REPORT OF HYDROGRAPHIC RESEARCHES NO. 9, MARCH 1974

EFFECT OF THE KUROSHIO SYSTEM ON THE SEA LEVEL AT THE SOUTHERN COAST OF JAPAN

Hideo Nitani*

Received 29 October 1973

Abstract

From the viewpoint of the geostrophic character of the Kuroshio, the numerical relationship between the surface transport of the Kuroshio System including the countercurrent north of the Kuroshio current and the sea level of the southern coast of Japan was investigated empirically. The dynamic depth anomalies of the Kuroshio off the coasts of Kii Peninsula and Omae-zaki in the period of 1958-1970 and the results of GEK observation in the Kuroshio region south of Japan during 1967-1969 and 1971 were used for this investigation.

When the surface transport of the Kuroshio decreases, the sea level difference of the Kuroshio decreases having a rise of sea level on the inner side of the Kuroshio and a fall on the outer side, and vice versa. Near the coast of Japan, the rise in sea level is equal to the sum of 0.36 times as large as the decrease of sea level difference in the Kuroshio and of the total increase of sea level difference in the countercurrent north of the Kuroshio. On an average, about a half of the abnormally high waters at the southen coast of Japan, which occurred in September 1971 and July 1972, seems to be caused by the decreases of surface transport of the Kuroshio System at these times.

1. Introduction

So far as the Kuroshio is regarded as a geostrophic current, it is natural that the sea level in the Kuroshio region and subsequently the coastal sea level varies in company with the variation of the Kuroshio.

Tsumura (1963) stated that the variation of sea level on the southern coast of Japan is closely connected with the variation of the Kuroshio, using several examples of the elevation of sea level along the coast of Enshu-nada during the period of the presence of a large cold water mass in the offing of Enshu-nada associated with the large meander of the Kuroshio. Moriyasu (1958, 1960 and 1961) also pointed out the remarkable difference between the monthly mean sea levels at Kushimoto and Uragami during the period of large meander of the Kuroshio. Shoji (1961 and 1972) indicated several examples of the variations in daily mean sea level on the southern coast of Japan and Izu Islands, which have the close relation with the variation of the Kuroshio axis.

* Japan Oceanographic Data Center

All these papers laid stress on the axis of the Kuroshio as a factor correlative with the variation of the coastal sea level. Of course, the variation of the velocity or surface transport of the Kuroshio has a correlation with the axis of the Kuroshio especially in case of the long-term variation of the Kuroshio. From the viewpoint of the geostrophic character, however, the influence upon the coastal sea level of the change of the velocity or surface transport of the Kuroshio will be larger than the influence of the change of the axis of the Kuroshio itself. Shoji and Nitani (1966) and Nitani and Shoji (1970) studied the relation between the sea levels on both boundaries of the Kuroshio and the surface transport of the Kuroshio off Cape Shiono-misaki for the very short-term variation. But they could not find the complete relation, because their aims of research were directed to somewhat other problems.

In this thesis, the relation between the surface transport of the Kuroshio System including the countercurrent north of the Kuroshio and the coastal sea level will be investigated quantitatively by making use of the dynamic depth anomaly and GEK data available.

2. Relation between the surface transport of the Kuroshio and the sea level on the north boundary of the Kuroshio

It is well known that the sea level is lower by about 1-1.5 meters on the north or inside the boundary of the Kuroshio than on the south or outside the boundary of it. The relative height of sea surface is expressed by the dynamic depth anomaly, ΔD, and the difference of ΔD on both sides of the Kuroshio is proportional to the surface transport of the Kuroshio which can be obtained from the integration of velocity over the width of the Kuroshio. It is convenient to use the mile·knot, *MK*, as the practical unit of it. Of course, from the viewpoint of the dimension the true surface transport is the product of mile·knot and unit depth, but only the product of velocity and width will be called the surface transport in this paper for convenience' sake.

Though it is clear that the difference of sea levels on both boundaries of the Kuroshio varies with the variation of the surface transport, the quantitative contributions from both of each boundaries of the Kuroshio to the sea level difference are not known at present. In Fig. 1, line BC shows the schematic sea level distribution in the Kuroshio region, and lines ①, ② and ③ show three schematic cases of decrease of sea level difference on both sides of the Kuroshio accompanying with the decrease of surface transport of the Kuroshio. In what manner does the sea level difference decrease with the decreasing of the surface transport? If case ① occurs, the rising of sea level appears on

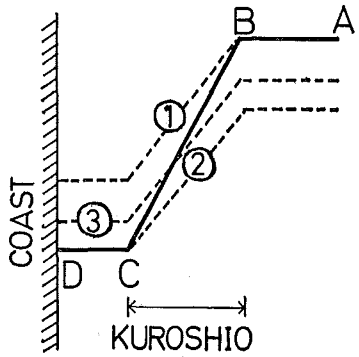


Fig. 1 Schematic representation of sea level in the region of the Kuroshio and its both sides. Line BC is the initial stage of sea level and one of the cases ①, ② and ③ will appear accompanying with the decrease of surface transport of the Kuroshio.

the north boundary of the Kuroshio or at the coast. The quantity of this rising is the same as the decrease of the difference of sea levels on both sides. In these models, it is assumed that there is no current between the Kuroshio and the coast. If case ② occurs, there is no change in the sea level at the coast. Case ③ shows a middle situation between case ① and case ②, where some rising of sea level at the coast and some falling of sea level on the southern boundary of the Kuroshio occur. These mechanisms lead to the solution of the problem pertinent to the lowering of the coastal sea level due to the existence of the Kuroshio south of Japan. To solve this problem, the use of dynamic depth anomaly is the only method available at present.

The serial observations were carried out on the sections along 135°15′E off Cape Shiono-misaki and 138°E off Enshu-nada by Japanese Hydrographic Office and Japan Meteorological Agency in the period 1958-1970. Fig. 2 shows the relations between $\Delta D_{max}-\Delta D_{min}$ and ΔD_{max} or ΔD_{min}, where ΔD_{max} and ΔD_{min} are the dynamic depth anomalies referred to 1000 db surface on the south and north boundaries of the Kuroshio, respectively. To estimate ΔD_{max} and ΔD_{min}, interpolation was used, and sometimes even extrapolation was adopted. The following empirical formulae for two sections in summer (July-September) and in winter (January-March) were obtained by making use of the method of least square.

$$\left.\begin{array}{lll}
135^\circ 15' \mathrm{E} & \text{Summer} & \triangle D_{max}=0.58(\triangle D_{max}-\triangle D_{min})+182.9 \\
 & \quad '' & \triangle D_{min}=-0.42(\triangle D_{max}-\triangle D_{min})+182.9 \\
 & \text{Winter} & \triangle D_{max}=0.68(\triangle D_{max}-\triangle D_{min})+170.3 \\
 & \quad '' & \triangle D_{min}=-0.32(\triangle D_{max}-\triangle D_{min})+170.3 \\
138^\circ \mathrm{E} & \text{Summer} & \triangle D_{max}=0.51(\triangle D_{max}-\triangle D_{min})+185.2 \\
 & \quad '' & \triangle D_{min}=-0.49(\triangle D_{max}-\triangle D_{min})+185.2 \\
 & \text{Winter} & \triangle D_{max}=0.57(\triangle D_{max}-\triangle D_{min})+169.8 \\
 & \quad '' & \triangle D_{min}=-0.43(\triangle D_{max}-\triangle D_{min})+169.8
\end{array}\right\} \quad (1)$$

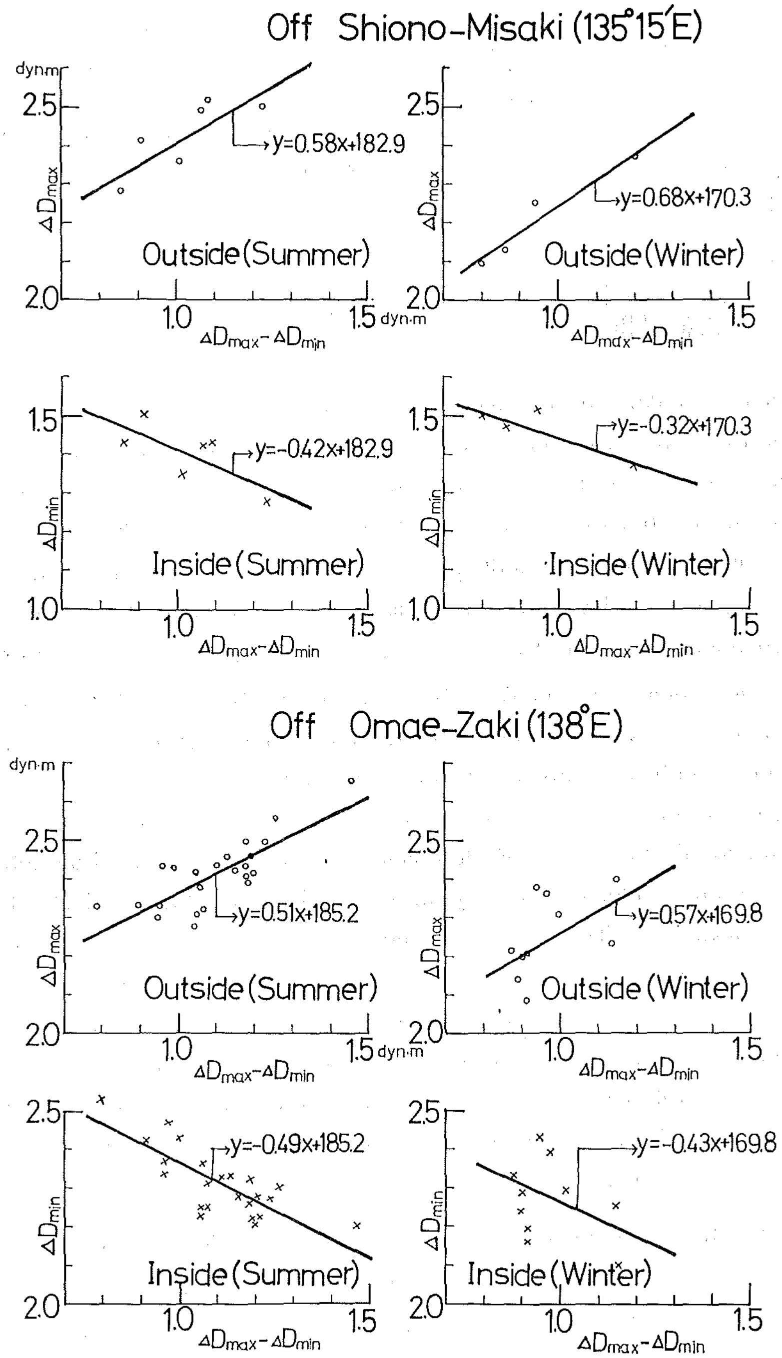


Fig. 2 Relations between $\triangle D_{max} - \triangle D_{min}$ and $\triangle D_{max}$ and between $\triangle D_{max} - \triangle D_{min}$ and $\triangle D_{min}$, where $\triangle D_{max}$ and $\triangle D_{min}$ are the dynamic depth anomalies, referred to 1000 db, on the south and north boundaries of the Kuroshio off Shiono-misaki (135°15′ E) and Omae-zaki (138°E). Data are based on the serial observations carried out in 1958–1970.

The unit used is dynamic centimeter which is nearly equal to centimeter in length. In the equations for ΔD_{min}, i.e. for the height of north boundary of the Kuroshio, linear coefficients for four cases are in the range of $-0.3 \sim -0.5$, and for ΔD_{max}, they are in the range of $0.5 \sim 0.7$. The scatter may be attributed to not so many observations, not so dense intervals of the stations and synthesizing of three months as one season. Then, the value -0.42, the arithmetic mean of four coefficients for ΔD_{min}, is adopted as the rising coefficient of the sea level on the north boundary of the Kuroshio and is assumed to be applicable to everywhere in the southern coast of Japan and in all seasons at the present stage. This value is negative, meaning that the increase of sea level difference or the surface transport brings the lowering of the sea level on the north boundary of the Kuroshio. The rising coefficient of the sea level on the south boundary of the Kuroshio is 0.58 on an average.

The manner of variation of the sea level in the Kuroshio region is like a seesaw corresponding to case ③ in Fig. 1. The fact that, when the Kuroshio exists, the sea level on the north boundary is lower than when no eastward current exists, is shown by Stommel (1948) and K. Yoshida (1965) in their papers in which they studied the oceanic circulations taking account of the wind stress and β effect etc., by assuming the barotropic or baroclinic field, respectively.

The reason of the smaller variation on the north boundary of the Kuroshio than on the south boundary is not clear. The relation between the sea level difference of both boundaries of the Kuroshio and the average sea level over the Kuroshio region expressed in dynamic depth anomaly is shown in Fig. 3 for the summer and winter using the same observations as those used in Fig. 2. Although the scatter is fairly large, it may be concluded that the variation of the average sea level over the Kuroshio region is nearly proportional to the

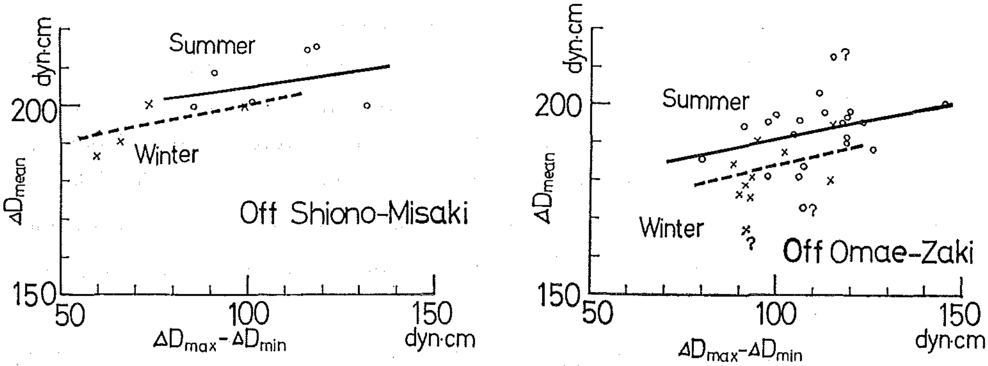


Fig. 3 Relations between the sea level differences of both boundaries of the Kuroshio and the averaged sea levels over the Kuroshio off Shiono-misaki and Omae-zaki. Unit is dyn. cm and data source is the same as in Fig. 2.

variation of the sea level difference of both boundaries of the Kuroshio, and this ratio is about 1/5 on an average. And the ratio of the variation of the sea level at the middle point of the Kuroshio to the variation of the difference of sea levels on both sides of the Kuroshio, though this is not shown by the figure, is nearly 1/5 on an average, too. From these facts, one can consider a certain model which enables us to approach the mechanism controlling the rise and fall of sea level (Fig. 4).

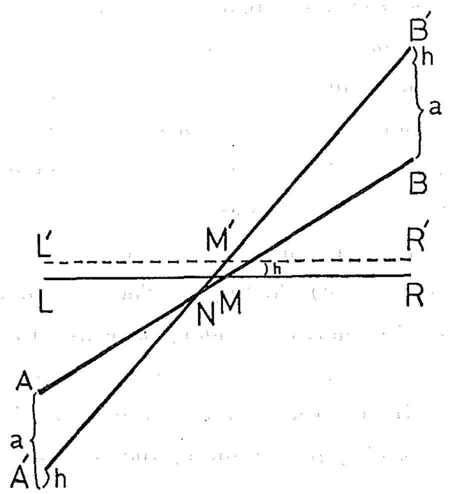


Fig. 4 Model of Sea level variation in the Kuroshio region for the study of the mechanism of the variation in sea level.

In this model, the sea level of the Kuroshio is assumed to be the straight line AMB, and the point M the center of the line. The averaged sea level over the Kuroshio LMR is assumed to rise by MM′$=h$ in association with the increase of sea level difference of the Kuroshio, $2a$, and a certain increase of surface transport of the Kuroshio, and subsequently the new sea level becomes line A′M′B′.

As the result, the sea level on the north boundary of the Kuroshio falls by AA′ $(=a-h)$, and the sea level on the south boundary rises by BB′ $(=a+h)$. The variation on the north boundary is less by $2h$ than that on the south boundary. If we use the values -0.42 and 0.58 which were obtained from eq.1 as the rising coefficients on the north and south boundaries, we get $h=0.08\times 2a$ from $\frac{a-h}{a+h}=\frac{42}{58}$, where $2a$ is increase of sea level difference of the Kuroshio. This value is about one half of the observed value $h=0.20\times 2a$ obtained from Fig. 3, but in a correct sense.

On the conteary, if $h=0.20\times 2a$ is taken, the ratio $\frac{a-h}{a+h}$ becomes 30/70. Anyway, such a mechanism that the increase of sea level difference or surface transport of the Kuroshio accompanies with the rising of avaraged sea level over the Kuroshio seems to be able to explain the falling of sea level on the north boundary which is less than the rising on the south boundary. If the variation of the Kuroshio is to take the form of a certain kind of wave, the wave must have such characters.

On the other hand, the above fact is explained by the use of another model in which the sea level of the Kuroshio varies like a seesaw having its fulcrum at a point where the width of the Kuroshio is divided into two portions, for example, in the ratio of 42:58. Of course, this seesaw-like motion brings the rise or fall on the averaged sea level over the Kuroshio region following the increase or decrease of surface transport or the sea level difference of the Kuroshio. The fulcrum (point N in Fig. 4) has no vertical motion except the seasonal change, and its height is the same as the sea level when Kuroshio disappears. Thus, the sea level on the north boundary of the Kuroshio is lower by 0.42 ($\varDelta D_{max}-\varDelta D_{min}$) than the sea level at point N. The point N is on the left of the middle point of the Kuroshio, and in general near the axis of the Kuroshio if the axis is defined as the place where the velocity is maximum.

3. Relationship between the surface transport of the Kuroshio System and the coastal sea level

When we study the effect of offshore currents upon the sea level along the southern coast of Japan, the effect of westward countercurrent which often appears to the north of the Kuroshio has to be considered as well as the effect of the Kuroshio itself. This countercurrent contributes to the rise of coastal sea level according to the geostrophic law, and its appearance is accompanied by various kinds of vortices between the Kuroshio and the southern coast of Japan. Hence the Kuroshio and its countercurrent are to be treated as parts of the Kuroshio System in the study of the variation of the coastal sea level.

The relation between the sea level difference of the Kuroshio and the surface transport of the Kuroshio is given as

$$\triangle D_{max}-\triangle D_{min}=2\omega\sin\varphi\times T_E,$$

where φ is the latitude of the Kuroshio and T_E the surface transport of the Kuroshio. If we assume the mean latitude of the Kuroshio south of Japan to be 32.5° N, and the unit of the surface transport to be mile·knot (*MK*), the above relation becomes as follows:

$$\triangle D_{max}-\triangle D_{min}=0.75T_E \text{ cm}, \qquad (2)$$

When the countercurrent exists between the Kuroshio and the coast, the coastal sea level is given by

$$H=H_o-0.75(0.42T_E-T_W) \text{ cm}, \qquad (3)$$

where H is the coastal sea level corrected for the effects of seasonal variation and pressure change by assuming the hydrostatic equilibrium, H_O the coastal sea level when the Kuroshio and the countercurrent north of it disappeare, and T_W the surface transport of the westward countercurrent which includes that of a small-scale eastward current, if any, north of the countercurrent.

The quantity $(0.42T_E-T_W)$ is called the "falling surface transport" hereafter, because it contributes to the falling of the coastal sea level, and the counterpart of it expressed by the dynamic depth anomaly is called the "falling dynamic depth anomaly difference". Of course, there is the seasonal variation of the sea level in the region of the Kuroshio as shown by the second terms of the right side of eq.1. According to eq.1, this variation is about 15 cm, but that along the coast is about 20-25 cm. This difference may be attributed to the averaging process by assuming three months as one season as in Fig. 2, and to the intense influences of the climate near the coast.

4. Comparison with the observed values

To examine the applicability of eq. 3 derived from a limited number of observations and locations, the studies were carried out, making use of statistics for the current data of long-term variation and using the observed values of individual cruises across the Kuroshio region for the phenomena in which the short-period variations are superimposed on the long-term ones.

1) Long-term variation

The statistics of the current observed by GEK in the period of 1954-1967 was carried out by Japan Oceanographic Data Center. About thirty-six thousand data used in the statistics were obtained mainly by research vessels of the Hydrographic Office and Meteorological Agency, and by patrol ships of Maritime Safety Agency.

Statistical calculations for the north and east components of the velocity were performed for every mesh of thirty minutes in latitude and longitude for every year. For example, the east components off Maisaka in Enshu-nada are shown in Fig. 5. The numerals in parentheses show the number of data used for each of the meshes. The existence of large meander of the Kuroshio in the offing of Enshu-nada during the periods of 1953-1955 and 1959-1962 is clearly shown. The countercurrents north of the Kuroshio in every year are more or less recognized.

From these results, values of the falling surface transport of the Kuroshio System off several tidal stations, averaged over one degree of longitude, were calculated for each year as shown in Fig. 6 in which yearly mean sea level deviations at the tidal stations were shown, too. The locations of the tidal stations used here are shown in Fig. 7. As the number of the current observations is not large enough, several current sections and tidal stations which have similar characters of variations were incorporated in one group, and expressed by an average value, so that we can get the comprehensive relation between the surface transport of the Kuroshio System and the coastal sea level. The sections off Tosashimizu, Kochi and Kushimoto are included in Group A, those off Toba, Maisaka and Omae-zaki in Group B, and that off Mera in Group

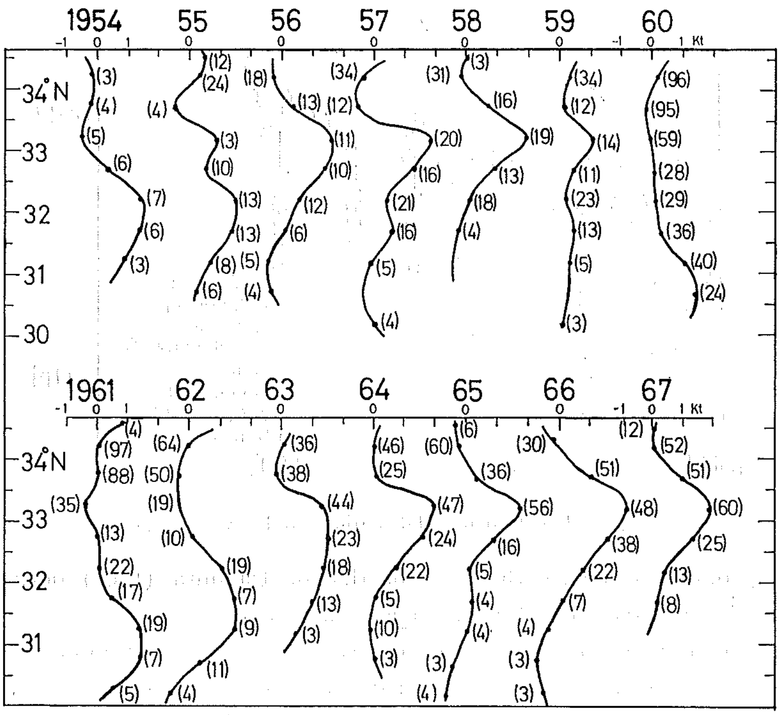


Fig. 5 East component of the current off Maisaka in Enshu-nada as one example of statistics of GEK data in the period of 1954-1967. Numerals in parentheses are the number of data used for each of every thirty minutes mesh in longitude and latitude.

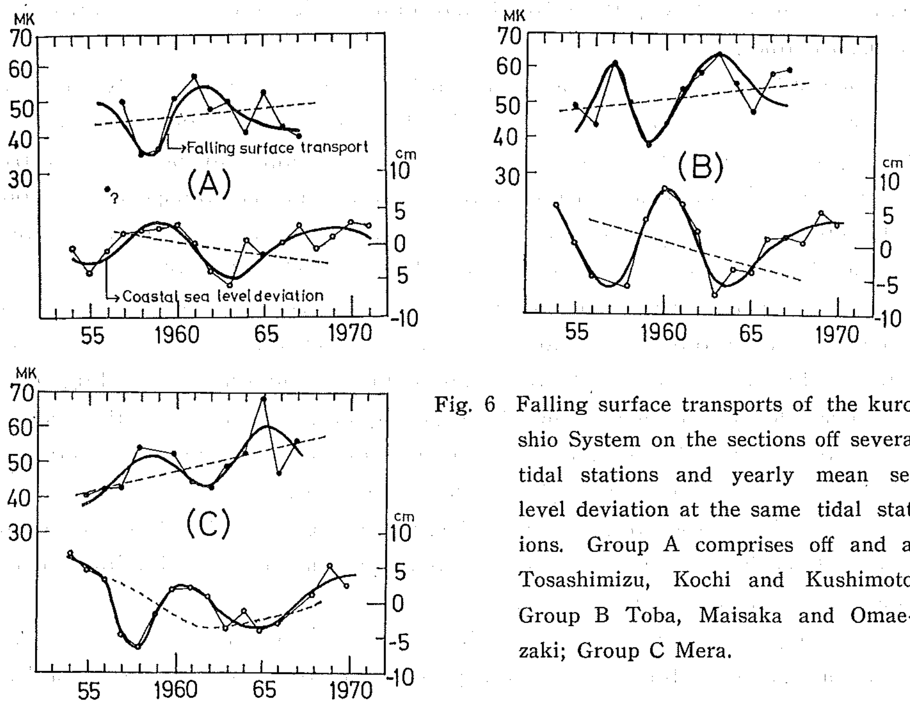


Fig. 6 Falling surface transports of the kuroshio System on the sections off several tidal stations and yearly mean sea level deviation at the same tidal stations. Group A comprises off and at Tosashimizu, Kochi and Kushimoto; Group B Toba, Maisaka and Omaezaki; Group C Mera.

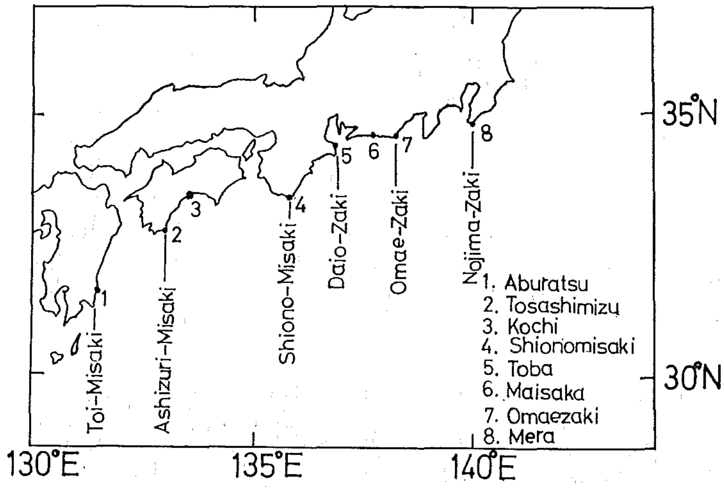


Fig. 7 Location of tidal stations and several capes.

C. This grouping is nearly the same as that of Tsumura (1963) derived from his viewpoint of characteristics of coastal sea level.

The smoothed running means of the coastal sea level at intervals of nine years are shown in the figure with dashed lines. For the Group B, the averaged running mean of coastal sea level is obtained only for Maisaka and Omae-zaki, taking account of the remarkable ground subsidence at Toba. The deviation from this smoothed running mean is indicated as the yearly mean sea level deviation. For the falling surface transport, the period used for the statistics is not so long, and then the long-term trend determined with the eye is shown with the dashed lines.

For the long-term trend, the falling surface transports are slightly increasing and the running means of coastal sea level are decreasing correspondingly except for the case of Group C in recent years. For example, in the ten years from 1956 to 1965, the increases in the averaged falling surface transports of Groups A, B and C are respectively 6.5, 6 and 8 *MK*, which correspond to falls of 5, 4.5 and 6 cm in coastal sea level estimated by eq.3. The observed falls in coastal sea levels of the same groups are respectively 4, 6.5 and 6 cm in nearly coincidence with those mentioned above. At present, we cannot know any certain uplift or subsidence of the ground unless true rising or falling of the coastal sea level is known. The above result, however, suggests that perhaps at least there may be no remarkable uplift or subsidence of the ground along the southern coast of Japan except the special locations such as Toba, Nagoya and Osaka etc. in the above-mentioned ten years, because the tendency of fall of coastal sea level may be roughly attributed to the increase of falling surface transport of the Kuroshio System.

From Fig. 6, we can see the long-term variations having the period of 7-10 years both in the falling surface transport and in the deviation of coastal sea level, though the correct periods of them cannot be determined from such a relatively short duration. These variations can be expected from the description of long-term variation of the Kuroshio mentioned in the author's paper (Nitani, 1972). According to the detailed inspection, the correspondence between falling surface transport and coastal sea level deviation in each group has the discrepancy of about one year in phase, and the ratio of the actual coastal sea level variation to the expected sea level from eq.3 due to the falling surface transport varies from 0.6-0.9, having the mean value of 0.8. However, we may say that the correspondence is comparatively good.

From the summer of 1959 to that of 1962, the well-known large meander of the Kuroshio off Enshu-nada developed associating with large cold water mass inside the Kuroshio. The coastal sea level was remarkably high in Group B as pointed out by Tsumura (1963), and the falling surface transport was very small in accordance with eq.3. However, these phenomena occurred not only in Group B but also in Groups A and C, though their scales were smaller than that of Group B. These long-period variations in the falling surface transport and coastal sea level propagate from west to east (A→B→C), taking 2-3 years in the same manner as the large meander of the Kuroshio.

2) Medium-term variation

Nitani (1973) showed that, the approximate relationships among maximum and mean surface velocities and surface transport of the Kuroshio were roughly confirmed statistically. So, the applicability of eq.3 for the medium-term variation is examined here by making use of the mean of the observed highest three velocities on the section across the Kuroshio instead of the surface transport, because we have not so many data of the latter to test eq.3.

The amplitudes of the mean sea levels corrected for the effect of air pressure at Kushimoto and Maisaka in the period of 1963-1971, which were obtained by the harmonic analysis, are shown in Fig. 8 together with the amplitudes of mean of the observed highest three velocities on the sections across the Kuroshio off the above stations. The peaks in the coastal sea level are found for the periods of 4, 6, 8-8.5 and 12 months completely corresponding to those in the velocity. In Fig. 9A, B, the relations between surface maximum velocity and the mean of the highest three velocities during 1963-1971 and surface transport of the Kuroshio off Enshu-nada in the periods of 1967-1969 and 1971 are shown. From these figures, we can confirm that the value of 0.15 knots, which is the mean of amplitudes of various periods except 12 months, corresponds to 9.8 *MK* of surface transport of the Kuroshio off Enshu-nada. Using this value we can get the value of 3.1 cm from eq.3, neglecting the contribution of the countercurrent north of the Kuroshio, as the mean amplitude of the sea level at the coast except the period of 12 months. This shows the agreement with the observed value of 2.3 cm at round numbers. If we assume that the results obtained from Fig. 9A, B, can be applied for the case off Shiono-misaki, the

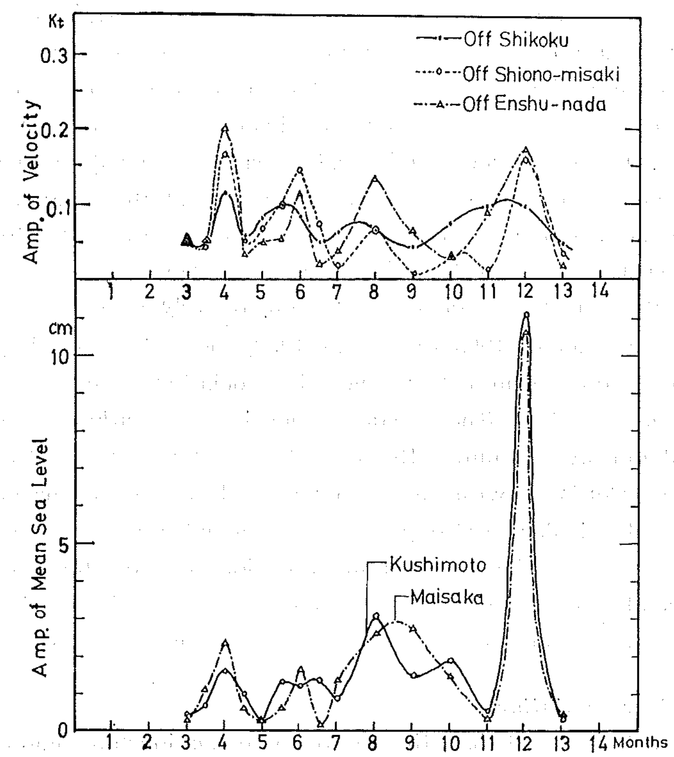


Fig. 8 Upper: Amplitudes of mean of the observed highest three velocities in the Kuroshio off Shikoku (Kochi), Shiono-misaki and Enshu-nada.
Lower: Amplitudes of the mean sea level corrected for the effect of air pressure at Kushimoto and Maisaka. These amplitudes are obtained by harmonic analysis based on the data in 1963-1971.

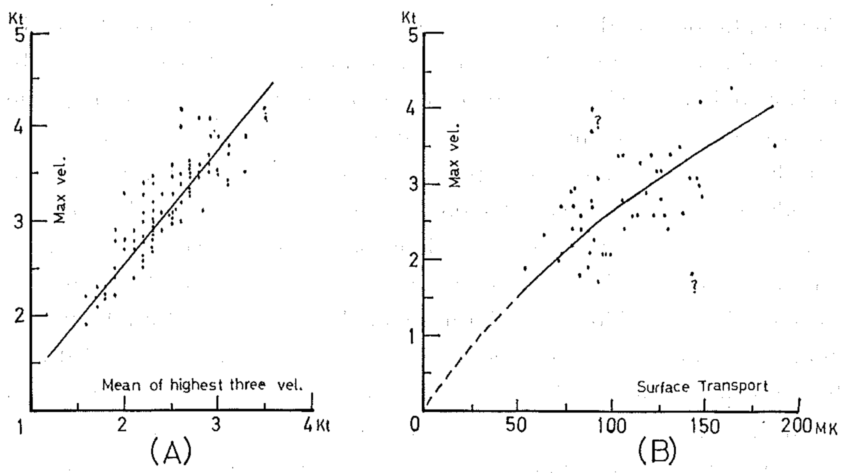


Fig. 9 (A) Relation between mean of the highest three velocities and maximum velocity on the section of the Kuroshio off Enshu-nada.
(B) Relation between surface transport and maximum velocity of the Kuroshio off Enshu-nada. These data are obtained by GEK observations in the period of 1963-1971.

expected mean amplitude from eq.3 and observed one are 2.7 cm and 2.0 cm, respectively, showing also the agreement with each other at round numbers. On the other hand, if we take the rising coefficient in eq.3 to be -0.30, the calculated sea levels at Maisaka and Kushimoto are 2.2 cm and 1.9 cm, respectively, showing the better accordance with the observed values than the cases where the rising coefficient is -0.42 as in eq.3. This estimation will be taken into account for the re-determination of the rising coefficient later. The amplitude of variation in the sea level having the period of 12 months is much affected by the change of density of sea water due to seasonal variation of solar radiation, and hence, the effect of the Kuroshio System having the period of 12 months to the sea level at the coast may be masked by this change.

TABLE. 1 PHASE LAGS IN THE VARIATIONS OF THE MEAN HIGEST THREE VELOCITIES AND THE COASTAL SEA LEVEL BOTH OFF AND AT KUSHIMOTO AND MAISAKA.

	Kushimoto			Maisaka			Maisaka−Kushimoto	
period (in months)	(a) Current	(b) Sea level	(b)−(a)	(c) Current	(d) Sea level	(d)−(c)	(c)−(a) Current	(d)−(b) Sea level
12	175°	247°	72°	229°	242°	13°	54°(1.8)	−5°(−0.2)
8	32	201	169	86	235	149	54 (1.2)	33 (0.8)
6	16	184	168	348	185	197	−28 (−0.5)	1 (0.0)
4	276	25	101	310	63	113	34 (0.4)	38 (0.4)
Mean except 12 months			146			153	(0.4)	(0.4)

Unit of lag is degree, but numeral in parenthesis is expressed in months.

In TABLE 1, the phase lags and the differences of these both at and off Kushimoto and Maisaka are shown. For the periods of 8 and 6 months, the differences between phase lags of velocity and coastal sea level are nearly 180° showing that the sea level is high when the Kuroshio is weak. These facts resulted from Fig. 8 and TABLE 1 support the appropriateness of eq. 3 for the medium-term variation of the sea level along the coast south of Japan.

The differences of the phase lags in the sea levels both at Maisaka and Kushimoto for the periods of 8, 6 and 4 months are 0.4 months on an average, which coincide with those in the velocities (Nitani, 1973). Hence, when the large meander is absent, the variation of sea level at the coast also progresses towards east with the mean phase velocity of about 7 mile/day nearly as well as the variation in the velocity or surface transport.

3) Phenomena with the short-term variation superimposed on the medium- and long-term variations

For the phenomena less than the several days in time scale, the relation between the variation of the Kuroshio and that of sea level difference of both sides of the Kuroshio was already reported by Shoji and Nitani (1966) and Nitani and Shoji (1970) as the results of the observations of extremely short-term variation of the Kuroshio off Shiono-misaki carried out in 1964 and 1965. It was concluded that the geostrophic balance between sea level difference and the surface transport of the Kuroshio was roughly satisfied, though the observed sea level variation was about 120% of that expected by geostrophic assumption. Each contribution from the variations of sea level on both sides of the Kuroshio to the variation of the sea level difference is about 50%, respectively. In those observations, however, the current in the southern half of the Kuroshio was observed only to the place where the velocity was about one knot, because the main object consisted in the repeated observation of the section across the Kuroshio as rapidly as possible. If the observations were continued as far as the true south boundary of the Kuroshio, where the velocity vanishes, the variation of the sea level on the south boundary would become larger, and subsequently the contribution of the north boundary would become less than 50%, showing the approach to eq. 3.

At present, however, there are no complete observations available for investigating the relationship between these short-term variations of which time scales are less than several days. Then, the fitness of eq. 3 will be examined for the variations including all kinds of time scales instead of pure short-term variation as the second best way. It will rather be considered as the synthetic examination of the applicability of eq. 3 for the relation between the variations of the Kuroshio System and the sea level along the southern coast of Japan. The falling surface transport obtained from the individual cruises in the past several years may be fit for this examination.

In Fig. 10 (A), the relations between the falling surface dynamic depth anomaly difference of the Kuroshio System obtained by individual cruises during 1958-1971 and the coastal sea level are shown using the data of the same origin as Fig. 2. In the figure, r determined with the eye is the ratio of the observed value of coastal sea level variation to the value of that expected from the falling dynamic depth anomaly difference. This ratio is 0.68 at Kushimoto and 1.00 at Omae-zaki, and the average of the two is 0.84. On the other hand, the relations between the falling surface transport of the Kushiro System obtained by GEK during 1967-1971 except 1970 (and 1972 only for off Shiono-misaki) and the coastal sea level are shown in Fig. 11 (A). The ratios r are in the range of 0.59-1.23 showing a fairly large scatter. The mean of these values is 0.83 coinciding with the case of the serial observations. But we can not get a clear relation for the offing of Toi-misaki.

The mean ratios in the above two cases are less than 1, and it is necessary to decrease the value of K, absolute value of rising coefficient, to make r to unity. If we adopt -0.30 as the rising coefficient instead of -0.42 in eq. 3, we get Fig. 10 (B) and Fig. 11 (B) corresponding to Figs. 10 (A) and 11 (A),

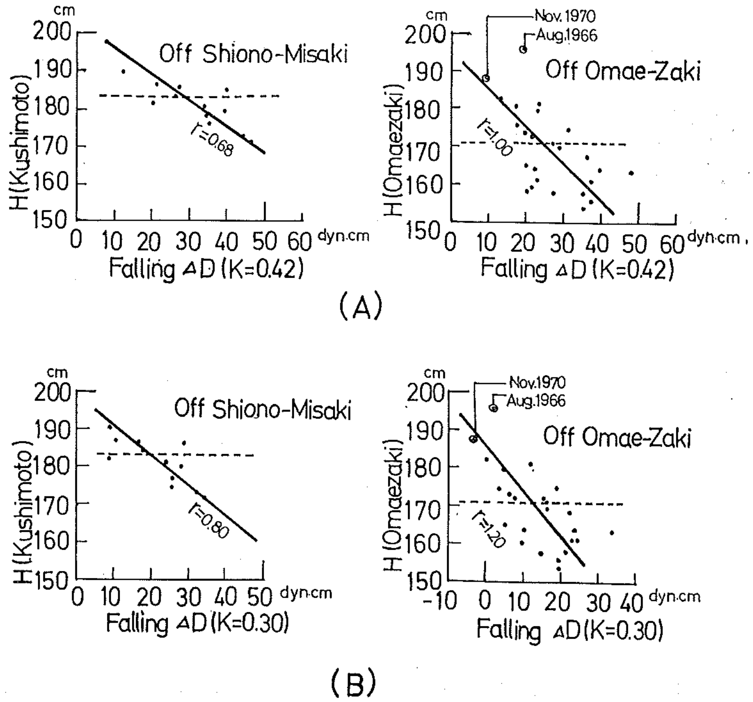
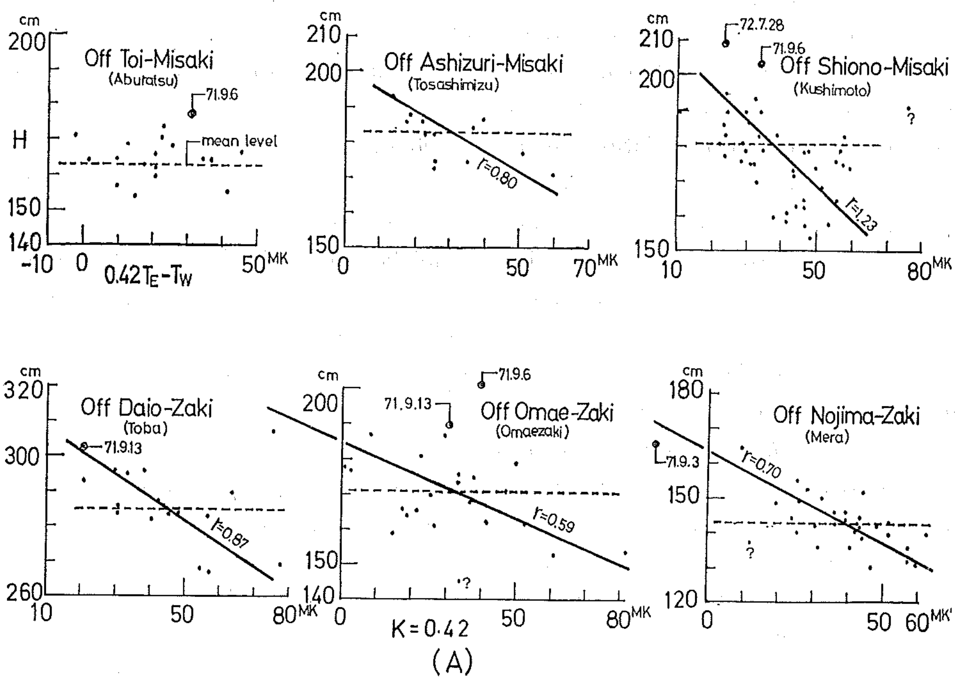


Fig. 10 Relations between falling surface dynamic depth anomalies and coastal sea levels both off and at Kushimoto and Omae-zaki in the period of 1958–1971, where K, absolute value of rising coefficient, is 0.42 in (A) and 0.30 in (B).



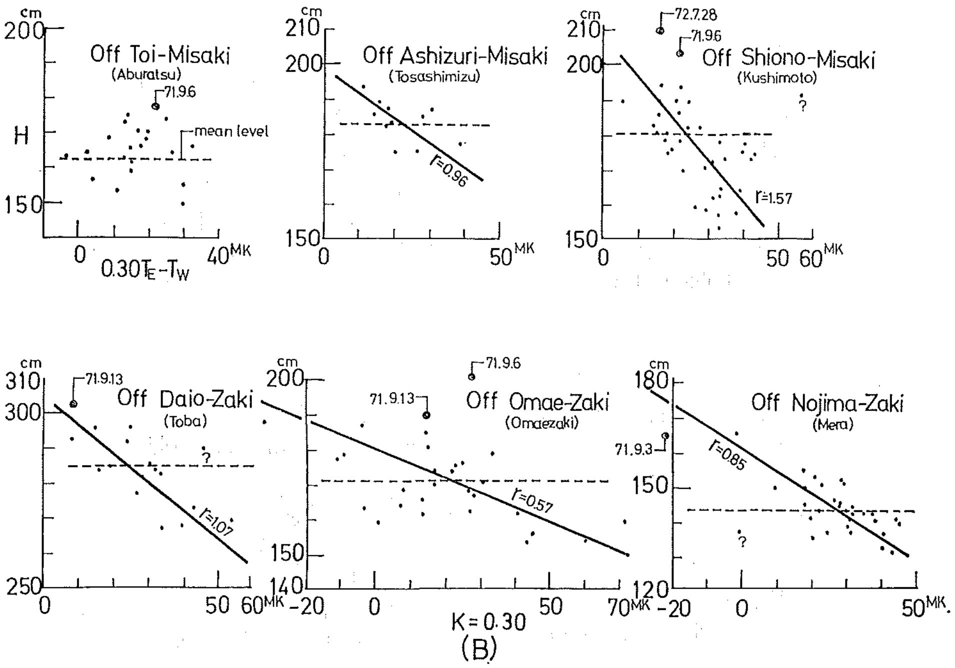


Fig. 11 Relations between falling surface transports obtained by GEK and coastal sea levels both off and at several tidal stations in the periods of 1967–1969 and 1971 , where K is 0.42 in (A) and 0.30 in (B).

respectively. Though the scatter of r is fairly large in these two figures, the mean values of r are 1.0 in both figures. Although such a good coincidence may be haphazard, it seems that the adoption of 0.30 as K fits better than that of 0.42. This is supported by the sea level model of the Kuroshio in Fig. 4 and by the examination of the relations between surface transport and sea level for the medium-term variations in paragraph 4.2.

On the other hand, the value 0.42 has its own foundation based on the observation, and all the relations obtained hitherto are accompanied by more or less large scatters. In addition, it may not be correct to decide K uniformly irrespective of locations and seasons etc. Anyway, however, if we decide only one value from the practical viewpoints, the value 0.36, mean of 0.42 and 0.30, will have to be chosen as the most probable value of K. Subsequently, eq. 3 has to be rewritten as follows:

$$H=H_0-0.75(0.36T_E-T_W)\ \mathrm{cm} \qquad (4)$$

Off the capes of Ashizuri-misaki and Shiono-misaki, the axis of the Kuroshio is almost close to the coast and the countercurrent north of it can not be developed except the special case such as the developing or existing stage of the large meander of the Kuroshio off Enshu-nada. In these locations, the variation of the surface transport of the Kuroshio itself is only a cause of the variation of coastal sea level due to the current system. However, off the capes of Daio-zaki and Omae-zaki, where the medium- and small-scale meanders of the Kuroshio accompanied by westward countercurrents near the coast exist almost always, the contribution to the coastal sea level change from the countercurrent is predominant, and the contribution from the Kuroshio itself is apt to be hidden as shown in Fig. 12. One reason for this is probably that the contribution from the countercurrent is about three times as large as that from

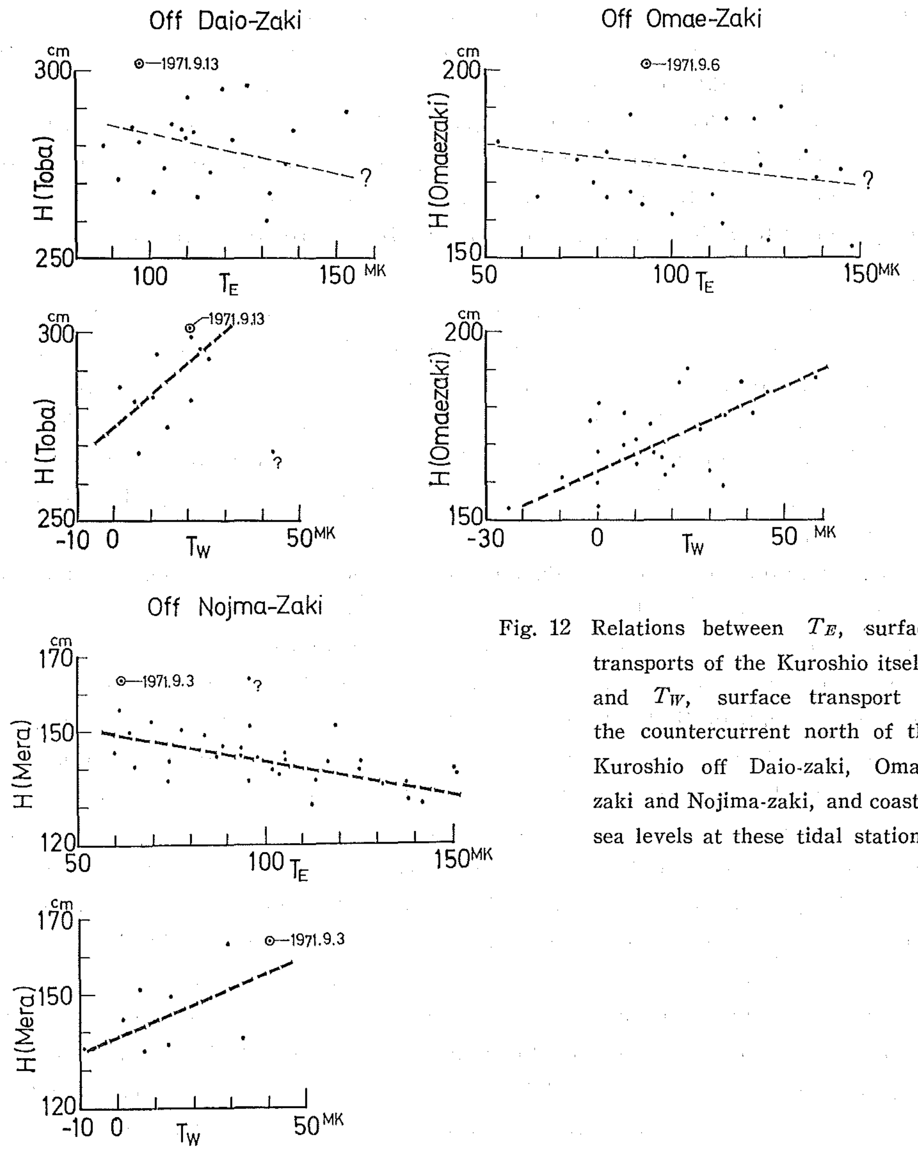


Fig. 12 Relations between T_E, surface transports of the Kuroshio itself, and T_W, surface transport of the countercurrent north of the Kuroshio off Daio-zaki, Omae-zaki and Nojima-zaki, and coastal sea levels at these tidal stations.

the Kuroshio as shown in eq.4. Off Cape Nojima-zaki, we can see both effects from the Kuroshio and from the countercurrent north of it, because the frequency of occurrence of the countercurrent lies midway between the above two cases. More of the current data, especially of continuous data, is required in order to obtain more detailed information concerning the local specific characteristics of the coastal sea level variations.

5. Effect of the Kuroshio System on the abnormally high sea level along the southern coast of Japan

In early September 1971 and late July 1972, the remarkable abnormally high sea levels occurred along the southern coast of Japan. The anomalous heights were 20-50 cm, and their durations were ten days or so. According to Shoji (1973) and Iida and Masuzawa (1973), the similar phenomena have happened once or twice a year in the past. They suggested that the original force of these phenomena may be a fairly strong and continual easterly or northeasterly wind stress caused by progressing typhoon or by the zonal pressure gradient high to the north and low to the south, over the sea south of Japan.

These stresses may produce some transformations to the Kuroshio System. In addition to the piling up of sea water by Ekman transport, they tend to weaken the Kuroshio and are apt to produce a countercurrent between the Kuroshio and the coast, which is considerably baroclinic, though the detailed mechanisms are not clear. According to equation 4, these processes may be one of the effective causes of the abnormally high sea level along the southern coast of Japan.

To examine the degree of dependence to the offshore current system for the abnormally high sea level along the coast, the ratio of the observed deviation from long-term (several years) mean sea level to the deviation expected from the falling surface transport of the Kuroshio System is a good measure. This ratio is substantially the same as the ratio r in Figs. 10 and 11, but here it is written R considering especially the correspondence to the abnormally high sea level. If R becomes zero, these abnormally high sea levels are considered to be independent of the geostrophic currents. We call this ratio as the ratio of dependence hereafter. We have only two serial observations off Omae-zaki just at the times when the abnormally high sea levels along the coast occurred in the past. The relations between the actual abnormally high sea level and falling dynamic depth anomaly difference in those times are shown in Figs. 10 (A) and (B) marked with double circles. These observations were carried out in August 1966 and November 1970. R are 0.88 and 0.24 for $K=0.42$, and 1.12 and 0.52 for $K=0.30$, respectively, and mean of the two is 0.69.

In Figs. 11 (A) and (B), the relations between the actual abnormally high sea levels in September 1971 and July 1972 and the falling surface transport of the Kuroshio System obtained by GEK are indicated with double circles. The ratios R are shown in TABLE 2 together with this ratio of above cases estimated by serial observations.

TABLE 2. RATIO OF DEPENDENCE TO THE VARIATION OF THE KUROSHIO.

Location	Serial obs. (1966, 1970)		GEK obs. (1971. 1972)	
	K=0.42	K=0.30	K=0.42	K=0.30
Kushimoto			0.14, 0.41	0.05, 0.27
Toba			0.89	0.72
Omae-zaki	0.88, 0.24	1.12, 0.52	0.05, −0.10	0.16, −0.07
Mera			1.27	1.41
Mean	0.56	0.82	0.44	0.43
	0.69		0.44	

R varies from -0.10 to 1.41, but all the values excepting one example at Omae-zaki in 1971 are positive. The mean values for $K=0.42$ and $K=0.30$ are nearly the same with each other, having the mean value of 0.44.

It is concluded that about half of the abnormally high sea level along the coast is due to the rise of the coastal sea level keeping the geostrophic balance with the Kuroshio System including the countercurrent, and the other half may be due to the progressive shelf wave towards southwest or the internal Kelvin wave very close to the coast, which may be difficult to be caught by the ordinary observations carried out only in the ocean areas.

Anyway, more observations which can be used for TABLE 2 are necessary for the development of the theoretical and numerical model considerations. For this purpose, the customary continuous current observations at selected several significant sections across the Kuroshio are desirable. If it is impossible, as the second best way, the concentrated continuous observations across the Kuroshio and its countercurrent during the occurrence of the abnormally high sea level with use of as many research vesseles as possible are necessary.

6. Conclusions

The investigation, in regard to the relation between the mean sea level along the southern coast of Japan and the surface transport of the Kuroshio System, was carried out under the concept of geostrophic balance, making use of the past data of serial and GEK observations. The conclusions are as follows:

(1) When the Kuroshio becomes strong and the surface transport increases, the sea levels on the north and south boundaries fall and rise, respectively, at a ratio of about 36:64 like an asymmetrical seesaw.

(2) The variation of the surface transport of the Kuroshio System affects the sea level along the southern coast of Japan in a manner as shown in eq. 4. The variation due to the surface transport of the countercurrent north of the Kuroshio is larger by about three times than the variation due to the same quantity of surface transport of the Kuroshio itself.

(3) The contribution from the surface transport of the Kuroshio System

to the abnormally high sea level on the southern coast of Japan occurred in September 1971 and July 1972 is about 40% on an average, and the most of the remainder may be attributed to other phenomena.

Acknowledgements

The author wishes to express his hearty thanks to Dr. D. Shoji, Counsellor, Hydrographic Department, for his criticism and encouragement throughout this study. The author also thanks to Messrs. S. Yoshida, J. Okumoto and K. Iwanami, members of Japan Oceanographic Data Centre, for their assistances in the statistical calculation. The author is indebted to the Ministry of Science and Technology for the resources of the statistics.

References

Iida, H. and J. Masuzawa 1973, "On the unusual sea level change along the coast of Japan (in Japanese)". Kaiyo Kagaku, **5**, 247.

Moriyasu, S. 1958, "On the fluctuation of the Kuroshio south of Honsyu (4)."—The influence of the oceanographic conditions upon the monthly mean sea level—Jour. Oceanogr. Soc. Japan, **14**, 137.

Moriyasu, S. 1960, "On the monthly sea level on the south coast of Japan." Memo. Kobe Mar. Obs., **14**, 19.

Moriyasu, S. 1961, "On the difference in the monthly sea level between Kushimoto and Uragami, Japan." Jour. Oceanogr. Soc. Japan, **17**, 197.

Nitani, H. 1972, "On the variation of the Kuroshio (in Japanese)." Jour Geogra. Soc. **81**, 17.

Nitani, H. 1973, "Variation of the Kuroshio." unpublished.

Nitani, H. and D. Shoji 1970, "On the variability of the velocity of the Kuroshio-II." The Kuroshio—A symposium on the Japan Current (edited by J. C. Marr). East-West Center Press, 107.

Shoji, D. 1961, "On the variations of the daily mean sea levels along the Japanese Islands." Jour. Oceanogr. Soc. Japan, **17**, 141.

Shoji, D. 1972a, "Time variations of the Kuroshio south of Japan." Kuroshio—Its physical aspects (edited by Henry Stommel and Kozo Yoshida), Univ. Tokyo Press, 217.

Shoji, D. 1972b, "The Kuroshio south of Japan in 1965. Researches in Hydrography."—In commemoration of the centenary of Hydrographic Department of Japan, Tokyo, 113.

Shoji, D. 1973, "Investigation of abnormal high sea level in Sept. 1971 along the south coast of Japan (in Japanese)." Kaiyo Kagaku, **5**, 230.

Shoji, D. and H. Nitani 1966, "On the variability of the velocity of the Kuroshio-I." Jour. Oceanogr. Soc. Japan, **22**, 192.

Stommel, H. 1948, "The westward intensification of wind-driven ocean currents." Trans. Amer. Geophys. Union, **29**, 202.

Tsumura, K. 1963, "Investigation of the mean sea level and its variation along the coast of Japan (part I)."—Regional distribution of sea level variation—(in Japanese). Jour. Geode. Soc. Japan, **9**, 49.

Yoshida, K. 1965, "A theoretical model on wind-induced density field in the oceans.—I." Jour. Oceanogr. Soc. Japan, **21**, 154.