-Potential Differences in the Kuroshio Area around the Izu Ridge

TOSHIHIKO TERAMOTO and HIROBUMI KOJIMA

School of Science, Kanagawa University, Hiratsuka 259-12, Japan

(Received 13 October 1992; in revised form 29 December 1993; accepted 3 January 1994)

The paper comprises analysis of telluric electric-potential differences measured across channels west and south of Oshima in the Kuroshio area to the south of Tokyo Bay during one to two years around 1960. The records are shown to involve ionospheric and magnetospheric induction noises, which are at the same or higher energy level compared to signals induced by Oceanic-dynamic processes in a frequency range of the daily and higher cycles. Channel transports estimated from potential records through eliminating the noises are verified, in reference to hydrographic observations as well as cross-channel difference in sea-level observations, to represent well the actual transport not only in the baroclinic geostrophic mode but also in the barotropic geostrophic mode and the mode deviated from geostrophy. The channel transports, which are obtained continuously in time, are proved to reveal especially well the detailed time-varying processes, on illustrating the case of an inverse-current burst happened in the Oshima-West Channel. At the end, results from spectral analyses of potential records in relation to reference quantities are presented.

1. Introduction

The transport of ocean current is one of the important kinematic properties which characterizes behaviours of the current. The term transport used in this paper is not defined as a vertical integral of velocity but is defined as an integral over a cross section of channel. The transport of Kuroshio may, for instance, be closely associated with the bimodal Kuroshio behaviours, the meandering and straight flowing, in the south of the Japanese Islands (Robinson and Taft, 1972; Nitani, 1975; White and McCreary, 1976; Masuda, 1982; Yasuda et al., 1985).

Kuroshio transports available so far were, however, all estimated from hydrographic observations and could only give baroclinic geostrophic transports, which were of a little ambiguity in determining a level of no motion. Whereas, measurements of cross-channel electric-potential difference induced across an oceanic flow have been treated theoretically and proved empirically to provide total flow transports, when an elimination of noise was made appropriately and a calibration was made adequately (Faraday, 1832; Stommel, 1948; Longuet-Higgins, 1949; Malkus and Stern, 1952; Longuet-Higgins et al., 1954; Bowden, 1956; Nitani et al., 1959; Bowden and Hughes, 1961; Teramoto, 1971; Sanford, 1971; Sanford and Frick, 1975; Robinson, 1976; Baines and Bell, 1987; Spain and Sanford, 1987; Larsen, 1992). One of the authors (Teramoto) carried out potential measurements for two to three years around 1960 on submarine cables laid across two channels west and south of Oshima (Fig. 1) with an expectation to give a new aspect to empirical studies of the Kuroshio. The Oshima-West Channel defined in this paper is the channel beginning from the west of the Izu Peninsula to the east of the Boso Peninsula through the Sagami Bay with the width of about 30 km, and the Oshima-South Channel
is that neighbouring south to the former one with the width of about 80 km (Fig. 1).

Superimposed upon signals from channel flows, a cross-channel potential measurement also involves noises, which are induced by ionospheric and magnetospheric fluctuations and which are induced from electric field caused by the water flow outside each channel. In our case, the former noises, which are especially energetic at the daily and higher cycles, are eliminated through a low-pass filtering of cut-off frequency at the daily cycle. The latter ones are neglected on taking into consideration that an influence is reduced rapidly outside the channel. The more essential to the estimation of transport from the potential is the inquiry of averaged channel-bed conductivity, which is requisite to the estimation. The conductivity is obtained from simultaneous measurements of potential difference, water velocity, electric current-density and sea-water conductivity of the channel as described in the previous paper by one of the authors (Teramoto, 1971).

Thus, the estimation of transport from potential records becomes possible. But, unfortunately, the validation of the estimated transport can not be made, because any other means to measure the actual transport (not the baroclinic geostrophic transport) were not developed in those days of our potential measurements. Moreover, the giving-up of the used cables due to a serious damage caused by typhoons, which attacked just after our measurements made absolutely impossible the validation forever. Consequently, the validation has remained unenforced. And so, the authors must lift their minds to derive its validity from the judgement on whether or not the analysis of the estimated transports could give reasonable results in revealing dynamical processes of the channel in reference to spatial and temporal changes in other independent
physical-quantities observed.

The time of our measurements is more than 30 years before the present time, however, an analysis of data from these continuous measurements clearly shows to reveal detailed time-varying processes of the flow in consistency with reference data. Thus, the estimated transports are proved to be valid and sufficiently useful for studying dynamical processes. This paper comprises results of the analysis.

2. Potential Measurements, Potential Noises and Data Processing

2.1 Potential measurements

Potential measurements were made on the two cables, one across the Oshima-West Channel between Kawazuhamae, the Izu Peninsula and Oshima and the other across the Oshima-South Channel between Oshima and Miyakejima (Fig. 1). The cables were sometimes injured by storms and accordingly the recordings of potential were interrupted. The records which are continuous and are available for analysing the monthly and longer-period fluctuations are as follows: the record from May, 1959 to May, 1960 for the Oshima-South Channel and that from June 1959 to July, 1961 for the Oshima-West Channel.

![Fig. 2. Configuration of non-polarized electrode used for potential measurements.](image)

![Fig. 3. Wiring for the potential measurements.](image)
At the ends of these periods of measurement, the cables were seriously damaged by strong typhoons. And the damaged cables were no longer repaired nor renewed, because in those days, the telephone communication was in the stage of changing from the cable communication to wireless communication.

Electrodes used for the potential measurements were of non-polarized characteristics. Their configuration is shown in Fig. 2. Electrodes were buried in the beach sand around cable houses at both ends of a cable in each measurement. The connection of an electrode to a cable was made at the neutral point of repeater coil on a telephone line and both the potential measurement and the telephone communication were carried out in parallel on a same cable without any interference. The recording of potential was made on an analogue recording voltmeter placed at a telephone repeater station (Fig. 3).

2.2 Potential noises

Potential records are seriously contaminated with noises mainly induced in association with ionospheric and magnetospheric fluctuations. Empirical studies on telluric electric field indicate that variations in east-west (E-W) component of the field are highly coherent to those in horizontal component of geomagnetic field and variations in north-south (N-S) component to those in declination of geomagnetic field, in general (Hatakeyama, 1940). In Fig. 4, simultaneous crude records of potential difference, $\phi_{KH} - \phi_{OM}$ (KH: Kawazuham, OM: Oshima, KH–OM: about 20 km) induced across the Oshima-West Channel, $\phi_{TB} - \phi_{IZ}$ (TB: Tobetsu, IZ: Ishizaki, TB–IZ: about 40 km) induced across the Tsugaru Straits (Fig. 5) and $\phi_{TB} - \phi_{MH}$ (TB: Tobetsu, MH: Moheji, TB–MH: about 5 km) induced along the coast of the straits are plotted together with the

![Graph showing potential differences](image)

Fig. 4. Crude records of $H$ (horizontal component of geomagnetic field at Kakioka), $\phi_{TB} - \phi_{MH}$ (potential difference along the Straits of Tsugaru), $\phi_{TB} - \phi_{IZ}$ (potential difference across the straits) and $\phi_{KH} - \phi_{OM}$ (potential difference across the Oshima-West Channel).
crude record of horizontal component of geomagnetic field, $H$ at the inland station Kakioka (Fig. 1) on Nov. 14, 1959. For surveying the influence of ionospheric and magnetospheric fluctuations upon the induction of potential difference, electric fields rather than the potential differences are better to be compared each other and so, scales for electric fields (potential values per unit distance) are illustrated on the left-side ordinates in the figure. Variation in geomagnetic E-W component are proportional to those in the declination of geomagnetic field.

On the direct inspection of the figure at eye, high coherence between these records are found to exist. Specially high coherence of $\phi_{TB} - \phi_{MH}$ to $H$ is clear at any frequency of variation involved in the records; that is, at the frequency of about one cycle per 20 hrs and higher. High coherence of $\phi_{TB} - \phi_{IZ}$ to $H$ is also existing, although variations in $\phi_{TB} - \phi_{IZ}$ reduce their amplitudes particularly at frequencies higher than one cycle per few hours. Coherence of $\phi_{KH} - \phi_{OM}$ to $H$ is detectable with the further reduction in amplitudes at frequencies higher than one cycle per few hours. The highest coherence of $\phi_{TB} - \phi_{MH}$ and higher coherence of $\phi_{TB} - \phi_{IZ}$ to $H$ are recognizable when we consider that these potential differences are measured in the N-S direction in contrast to $\phi_{KH} - \phi_{OM}$ being measured in the E-W direction. The intensified induction of potential differences, which bears the highest and higher coherences in the Tsugaru Straits region, seems partly attributed to the abnormally high conductivity of sea-bed of the straits ($6.0 \times 10^{-2}$ mhos m$^{-1}$ compared to $2.2 \times 10^{-2}$ mhos m$^{-1}$ of the Oshima-West Channel). The straits is about 500 km to the north of Kakioka and the channel about 100 km to the south of that station. The coherent relations under consideration show that the process which produces the relations is at least of the horizontal scale of 600 km and is of the time scales over the wide range from 20
hrs to one hour or shorter. We have no such knowledge on hydrodynamical process in the ocean that satisfies these two conditions and takes place unceasingly as seen in the figure. Thus, potential variations coherent to those in the geomagnetic field are strongly suggested to be induced in association with ionospheric and magnetospheric fluctuations.

The examination of these noises at around the diurnal and semi-diurnal periods is essentially important from the standpoint of studying tidal phenomena by the use of potential records. For the examination, harmonic constants (amplitudes) of potential data in three different periods of a fortnight to a month for the Oshima-West Channel are shown in Table 1. Comparing these amplitudes with those of tidal elevation at Oshima, which are shown at the bottom of the same table, the following facts are pointed out. In the potential records, amplitudes of $M_2$, $O_1$ and $S_2$ are much variable from period to period. And furthermore, amplitudes of $S_2$ are too big and those of $O_1$ are too small compared to those of $K_1$, which are fairly stable. The period of a fortnight is not enough long for accurate tidal analysis but is not too short to produce amplitude error of major constituents such as $M_2$, $S_2$, $K_1$ and $O_1$ to reach a factor 1.5 or larger of their estimates. These characteristics are thought to be due to the induction from ionospheric and magnetospheric fluctuations. Hatakeyama (1940) showed that telluric electric fields at mid-latitude varied with semi-diurnal period. He illustrated typical records at Yuzhino-Sakhalinsk and Kakioka, which are both located inland (Fig. 5(b)). These are naturally much less influenced by electromagnetic induction from tidal current than cross-channel potential records. Amplitudes of semi-diurnal component of the electric field are typically 2 mV km$^{-1}$ for Yuzhino-Sakhalinsk and 5 mV km$^{-1}$ for Kakioka in east-west direction. These values suggest that our potential record across the Oshima-West Channel, which is about 30 km in width in the E-W direction, can reach 60 to 100 mV in amplitude of noise. These noises are sufficient for contaminating signals induced by tidal currents in the ocean. Namely, when we assume the tide waves in the channel to be one-dimensional long gravity-waves in a sinusoidal form with elevation amplitude of 1 m and so velocity amplitude of 15 cm s$^{-1}$, the potential difference induced across the channel is estimated to vary with the amplitude of 80 mV by the use of Eq. (6), which is derived in the following section. Both potential are comparable in magnitude and moreover the separation of those are difficult. Thus, our potential records are not appropriate for studying ocean tides and so this subject is omitted in the present study.

2.3 Data processing

In order to eliminate these noises, original records are subjected to the analogue electric low-

<table>
<thead>
<tr>
<th>Period of record</th>
<th>$K_1$</th>
<th>$O_1$</th>
<th>$M_2$</th>
<th>$S_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 2 to May 16, 1958</td>
<td>42</td>
<td>27</td>
<td>71</td>
<td>48</td>
</tr>
<tr>
<td>June 27 to July 11, 1959</td>
<td>35</td>
<td>31</td>
<td>60</td>
<td>74</td>
</tr>
<tr>
<td>June 16 to July 15, 1960</td>
<td>35</td>
<td>17</td>
<td>78</td>
<td>52</td>
</tr>
<tr>
<td>(Tide level at Oshima, cm)</td>
<td>22</td>
<td>19</td>
<td>35</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 1. Major four harmonic constituents (amplitudes) estimated from potential records for three periods of measurement. These constituents from tide record at Oshima are also shown for reference.
pass filtering which is of the characteristics shown in Fig. 6. The reference quantities such as the cross-channel and downchannel sea-level differences are also subjected to the low-pass filtering of the same characteristics.

3. Formulae to Estimate Transports from Cross-Channel Electric-Potential Differences

For simplicity, let assume a long, straight channel of the rectangular cross section with a uniform depth, \( h \), and breadth, \( D \), which are set equal to the mean depth and breadth of the actual channel (Fig. 7). The Cartesian coordinate axes, \( x, y, z \), are taken in the cross-channel, downchannel and vertically upward directions, respectively. The cross-channel gradient of electric potential in the model channel is given by the following formula.

\[
\frac{\partial \phi}{\partial x} = v H_Z - r j_x
\]  \( \quad (1) \)

where \( v \) is the downchannel component of velocity, \( H_Z \) the vertical component of geomagnetic field, \( r \) the electric resistivity of sea water and \( j_x \) the cross-channel component of electric-current density in the channel. Integrating this equation over the cross-sectional area \( \pi \), we have

\[
h(\phi_A - \phi_O) = Q H_Z - \int_\pi r j_x dxdz
\]  \( \quad (2) \)

provided that \( D \) is much larger than \( h \). In this formula, \( \phi_A - \phi_O \) is the cross-channel potential difference and \( Q \) the volume transport of the channel. Here, let introduce \( J_X \) to denote the vertically integrated electric current in the channel water and \( R \) to denote the averaged resistivity of the water defined by

\[
J_XRD = \int_\pi r j_x dxdz.
\]  \( \quad (3) \)

Let also introduce \( R_e \) to denote the effective electric resistivity of sea bed defined by
Fig. 7. (a) Actual cross-section of Oshima-South Channel. (b) Actual cross-section of Oshima-West Channel. (c) Model channel and Cartesian coordinates $x, y, z$, used to derive a formula for estimating the transport from the cross-channel electric-potential difference.
\[ R_e = \left( \phi_A - \phi_O \right) / J_x. \]  
(4)

Substituting Eqs. (3) and (4) into (2), the following formula is derived.

\[ Q = \frac{h}{H_z} \left( 1 + \frac{RD}{R_e h} \right) (\phi_A - \phi_O). \]  
(5)

This simple relation seems applicable, to the first order of approximation, to the estimation of transports of the Oshima-West Channel and Oshima-South Channel, because the assumed conditions are almost satisfied. For the former channel, \( R_e \) was estimated to be \( 4.5 \times 10^5 \text{ } \Omega \text{m} \) in the preceding paper by one of the authors (Teramoto, 1971).

We assume the same value of effective resistivity for the sea bed of the latter channel. Then, Eq. (5) is specified as follows:

for the Oshima-West Channel,

\[ Q_{\text{OW}} = 1.4 \times 10^4 (\phi_{KH} - \phi_{OM}) \text{ m}^3 \text{s}^{-1} \]  
(6)

by taking

\[ H_z = 0.34 \text{ Gauss}, \quad R_e = 4.5 \times 10^5 \text{ } \Omega \text{m}, \]
\[ D = 2.1 \times 10^4 \text{ m}, \quad h = 3.6 \times 10^2 \text{ m}, \]
\[ R = 2.5 \times 10^3 \text{ } \Omega \text{m}, \quad \phi_{KH} - \phi_{OM} \text{ in mV}, \]

and for the Oshima-South Channel,

\[ Q_{\text{OS}} = 2.0 \times 10^4 (\phi_{OM} - \phi_{MJ}) \text{ m}^3 \text{s}^{-1} \]  
(7)

by taking

\[ H_z = 0.34 \text{ Gauss}, \quad R_e = 4.5 \times 10^5 \text{ } \Omega \text{m}, \]
\[ D = 6.6 \times 10^4 \text{ m}, \quad h = 4.0 \times 10^2 \text{ m}, \]
\[ R = 2.5 \times 10^3 \text{ } \Omega \text{m}, \quad \phi_{OM} - \phi_{MJ} \text{ in mV}. \]

The validity of transports derived from these two formulae is examined through the analysis in the following sections. And the accuracy of the formulae is dealt with in the section of conclusions and discussions.

4. Results of Analysis

4.1 Examination of transport from cross-channel potential measurement in reference to baroclinic geostrophic transport from hydrographic observations in the Oshima-South Channel

During about one-year period of the electric-potential measurement across the Oshima-South Channel, cross-channel hydrographic observations around the section of our measurement
Fig. 8. Record of potential difference over the Oshima-South Channel, from which transport of Oshima-South Channel ($Q_{OS}$) is estimated, is plotted together with record of sea-level difference between Hachijojima and Oshima ($\zeta_{HJ} - \zeta_{OM}$). On $Q_{OS}$ record, baroclinic geostrophic transports estimated from hydrographic observations are plotted (black circle). On $\zeta_{HJ} - \zeta_{OM}$ record, the steric sea-level difference between $D_3$ and $D_2$ and between $D_{32}$ and $D_{41}$ are plotted (black circle). 21 and 31 day running averages of $<\phi_{OM} - \phi_{MJ}>$ and $<\zeta_{HJ} - \zeta_{OM}>$ are also plotted in the lower panel.
Table 2. Ratios of baroclinic geostrophic transport $Q_G$ from hydrographic observation to actual transport $Q$ from electric-potential measurement and to its averages $\langle Q \rangle$ over 5, 11, 21 and 31 day-period, which are centered at the date of hydrographic observation, are listed for seven cases. Deviations of the ratios from unity are also listed.

<table>
<thead>
<tr>
<th>Date of hydrogr. observation</th>
<th>$Q_G/Q$</th>
<th>$Q_G/\langle Q \rangle_{5}$</th>
<th>$Q_G/\langle Q \rangle_{11}$</th>
<th>$Q_G/\langle Q \rangle_{21}$</th>
<th>$Q_G/\langle Q \rangle_{31}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 28, 1959</td>
<td>0.65</td>
<td>0.61</td>
<td>0.59</td>
<td>0.56</td>
<td>0.56</td>
</tr>
<tr>
<td>June 26, 1959</td>
<td>0.95</td>
<td>0.91</td>
<td>0.93</td>
<td>0.92</td>
<td>0.95</td>
</tr>
<tr>
<td>June 27, 1959</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>July 26, 1959</td>
<td>0.68</td>
<td>0.68</td>
<td>0.68</td>
<td>0.67</td>
<td>0.70</td>
</tr>
<tr>
<td>Nov. 16, 1959</td>
<td>3.3</td>
<td>2.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Mar. 12, 1960</td>
<td>0.58</td>
<td>0.73</td>
<td>0.83</td>
<td>0.93</td>
<td>0.89</td>
</tr>
<tr>
<td>Mar. 25, 1960</td>
<td>2.1</td>
<td>2.3</td>
<td>1.7</td>
<td>1.6</td>
<td>1.5</td>
</tr>
</tbody>
</table>

were carried out seven times by the Hydrographic Office. The positions of the hydrographic stations $D_2$ and $D_3$ (to the east of the ridge) and $D_{51}$ and $D_{52}$ (to the west of the ridge) are shown in Fig. 1. The baroclinic geostrophic transports $Q_G$ between stas. $D_2$ and $D_1$ and between stas. $D_{51}$ and $D_{52}$ are plotted on the curve of the transport $Q$ estimated from the continuous electric-potential measurement (Fig. 8). A reference level for the computation of $Q_G$ is selected at 500 decibar level, because the water depths at stas. $D_2$ and $D_{51}$ are about 500 m.

The ratios of $Q_G$ to $Q$ from seven simultaneous electric-potential and hydrographic measurements are estimated. The ratios range from 0.58 to 3.3 as indicated in Table 2. The deviation of the ratio values from unity would mainly be due to the barotropic geostrophic component and/or non-geostrophic component (component deviated from geostrophy) involved in the electric-potential measurements. Needless to say, hydrographic measurements involve baroclinic geostrophic signals only.

As presented in Subsection 4.5, the record has spectral peaks at frequencies around 0.04, 0.14, 0.24 and 0.34 cpd (cycle per day) and consequently at periods around 25, 7, 4 and 3 days. The variations of 25-day period are of possibilities to be due to barotropic waves, which were found through long-term current measurements made simultaneously at 300 m and 1650 m depths in the region under consideration about 20 years later (Taira and Teramoto, 1981). The variations of 7-day period are wind-induced, non geostrophic ones as described in Subsection 4.5. In order to examine how the elimination of these variations get the ratios to approach nearer to unity, the time series of $Q$ is subjected to running averaging over 5, 11, 21 and 31 days and the values for the date of each hydrographic observation, $\langle Q \rangle_{5}$, $\langle Q \rangle_{11}$, $\langle Q \rangle_{21}$ and $\langle Q \rangle_{31}$ are read out. Then, the ratios of $Q_G$ to these averaged values $\langle Q \rangle$ are estimated and presented in Table 2. For the first four of the seven cases, the comparison of the low-pass filtering of $Q$ through the running averaging over any of 5, 11, 21 and 31 days does not bring better results, while the rest of the three cases, around which variations of several-day period are dominant, the averaging over 11, 21 and 31 days gives distinctly nearer values of the ratio to unity. This fact indicates that the elimination of wind-induced, non geostrophic components of period around 7 days greatly improved the ratio values. The running averaging over 21 and 31 days improves the ratio value to approach a little nearer to unity than that over 11 days. This fact seems to be due to barotropic
variations of about 25-day period being eliminated. Through the examination, the transport estimated from potential difference has been proven to be valid and is useful for process studies.

4.2 Comparison of transport from potential difference across the Oshima-South Channel to sea-level difference between Hachijojima and Oshima

In order to examine further the characteristics of the transport from potential measurements, the sea-level difference \( \Delta \zeta = \zeta_{HJ} - \zeta_{OM} \) (HJ: Hachijojima (Fig. 1), which is about 50 km to the South of Miyakejima) is illustrated in Fig. 8. \( \zeta_{HJ} \) is used as an alternative of \( \zeta_{OM} \) because there was no tide station at Miyakejima at the time of our potential measurements. \( \langle Q \rangle_{21} \) and \( \langle Q \rangle_{31} \) curves as well as the 21-day and 31-day averaged curves of the sea-level difference \( \langle \Delta \zeta \rangle \) are also illustrated in the lower panel of the figure.

The 15°C isotherm on 200 m depth is statistically recognized (Kawai, 1969), on the basis of the thermal-wind approximation, to coincide almost with the axis of the Kuroshio. The axis defined here implies the stream line of the greatest speed. On summarizing historical data on isotherms at 200 m, the following statistical results is obtained. When the Kuroshio follows the meandering path in the west of the Izu Ridge, the Kuroshio goes up to the north along the western side of the ridge (Kawabe, 1985) and passes over it mainly through the Oshima-West Channel and Oshima-South Channel.

In the period of our potential measurement, the main part of the Kuroshio flowed to the north of Miyakejima in association with the large, steady meandering and there is no significant flow between Hachijojima and Miyakejima (Fig. 9). Consequently \( \Delta \zeta \) is believed to reflect the flow change of the Kuroshio. For reference, steric sea-level difference \( \Delta D \) between \( D_3 \) and \( D_2 \) and between \( D_{31} \) and \( D_{31} \) are plotted on the curve of sea-level difference \( \Delta \zeta \) in Fig. 8. \( \Delta \zeta \) involves arbitrary bias due to no leveling between the two tide stations. \( \Delta D \) are plotted so as to give the best fit in a sense that deviations of \( \Delta D \) from \( \Delta \zeta \) become minimum. Actually, the averaged deviation is 44 cm², the square root of which (=6.6 cm) is far smaller than 80 cm of difference between maximum and minimum in \( \Delta \zeta \). This fact shows the appropriateness of using \( \Delta \zeta \). The

![Fig. 9. Typical isotherm pattern around the Izu Ridge during the period of our potential measurement. The Kuroshio was under the condition of meander path (from Kaiyosokuho).](image-url)
visual inspection of $\langle Q \rangle_{21,31}$ and $\langle \Delta \zeta \rangle_{21,31}$ curves shows that these vary almost synchronously at the periods of two to several months. $\langle Q \rangle_{31}$ and $\langle \Delta \zeta \rangle_{31}$ are especially in a visual coherence with each other. Both curves also involve concurrently the general trend decreasing gradually with time throughout the whole period. These relations suggest the two-month and longer period variations being in a geostrophic balance.

The above studies support that the transport estimated from potential measurements on the basis of simple formula is valid.

4.3 Transport from potential difference across the Oshima-West Channel

As seen in Fig. 10, $Q_{OW}$ varies from $-1 \times 10^6$ m$^3$s$^{-1}$ to $6 \times 10^6$ m$^3$s$^{-1}$ with the average of about $3 \times 10^6$ m$^3$s$^{-1}$ during 26 months from June 1959 to August 1961. For a week from 17 to 23 in March, 1977, the transport of the channel was measured by mooring 6 current-meters (Taira and Teramoto, 1986). The Kuroshio in this period was also in the condition of meandering. The daily averaged transports are from $1.5 \times 10^6$ to $2.1 \times 10^6$ with the mean of $1.8 \times 10^6$ m$^3$s$^{-1}$. These values are involved in the range shown above. There is no contradiction between the two measurements although the periods and methods are different.

4.4 Total Kuroshio transport over the Izu Ridge and the indication of deep recirculation in the west of the ridge

As described in the previous subsection, the sum of the transports in the Oshima-West Channel and Oshima-South Channel, $Q_{OW} + Q_{OS}$, approximately gives the total Kuroshio transport passing over the Izu Ridge, when the Kuroshio forms the meandering as in our case. The total transport $Q_{OW} + Q_{OS}$ is illustrated at the top of Fig. 10. It ranges from $4 \times 10^6$ to $11 \times 10^6$ m$^3$s$^{-1}$ with the average of $7 \times 10^6$ m$^3$s$^{-1}$. This average, which gives well the baroclinic geostrophic transport as treated in the preceding subsection, is to be compared to the transport of $25 \times 10^6$ m$^3$s$^{-1}$ estimated from hydrographic observations which were made by Taft and Freitag (1978) over the ridge under the condition of the Kuroshio straight path. The difference of about $20 \times 10^6$ m$^3$s$^{-1}$ in transport under these two different Kuroshio-path conditions are almost the same to the difference between transports of upstream Kuroshio off the Kii Peninsula of $50$ to $60 \times 10^6$ m$^3$s$^{-1}$ under the condition of the Kuroshio straight path and $30$ to $40 \times 10^6$ m$^3$s$^{-1}$ under the condition of Kuroshio meandering path (Nitani, 1975). From these facts it becomes clear that excess in the transport of the upstream Kuroshio off the Kii Peninsula (Fig. 5) over the Kuroshio passing across the Izu Ridge is almost kept constant as $20$ to $30 \times 10^6$ m$^3$s$^{-1}$, irrespective of the Kuroshio path being meandering or straight in the west of the ridge. This transport difference leads to a thought that a subsurface part of the Kuroshio flow, whose level of no motion is at the depth of about 2000 m (Fukasawa and Teramoto, 1986), turns backward at the ridge forming the anticyclonic recirculation. Here, we notice that the averaged depth of the ridge top is around 1000 m as shown in Fig. 1. Recently, the recirculation is almost confirmed to exist through the Lagrangian measurement of current path by means of SOFAR Float at 1500 m depth during two years from 1988 to 1990 (Taira and Yanagimoto, 1993). The equality in estimates of transport difference between the above areas under the two different situations of the Kuroshio gives the validity of our transport estimates from potential measurements.

4.5 Inverse current bursts in the Oshima-West Channel associated with the westward migration of Kuroshio meander

The $Q_{OW}$ curve in Fig. 10 shows that the transport of the Oshima-West Channel is usually
Fig. 10. Volume transports of the Oshima-South Channel, $Q_{OS}$, and Oshima-West Channel, $Q_{OW}$, which are estimated from cross-channel electric-potential differences, are illustrated in the middle and bottom panels, respectively. Running averages of these records over 31 days are delineated with heavy lines. The sum of these two records, $<Q_{OS}>_{31} + <Q_{OW}>_{31}$ is also illustrated in the top panel. On the right-hand side of the top panel, a partially enlarged curve of $Q_{OW}$ is illustrated. For reference, records of $\zeta_{CS} - \zeta_{IT}$ (sea-level difference between Choshi and Ito), $\zeta_{IT} - \zeta_{OZ}$ (sea-level difference between Ito and Omaezaki), $\zeta_{CS} - \zeta_{OZ}$ (sea-level difference between Choshi and Omaezaki) and $\zeta_{IT} - \zeta_{OM}$ (sea-level difference between Ito and Oshima) are plotted for the period from Jan. to May in 1961. On these reference records, their 31-day averaged records are also delineated with thin line.
of positive value, which indicates the branching of the Kuroshio north-eastward into the channel. This flow then turns around the northern margin of the ridge and runs off eastward. During about two years from June 1959 to August 1961, however, there exists four abnormal cases, in which $Q_{OW}$ reduces below zero accompanied with the inverse current bursts (Fig. 10). The negative transport means that the flow of the Oshima-West Channel is directed south-westward. Among the four cases, that happened towards the end of March 1961 is most dominant in the sense that the negative transport was largest in magnitude and continued for the longest period. In addition, the most thorough information on temporal changes in isotherm pattern of the Kuroshio is available from Kaiyosokuho, which has been published bimonthly by the Japanese Hydrographic Office since April 1960. Thus, the investigation is focussed on this case only.

On the basis of Kaiyosokuho, the configuration of isotherms for 15°C and its vicinity are presented at bimonthly cycle for the period from 17 Jan. to 30 April, 1961 in Figs. 11(a)–(f). Unfortunately, however, the figure for the period from 30 Jan. to 21 Feb. 1961 is omitted. This is because the delineation of isotherm configuration is too fragmental due to sparse observations and is quite insufficient to provide the feature of the Kuroshio meander and associated eddies. Here, it is noted that deforming processes of the Kuroshio path are well picked up from configurational changes of 15°C isotherm in time and that behaviours of cold and warm waters are successfully inferred from configurational changes of 13°C or lower temperature isotherms and 17°C or higher temperature isotherms in time, respectively. Temporal changes in these isotherm configurations are examined in reference to those in $Q_{OW}$ in Fig. 10. $Q_{OW}$ was at the value of about $2.5 \times 10^6$ m$^3$s$^{-1}$ in the middle of Jan., 1961 and then was in the gradually reducing trend towards the middle of March in the same year. Figure 11(a) indicates that the 15°C isotherm was very close to the top of the Izu Peninsula in the period from 17 to 29 Jan., 1961. In comparison to this figure, Fig. 11(b) clearly indicates the westward migration of the system, which consists of the Kuroshio meander and warm and cold eddies, during the period from 22 Feb. to 2 March, 1961. In association with the migration, the 15°C isotherm and so the Kuroshio path shifted offshore from the top of the peninsula. In the next period from 4 to 17 March, 1961 the system moved further westward and associatively the Kuroshio path shifted further offshore from the top of the peninsula (Fig. 11(c)). Synchronously with these, a new cold eddy was yielded off the Suruga Bay (Fig. 1) west of the peninsula. Then, on 18 March $Q_{OW}$ became negative as shown in Fig. 10, indicating the start of a south-westward flow. $Q_{OW}$ further reduced with time to reach the negative maximum of $-1 \times 10^6$ m$^3$s$^{-1}$ on 23 March, 1961. The 15°C isotherm configuration and the distribution of warm and cold eddies during the period from 17 to 29 March, 1961 are presented in Fig. 11(d). The figure shows that the Kuroshio-meander configuration was seriously folded up, involving warm and cold eddies and grew up to the most developed stage, in which the Kuroshio path at the top of the peninsula shifted to the southernmost position. After reaching the negative maximum, $Q_{OW}$ rapidly recovered and become positive on 29 March, 1961 as shown in Fig. 10.

The temporal coincidence between the growing up of the new cold eddy and the south-westward flow in the Oshima-West Channel leads to a thought, in reference to the temperature distribution, that the cold watermass occupying the offshore area of the Boso Peninsula (Fig. 1) migrated through the channel successively along the Boso Peninsula, the coast of Sagami Bay and Izu Peninsula (Fig. 1) until reaching to the south of the Suruga Bay to form the new cold eddy. Actually, the total volume of water migrated across the section of potential measurement during the period of 18 to 29 March, 1961 is estimated to amount to $4 \times 10^{11}$ m$^3$ from the time integral of the negative transport. This volume can fill a cylindrical space of 50 km in diameter and 200
m in thickness, which occupied the significant part of the new cold eddy in its most developed stage. The seriously folded-up configuration of the meander-eddy system could not exist steadily and soon began to change its feature (Fig. 11(e)). The system finally recovered to the situation very resemble to that in the first stage (Fig. 11(a)) as shown in Fig. 11(f), which is the configuration for the period of 17 to 30 April, 1961.
From the change in temperature distribution around the 15°C isotherm in the final two stages, together with the change in $Q_{OW}$ in Fig. 10, it is inferred that the water which occupied the new cold eddy returned inversely to the original position in the offshore area of the Boso Peninsula. The new cold eddy generated off the Suruga Bay might not reach so deep below several hundred meters even under the most developed condition. Its depth would be similar, at most, to the depths of the channel and ridge top. Thus, the eddy treated here is naturally of properties different from the major, steady, cold eddy, which reaches near the bottom of 4000 m in depth and exist steadily for a few or more years (Nishida, 1982). The period of the total process is about a month from the middle of March to middle of April in 1961.

In the above treatment, the inverse current burst is defined as a process which produces a negative transport (south-westward flow) in the Oshima-West Channel. Actually, however, a process of positive transport, which follows the process of negative one, should be considered as the recovery process of the phenomenon. More in general, these processes are better to be treated as the successive processes which form a system.

In Fig. 10, the sea level differences $\zeta_{CS} - \zeta_{IT}$ between Choshi at the basement of the Boso Peninsula (Fig. 1) and Ito on the Izu Peninsula and sea level difference $\zeta_{IT} - \zeta_{OZ}$ between Ito and Omaezaki at the mouth of the Suruga Bay (Fig. 1) are plotted as well as sea level difference $\zeta_{CS} - \zeta_{OZ}$ between Choshi and Omaezaki. The 31-day running averages of these sea-level differences are also delineated with thin lines. From the comparison of the transport curve to the sea-level difference curves, the following things are pointed out. The negative deviation in $Q_{OW}$ from its 31-day average is coherent with the positive deviation in $\zeta_{CS} - \zeta_{IT}$ from the similar average with the detectable phase shift ($\zeta_{CS} - \zeta_{IT}$ behind $Q_{OW}$) and the successive positive deviation in $Q_{OW}$ is also coherent with the negative deviation in $\zeta_{CS} - \zeta_{OZ}$. These facts indicate that the downchannel pressure gradient plays a significant role in the processes. The deviation of $\zeta_{IT} - \zeta_{OM}$ (Fig. 10), however, does not show the coherent relation to the deviation of $Q_{OW}$. This fact is interpreted as follows. The current burst intrudes close to the coast and flows successively along the coast of Sagami Bay and of the Izu Peninsula and so is incident oblique to the Ito-Oshima section, in contrast to the ordinary Kuroshio branch current. Therefore, the coastal friction as well as the bottom friction also contribute to the balance of force in the process in addition to the pressure gradient force and Eulerian (local) mass acceleration. Actually, these forces are estimated to reach to the order of $10^{-4}$ dynes cm$^{-3}$, when we consider that the speed deviation is 30 cm s$^{-1}$ (estimated from the deviation in $Q_{OW}$ of $2 \times 10^6$ m$^3$ s$^{-1}$) and that the time scale, cross-channel scale and downchannel scale of the process are 10 days, 30 km and 200 km, respectively. Owing to the Ito-Oshima section is in the oblique direction to the current burst as mentioned, $\zeta_{IT} - \zeta_{OM}$ involves both the cross-channel sea-level difference induced in association with Coriolis force and the downchannel sea-level difference induced in association with the pressure-gradient force. The cross-channel sea-level difference is in phase with the deviation of $Q_{OW}$ but the downchannel sea-level difference is in shift of phase with that. Thus, the superposition of those makes unclear the coherence of $\zeta_{IT} - \zeta_{OM}$ to the deviation of $Q_{OW}$.

This study indicates that the potential measurement is very useful for revealing the details of time-varying processes.

4.6 Statistical properties of monthly and the shorter-term variations in the transport over the Izu Ridge

(1) Frequency distributions of spectral densities

Prefiltered records of $Q_{OS}$ for June 1, 1959 to February 28, 1960 and $Q_{OW}$ for June 1, 1959
to August 16, 1961 (Fig. 8), are sub-sampled at the time interval $\Delta t$ of 12 hrs, and are subjected to the spectral analysis by the use of Tukey's method (Blackman and Tukey, 1958) with the maximum lag number $m$ of 50. Hereafter, we denote the cross-channel and downchannel directions as $x$ and $y$ directions, and so $Q_{OS}$ and $Q_{OW}$ are both denoted as $Q_y$. Total data numbers $N$ of $Q_y = Q_{OS}$ and $Q_y = Q_{OW}$ are 546 and 1583 and the degree of freedom in the spectral calculations are approximately 20 and 60, respectively. The nyquist frequency $f_N = 1/2\Delta t$ and frequency resolution $f_s = 1/2m\Delta t$ are 1 cpd and 0.02 cpd. The frequency spectra are presented in Figs. 12(a) and (b). The arrows in these figures illustrate the 90% confidence limit of the estimated spectral densities. Both spectra are very red. The spectral densities decrease with increasing frequency at an average rate of $f^{-2.4}$ for $Q_{OS}$ and an average rate of $f^{-2.3}$ for $Q_{OW}$ in a range of frequency from 0.1 to 0.4 cpd. $Q_{OS}$ has statistically significant spectral peaks at frequencies around 0.04, 0.14, 0.24 and 0.36 cpd and so at periods around 25, 7, 4 and 3 days. $Q_{OW}$ has the spectral peaks at frequencies around 0.11, 0.20, and 0.38 cpd and so at periods around 9, 5 and 3 days.

(2) **Statistical relations of variations in transport $Q_{OS}$ to those in reference quantities**

The record of $Q_y = Q_{OS}$ are subjected to the spectral and cross-spectral analyses in relation to reference quantities such as $(\Delta \zeta)_x$, downchannel sea-level difference $(\Delta \zeta)_y = \zeta_{OM} - \zeta_{OZ}$ (OM:
Oshima, OZ; Omaezaki), cross-channel atmospheric-pressure difference \((\Delta P_A)_x = (P_A)_{OM} - (P_A)_{HI}\), downchannel atmospheric-pressure difference \((\Delta P_A)_y = (P_A)_{OM} - (P_A)_{OZ}\), cross-channel and downchannel wind-stress components \((\tau_x)_{MJ}\) and \((\tau_y)_{MJ}\) (MJ: Miyakejima), and cross-channel sea-surface temperature difference \((\Delta \theta)_x = \theta_{OM} - \theta_{MJ}\) (NJ: Niijima), which are all prefiltered and subsampled in the same manner as in \(Q_{OS}\) and \(Q_{OW}\). \((\tau_x)_{MJ}\) and \((\tau_y)_{MJ}\) are estimated from wind data at Miyakejima by the use of the bulk formula, \(\tau_i + \tau_j = \rho_a C_D W_i W_j\) where \(i\) and \(j\) are unit vector in \(x\) and \(y\) direction, \(\rho_a\) and \(C_D\) are the air density and wind drag-coefficient. For examining the influence of noise induced in association with ionospheric and magnetospheric fluctuations, the cross-spectral analyses are also made in relation to the magnetic field components \(\Delta H_x\) and \(\Delta H_y\) as well as the electric field components \(\partial \phi/\partial x\) and \(\partial \phi/\partial y\) in the east-west and north-south directions at Kakioka.

The coherence functions between \(Q_y\) and the reference quantities are presented in Table 3a for the frequency range from 0 to 0.5 cpd. In the table, a coherence between a quantity denoted by a symbol at the top row and that at the left column of the table is presented in a small quadrangle at the cross of the row and column for these quantities. Regarding coherence function there is 95% chance that the true value of coherence \(R\) is greater than zero, provided that the estimated value of coherence \(R^2\) exceeds \(4/\nu\), where \(\nu\) is the degree of freedom of the analyses. As the value of \(\nu\) is 21.84 in our case, the confidence limit is about 0.19. This limit is indicated as a horizontal bar in each table. The partial coherence function (Bendat and Piersol, 1966) is also calculated as presented in Table 3b in order to examine relations between any two variables, \(A\) and \(B\), with the third variable \(C\) being removed from the two variables through the linear prediction.

The coherence table indicates that to any reference quantities the transport \(Q_y = Q_{OS}\) is generally in a low coherence, which is in a clear contrast to, for instance, high coherence of \((\Delta \zeta)_x\) to \(\tau_x\) and \(\tau_y\). At a few frequencies between 0 to 0.40 cpd, however, \(Q_y\) is in a statistically significant coherence to \(\tau_x\), \(\tau_y\), \((\Delta P_A)_x\), and \((\Delta \zeta)_x\) as shown in small quadrangles bounded with thick frames. These facts are more clearly observed in the partial coherence table. We notice the specially high partial-coherence of \(Q_y\) to \(\tau_y\) on \((\Delta \zeta)_x\) being removed, to \((\Delta P_A)_x\) on \((\Delta P_A)_y\) being removed and to \((\Delta \zeta)_x\) on being \((\Delta P_A)_y\) removed. In more detail, the high coherence is held between \(Q_y\) and \(\tau_y\) at frequencies of 0.12 to 0.14 cpd and between \(Q_y\) and \((\Delta P_A)_x\) at frequencies of 0.12, 0.14, 0.26 and 0.28 cpd. Between \(Q_y\) and \((\Delta \zeta)_x\), on the other hand, the high coherence is held at frequencies of 0.22, 0.24 and 0.34 cpd.

From these relations, the following two facts are suggested to be derived. Firstly, variations in \(Q_y\) of frequency around 0.12 and 0.14 cpd (and so period of 7 to 8 days) are wind-induced and are deviated from geostrophy. These variations form a peak in the spectral distribution as already mentioned (Fig. 12(a)). Secondary, variations in \(Q_y\) of frequency around 0.24 and 0.26 cpd (and so period of around 4 days) are in geostrophic balance with variations in cross-channel sea-level gradient, which are caused by hydrostatic forcing of atmospheric pressure.

In calculation of the partial coherence of \(Q_y\) to reference quantities, the removal of components linearly related to any of geomagnetic and telluric-electric fields does not produce the prominent improvement in coherence. This fact suggests the poor association of \(Q_y\) variations with those in ionospheric and magnetospheric fluctuations in the range of frequency lower than the diurnal frequency.

(3) Statistical relations of variations in transport \(Q_{OW}\) to those in reference quantities

The number of \(Q_{OW}\) data are 1583 as described already, the data used for the cross-spectral analysis is 1146 in number, which is sub-sampled at the time interval of 12 hrs from the record for the period of 21 Jan., 1960 to 15 Aug., 1961. This reduction in data number is because of the
Table 3a. Table for coherence of $Q_y = Q_{OS}$ to reference quantities such as cross-channel and downchannel differences in sea level, sea surface temperature and atmospheric pressure as well as cross-channel and downchannel components of wind stress, geomagnetic field and telluric electric current in the area around the Izu Ridge. 95% confidence limit for coherence square to be greater than zero is delineated as a horizontal line at a value of 0.19.

1 June, 1959 — 28 February, 1960
Oshima—Miyakejima, Izu Island region

---

lack of data in reference quantities. Thus, the 95% confidence limit for the computed coherence square is 0.088. The coherence table and partial coherence table are presented in Table 4a and b. $Q_y = Q_{OW}$ has a significant coherency to $\Delta \zeta$ (cross-channel sea-level difference) at around 0.2 and 0.4 cpd, where $Q_y$ has spectral peaks (Fig. 12(b)). The partial coherences of $Q_y$ to $(\Delta \zeta)_x$ reduce below the confidence limit at frequencies around 0.2 to 0.4 cpd, when components linearly related to variations in $\Delta H_x$ and $\Delta H_y$ are eliminated. This reduction is due to the high coherency of $(\Delta \zeta)_y$ to $\Delta H_x$ and $\Delta H_y$ at frequencies below 0.2 cpd. The reason for this high coherency as well as high coherency of $(\Delta \theta_y)_x$ to $\Delta H_x$ and $\Delta H_y$ at frequencies between 0.2 and 0.4 cpd cannot be understood at all. $Q_y$ is also highly related to $(\Delta P_y)_x$ at frequencies around 0.02, 0.04, 0.20 and
Table 3b. Table for partial coherence of $Q_y - Q_{OS}$ to a reference quantity, from which components linearly related to another reference quantity are eliminated.

<table>
<thead>
<tr>
<th>Set of two quantities removed</th>
<th>$Q_y, \Delta \xi_x$</th>
<th>$Q_y, \Delta \xi_y$</th>
<th>$Q_y, \tau_x$</th>
<th>$Q_y, \Delta H_x$</th>
<th>$Q_y, \Delta H_y$</th>
<th>$Q_y, \frac{\partial}{\partial x}$</th>
<th>$Q_y, \frac{\partial}{\partial y}$</th>
<th>$Q_y, \xi_{NH}$</th>
<th>$Q_y, (\Delta P)_x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta H_x$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta H_y$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\frac{\partial}{\partial x}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta \theta$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau_x$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau_y$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(\Delta P)_y$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(\Delta P)_x$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(\Delta \theta)_x$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(\Delta \xi)_x$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

0.28 cpd, but the partial coherences of $Q_y$ to $(\Delta P)_x$, at these frequencies do not reduce their values even though components linearly related to $\Delta H_x$ and $\Delta H_y$ are eliminated. Thus, it is clear that $Q_y$ involve components closely related to northward wind of these frequencies, namely periods of 50, 25, 5 and 4 days.
Table 4a. Coherence table for $Q_y = Q_{OW}$ prepared in the similar manner to Table 3a. 95% confidence limit for coherence square is delineate as a horizontal line at a value of 0.09.

Table 4b. Partial coherence table for $Q_y = Q_{OW}$ prepared in the similar manner to Table 3b.

5. Conclusions and Discussions

Through this study, our measurements of telluric electric-potential differences induced across channels are verified to reflect very well flow-transport fluctuations in the range of frequency lower than the diurnal cycle.

The potential measurement is the spatially-integrated method of measurement. And informations from this method is naturally not appropriate for revealing processes small in time and space.

Cross-channel electric-potential differences induced by water flows through cutting the geomagnetic field generally depend upon various factors such as the intensity of geomagnetic
field, shape of channel sections, downchannel changes in channel sections, changes in three-dimensional structure of flow fields normalized with typical flow velocity, changes in three-dimensional structure of water-property fields normalized with their typical values. Among these factors, the former three can be considered to be almost invariable in time in our case. Contrarily, the rest of the factors might vary although we could not have any information on their variation in time. Under such a circumstance, our modelling of the induced electric field is made on assuming the invariability of structure of the normalized flow fields and associated property fields. The modelling is made on the further assumptions that channel sections are square-shaped with areas same to the actual ones and that downchannel changes in channel sections are neglected. Through these assumptions flow transports estimated from measured cross-channel potential-differences only have their confidence to keep one significant digit in their absolute

Fig. 13. (a) Potential record across the Oshima-South Channel at the time of arrival of Chilean Tsunami in the area around the Izu Ridge. (b) Tide record at Okada, Oshima showing the sea-level changes due to Chilean Tsunami. (c) Tide record at Ito, the Izu Peninsula showing the sea-level changes due to Chilean Tsunami.
values. This accuracy in transport estimation is, however, almost similar to that of dynamic computation on the basis of hydrographic observations. Our potential methods of transport estimation are rather characterized to be more accurate in revealing time-varying processes of channel flows, because the measurements were made continuously in time.

During the potential measurements, the Chilean Tsunami, 1960 attacked the Pacific coast of Japan about 4 O’clock on May 24, 1960, and unusual sea-level oscillations lasted for more than 10 hrs with the dominant frequency around 1 cph. At Okada station in Oshima and coastal stations in Sagami Bay and Tokyo Bay (Fig. 1), the oscillations were typically of the visual maximum amplitude of 0.5 m (Figs. 13(b) and (c)). The tsunami waves produce the water motion of 5 cm s\(^{-1}\) in velocity amplitude, when we assume the Tsunami to be one-dimensional barotropic gravity-waves propagating westwards over the Izu Ridge and assume the mean depth of the area to be of the order of 1000 m as in the actual case. This water motion is estimated to induce the electric-potential changes of the order of 50 mV in amplitude across the Oshima-South Channel. This value is sufficient to be visually observed on the potential record. The potential record, however, does not involve clear changes coherent with the sea-level changes caused by the Tsunami (Fig. 13(a)). The low value of coherence is undoubtedly due to the contamination of the potential record with the high-level background noise, which should be induced by the ionospheric and magnetospheric fluctuations as discussed in the earlier section.

Acknowledgements

The authors wish to express their sincerest thanks to Prof. C. S. Cox of the Scripps Institution of Oceanography, who led one of the authors (Teramoto) to the potential measurements when he stayed at the University of Tokyo for several months from 1957 to 1958. Their thanks are also dedicated to the late Profs. K. Hidaka and K. Yoshida of the University of Tokyo, under the guidance of whom one of the authors (Teramoto) could carry out the study. They are very much indebted to the help given by Drs. M. Tsuchiya and Y. Nagata for continuing the measurements during the graduate-school course at the University. Their thanks are also extended to Nippon Denshin Denwa Kosha (Japan telegram and telephone public corporation), who made the telephone cables available for the measurements. Much help was given by Messrs. A. Nakamura and M. Watanabe in carrying out the data processings and by Misses N. Kimura, R. Sekai, and to Mr. Yotaro, T. in preparing the manuscript.

References


