The Journal of the Oceanological Society of Korea
Vol.12, No. 2, p. 67-74, December 1977

AN ESTIMATION OF AVERAGE CURRENT VELOCITY IN THE WESTERN CHANNEL OF THE KOREA STRAIT FROM MEAN SEA LEVEL DATA

Jae Chul Lee* and Chang Hee Jung**

*Department of Oceanography, Seoul National University

**Department of Meteorology, Seoul National University

ABSTRACT

With the serial observation data and the tidal records at Busan and Izuhara from 1966 to 1973, the geostrophic current velocity and its relation to the difference of mean sea level of both sides were studied in order to estimate indirectly the average current velocity from the tidal observations.

The result shows that the current velocity is estimated by the relationship $V=4.016(H-98.3)$ with the 95% confidence limits of $V \pm 4.2$ cm/sec. The relationship between the observed current velocity and the simultaneous daily mean sea level difference shows a similar result, $V=4.717(H-99.6)$. The two equations were applied to the evaluation of annual variations of current velocity from the average monthly mean sea level data of both stations.

I. INTRODUCTION

The Korea Strait beween Korea and Japan is divided into the Western Channel and the Eastern Channel by the Tsushima Island. The Sea of Japan is connected with the East China Sea by this strait.

The warm water of high salinity which branches off the Kuroshio and flows through the Korea Strait is called the Tsushima Current. The main stream of the Tsushima Current enters the Japan Sea through the Western Channel at a rate of about 10^6 m^3/sec (Moriyasu, 1972), but the volume transport through the Eastern Channel is about 27% of the former(Yi, 1966).

As the Tsushima Current flows northeastward predominantly along the western coast of Japan with a wide meandering pattern, its fluctuations have an absolutely important influence on the hydrography and the cyclonic circulation pattern in the Japan Sea. Hence the study on the current of the Korea Strait is very important. However, regular measurements of the current velocity in fields by direct methods are rather difficult. Accordingly, the fact that we can find the gross features of the currents in this strait indirectly will be helpful to interpret the changes of various oceanographic phenomena.

Dietrich proved the validity of the geostrophic equilibrium in the Baltic Sea by research into the relation between the observed current data and the simultaneous tidal recordings across the Great Belt. It is remarkable enough that the ratio of the sea surface gradient to current velocity agrees fairly well to the theoretical value of the gradient equation in spite of the frictional effects due to its shallow and narrow cross section. Moreover, he emphasized that the quasi-levelling, the method of obtaining a levelling by means of current data, is more accurate than geodetic levelling (Dietrich, 1963).

Proudman(1953) explained the relation between the current velocity and the sea surface gradient in the Strait of Dover, and above all, continuous studies on it helped to determine the levelling systems in England and France (Neumann, 1968).

Yi(1970) studied the relation between the mean sea level and the variations of extensive oceanic conditions in the Western Channel including the current velocity calculated by Margule's equation, with the tidal data from 1962 to 1967 and the oceanographic data from 1965 to 1966.

Hidaka & Suzuki (1950) computed the annual and long-term variations of current in the Western Channel by Margule's equation.

Lee(1970, 1974) observed the current in the Western Channel chiefly on Line 207.

The purpose of this study is to establish the precise relationship between the current velocity and the sea surface inclination with more sufficient data than Yi's (1970) in the Western Channel, furthermore, to provide a way to estimate the instantaneous conditions of current from the tidal recordings.

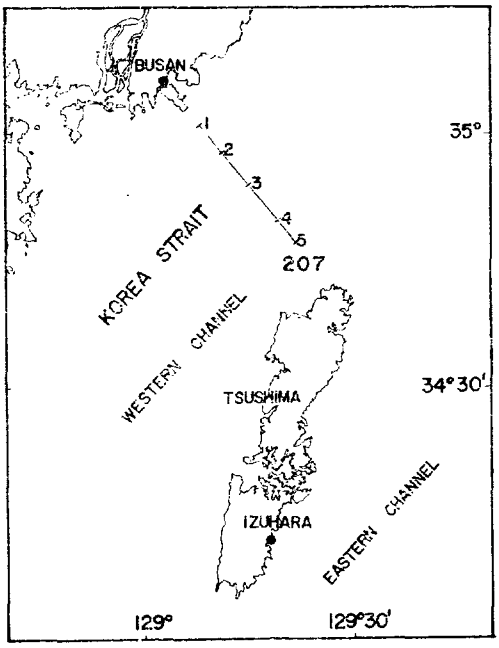

Fig 1. Oceanographic stations and tidal stations.

II. ASSUMPTIONS

Defant(1961) treated the currents in sea straits as frictional flows. Certainly, shallow and narrow straits like the Bosphorus, the Dardanelles, and the Strait of Bab el Mandeb may be affected by frictional forces, but most straits are short and wide enough for flows to be dominated by frictionless hydraulic principles (Whitehead, et al., 1974). As a matter of fact, the dimensions of the Korea Strait are so much larger than those of other straits that the current in this strait can be approximated as a geostrophic flow.

On the coast of the Japan Sea, especially on the coast of the western half of the Japan Sea from Noto peninsula, the influence of atmospheric pressure on the variation of sea level is different from theoretical sea level change(−1.01 cm/mb) and is also different from place to place but is disturbed by the synoptic wind system (Isozaki, 1969). Because the distance from Busan to Tsushima is at most about 50km, the difference in atmospheric pressure is quite small. Above all, the effect due to the tractive force of the wind is much larger(Rossiter, 1962), but it is very difficult to analyze such an effect. Hence the meteorological influence on the sea level difference between Busan and Tsushima can be neglected.

Defant (1961) explained the currents in several straits. There are continuous interchange of water between mediterranean and adjacent seas in those straits. He defined the mechanism of circulation in such a strait system as the thermodynamic machine owing mainly to the density difference of two different layers. Assaf & Hecht (1974) and Whitehead(1974) studied the dynamical model of straits which have two-layer characteristics. But the Korea Strait has geographic and hydrographic peculiarities. The influx of Tsushima Current never returns to the

Korea Strait, because most water flows northeastward along the western coast of Japan and 75% of the volume transport through this strait discharged to the Pacific Ocean through the Tsugaru Strait, and most of the residue through the Soya Strait (Moriyasu, 1970). The cold water near the continent cannot originate from the Okhotsk Sea through the narrow Tatar Strait, therefore it must be formed in the Japan Sea by excessive cooling in winter and no great outflow of cold water takes place from the Japan Sea(Sverdrup, et al., 1946). Since there is no significant outflow from the Japan Sea through the Korea Strait, the current in the Korea Strait is not composed of two different layers.

The averge values of the current data observed by Lee(1970, 1974) were computed (Table. 1) in order to show the vertical distribution of current velocity regardless of direction because the northeastward flows were predominant. This result supports such ideas. There is no great change in vertical distribution of velocity. Even the lower layer of no motion seems to be hardly found. One can see the core of the current near Station 4.

Yi(1967) concluded that the sea level variations at Busan are owed entirely to the change of the density distribution, i.e., the variation of steric sea level. The relation between mean sea level and dynamic depth anomaly has a very high correlation coefficient in Goto-nada near the Tsushima Island (Tsuchida, 1973). So, because the change of mean sea level has a close interrelationship with the density distribution in the Korea Strait, the current velocity as a geostrophic flow which is computed from the density field can be inferred from the mean sea level data.

From these considerations four assumptions are summarized as following:

(i) Current in the Korea Strait can be regarded as a stationary frictionless flow so that it is approximated as geostrophic current.

(ii) The influences of meteorological factors on the sea level difference between Busan and Izuhara are negligible.

(iii) The structure of the current is nearly one-layer model.

(iv) The sea level variation is closely interrelated with the current velocity.

Table 1. The Average values of current data measured by Lee (1970, 1974).

Depth (m)	Average Current Velocity on Line 207 (cm/sec)			
	Station 1	Station 2	Station 4	Station 5
5	33.1	31.1	54.6	33.2
20	27.9	31.6		34.0
50	24.5	26.8	41.6	34.1
75	21.3	21.3		
100			37.3	26.5
150			45.6	18.9
200			15.0	

III. THEORY

When a stationary frictionless flow without any external forces but gravity is assumed, the following gradient equation is readily derived from the equations of geostrophic current:

$$\tan\beta=\frac{f}{g}V \quad \cdots\cdots(1)$$

where $\tan\beta$ is gradient of the isobaric surface, and f is Coriolis parameter.

In a continuously stratified ocean, Helland-Hansen's formula is derived from the gradient equation:

$$V_1-V_2=\frac{10}{Lf}(\triangle D_A-\triangle D_B) \quad \cdots(2)$$

where V_1 and V_2 are velocities of layer 1 and 2 respectively, L is horizontal distance between station A and B, and $\triangle D_A$ and $\triangle D_B$ are dynamic depth anomalies at station A and B respectively.

The differences in velocity between each layer are computed successively by means of equation (2), this relative velocity field can be transformed into the absolute velocity field if the reference level or the layer of no motion is determined. This method of obtaining the geostrophic current velocity from the density field is called the dynamic computation.

In the open ocean, it is nearly impossible to measure the sea surface inclinations against a level surface, so the fundamental relationship between current velocity and sea surface slope cannot be investigated in detail. However, across the strait, it is easy to know the gradients from the tidal data, so that there is a constant relation between them for a specific area as the following formula:

$$V = \frac{g}{Lf} H \cdots\cdots\cdots\cdots\cdots\cdots (3)$$

where L is vidth of strait, and H is sea level difference across the strait.

In the Western Channel the theoretical value of $\frac{g}{Lf}$ is 2.731(L=43 km at 75 m isobath).

If the tidal station of the Tsushima Island is located in the upper end where the extended line of 207 meets the island, the above relationship will be correctly consistent, in the light of other examples. But, because there is only one tidal station in the southern part, Izuhara, the difference in mean sea level at both sides can not correspond to the current of the cross section of Line 207 so that the coefficient of the above equation must be different to some extent.

In spite of such disadvantage the data can be applied to the estimation of current because the statistical coefficient will be obtained independently from the data and it will form the characteristic relationship in the Western Channel.

If the geodetic zero levels of both sides established, more definite results may be obtained. In reality there is no information about the geodetic levelling across the Korea Strait, this gives no serious problem since the discrepancy may appear as the difference of the datum levels in the end.

IV. MATERIALS AND METHODS

The following data were used in this study.

(1) The results of serial oceanographic observations on Line 207 from 1966 to 1973 by the Fisheries Research and Development Agency in Korea.

(2) The results of tidal observations at Busan from 1966 to 1973 by the Hydrographic Office in Korea.

(3) The mean sea level data at Izuhara in Tsushima from 1966 to 1973 by the Hydrographic Division in Japan.

(4) The observed current data carried out by Lee (1970, 1974).

The distributions of geostrophic current velocity between five stations on Line 207 were calculated by the method of dynamic computation from the oceanographic observation data. In this procedure the depths of reference level were made large as far as the data permit with a few exceptional cases, because of the relatively shallow depth of the channel.

In principle, the average values of surface velocity over the whole sections were used. But if the average values were negative or quite small in magnitudes as in a few cases of winter to spring, the average values of surface velocity of the section between the stations 3-4 and 4-5 were used, because these values were considered to be closer to the real velocity owing to their relatively larger depths than other stations. Of course, the values of current is positive if the flow is northeastward and negative in the reverse case.

By subtracting the daily mean sea levels of

Busan from the correspondent values of Izuhara, the differences between both sides were calculated. In subtraction, the raw data, 3 day moving mean, and 5 day moving mean of daily mean sea level at both sides were used for comparison, and denoted them H_1, H_3, H_5 respectively. Accordingly the values of H are the measures of sea surface slope across the Western Channel.

The correlation coefficients between the surface velocity and H_1, H_3, H_5 were computed and the equations of regression line were determined by least square method. In the same way, the observed data of surface current velocity by Lee (1970, 1974) were compared with simultaneous values of H_1, H_3, H_5.

V. RESULTS AND DISCUSSION

The most important results in this study are summarized in Table 2. One can see that the average geostrophic current velocity by dynamic computation is smaller by 5 cm/sec than the observed one and there is no great difference between H_1, H_3 and H_5 with its maximum difference of 0.6 cm. Even if the strong current, 100 cm/sec, is assumed, the greatest difference between each H value is 0.3 cm and 2.1 cm for each group, these small values lie within the limit of error of precise levelling. Consequently all of the equations can be applied to the estimation of average current velocity. Besides, it is likely that the instantaneous current velocity can be evaluated by subtraction of simultaneous tidal recording at Busan from that of Izuhara. It is not difficult to find that the correlation coefficients of the observed data are somewhat small on account of small numbers of data points, so that the coefficients of equations from the observed data have larger discrepancies than those of geostrophic currents.

Because the geostrophic current velocity was smoothed out to greater extent than the observed velocity, it is natural that the geostrophic currents are the most significantly correlated with H_5, in which the variations of short period have been removed. At any rate, the following equations are regarded as typical ones in each case:

$$Vg=4.016(H_5-98.3) \quad \cdots\cdots\cdots\cdots(4)$$

$$Vob=4.717(H_3-99.6) \quad \cdots\cdots\cdots\cdots(5)$$

where Vg is geostrophic velocity and Vob is observed velocity.

It is easy to know from the above that the zero level of Izuhara is lower than that of Busan by 98.3 cm and 99.6 cm respectively.

Current velocity is evaluated with the 95% confidence limits of V±4.2 cm/sec by means of the equation (4). In the cases of other equations, the 95% confidence limits are greater because of larger dispersion.

The coefficients are much greater than the theoretical value, 2.731. The reasons of this

Table 2. Comparison of the results.

Current Velocity	H	Mean (cm)	Correlation Coefficient	Equation of regression	
	H_1	107.4	0.746	$H_1=99.3+0.236Vg$	$Vg=4.237(H_1-99.3)$
Geostrophic	H_3	107.2	0.765	$H_3=98.8+0.242Vg$	$Vg=4.132(H_3-98.8)$
Vg=34.6cm/sec	H_5	106.9	0.780	$H_5=98.3+0.249Vg$	$Vg=4.016(H_5-98.3)$
	H_1	107.4	0.606	$H_1=98.3+0.231Vob$	$Vob=4.329(H_1-98.3)$
Observed	H_3	108.0	0.615	$H_3=99.6+0.212Vob$	$Vob=4.717(H_3-99.6)$
Vod=39.6cm/sec	H_5	107.8	0.585	$H_5=100.3+0.190Vob$	$Vob=5.263(H_5-100.3)$

Vg, *Vob*: Average velocity

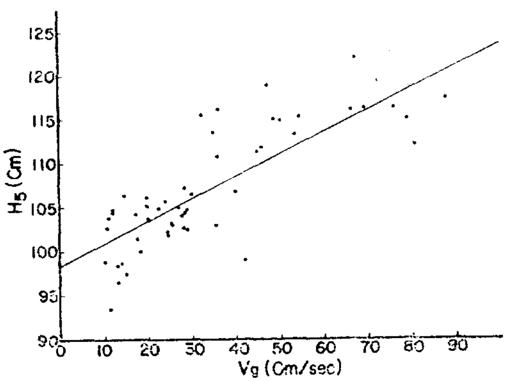

Fig 2. Relationship between geostrophic current velocity and sea surface gradient.

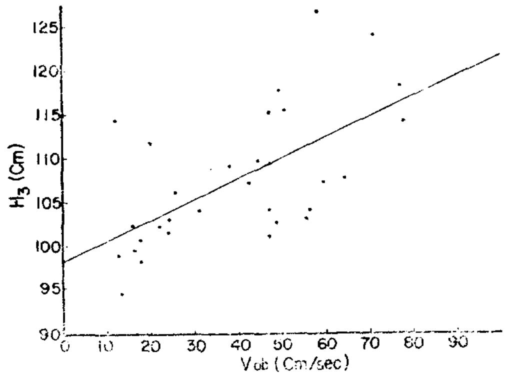

Fig 3. Relationship between observed current velocity and sea surface gradient.

large difference are explained as following: Izuhara is located upstream and its distance from the northern end of the Tsushima is greater than 50 km. The cross section of Line 207 is narrower than the southern section. The narrowing of the channel of Busan plays a decisive role in the hydrography in the Korea Strait as Stommel (1965) interpreted. In order to satisfy

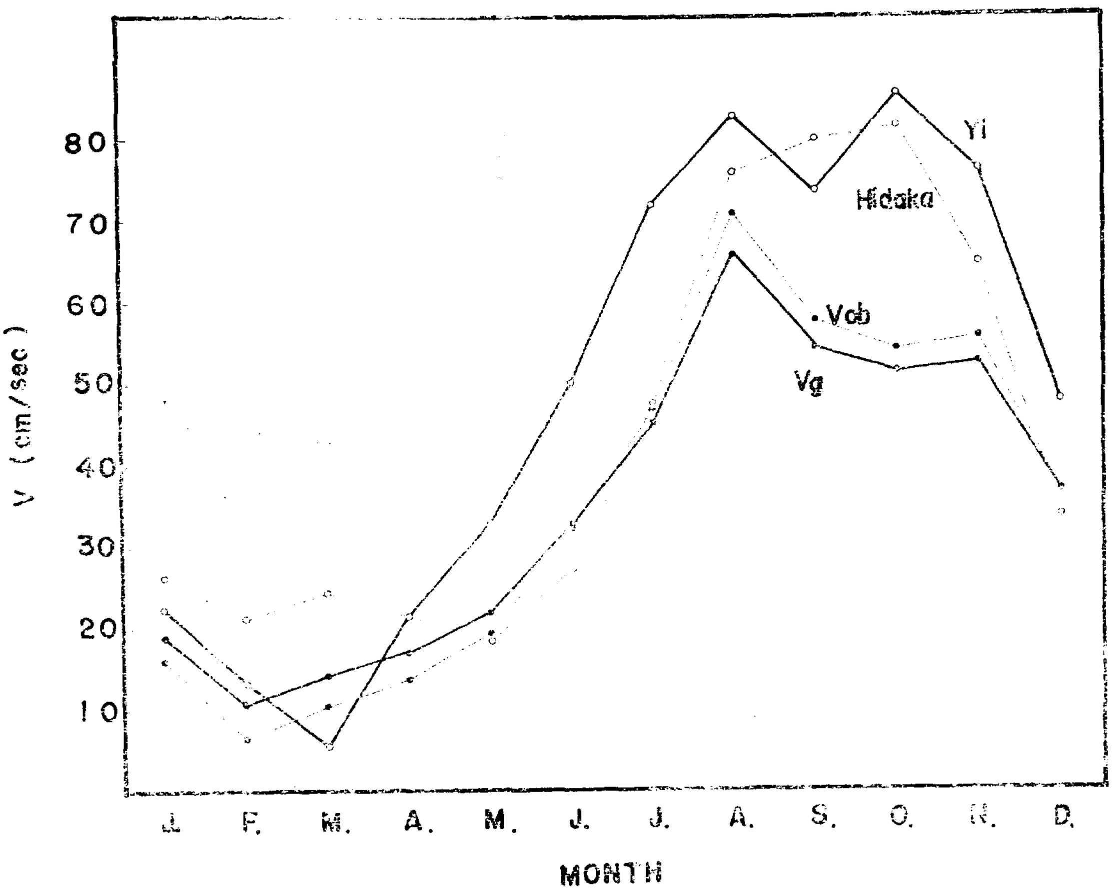

Fig 4. The annual variation of current velocity.

the continuity equation, the stream must be accelerated. As a result, the velocity of southern section near Izuhara must be smaller than that of Busan. At present the investigation into such a phenomenon in the Korea Strait is absent. Furthermore, Izuhara fronts the Eastern Channel where not only current velocity but also volume transport is quite small. Probably the frequent counter currents along the eastern coast of Korea may have influece on the mean sea level at Busan(Yi, 1970). The two representative results are plotted in Fig 2 and Fig 3.

By the average values of monthly mean sea level differences, the annual variations of currents with the two equations were computed (Table 3) and compared with the results of Yi (1970), and Hidaka & Suzuki (1950) in Fig 4, their results are of larger magnitudes.

Its value ranges from 10.8 cm/sec in February to 65.5 cm/sec in August. Result from observed current data has greater variation from 6.6 cm/sec in February to 70.8 cm/sec in August.

Table 3. Annual variation of average current velocity and difference of monthly mean sea level.

Month	H(cm)	Vg(cm/sec)	Vob(cm/sec)
Jan	103.0	18.9	16.0
Feb	101.0	10.8	6.6
Mar	101.8	14.1	10.4
Apr	102.5	16.9	13.7
May	103.7	21.7	19.3
Jun	106.4	32.5	32.1
Jul	109.5	45.0	46.7
Aug	114.6	65.5	70.8
Sep	111.8	54.2	57.5
Oct	111.1	51.4	54.2
Nov	111.4	52.6	55.7
Dec	107.4	36.5	36.8
Mean	107.0	35.0	35.0
Period	1966-73	1966-73	1968-73

Vg: Current Veloity computed by means of the equation $V=4.016(H-98.3)$, which is derived from geostrophic current.

Vob: Current velocity computed by means of the equation $V=4.719(H-99.6)$, which is derived from the current observed by Lee.

H: Average difference of monthly mean sea level.

VI. CONCLUSION

The purpose of this study is to grasp the gross feature of an instantaneous state of current from the daily mean sea level data.

(i) Average current velocity of the Western Channel is estimated from the difference of daily mean sea level data at both sides with the equation $V=4.016(H-98.3)$.

(ii) Coefficient of trend line(4.016) is much larger than the theoretical value(2.731) because Izuhara is located on the southeastern part of the Tsushima Island and because of the frequent counter current near Busan.

(iii) The analysis of the observed current data seems to show that the density discontinuity does not coincide with the reference level in dynamic computation as well as the boundary surface where the inversion of current direction occurs in two layer model.

(iv) The annual variations of current velocity is about 55 cm/sec with its range from 10.8 cm/sec in February to 65.5 cm/sec in August.

VII. ACKNOWLEDGEMENT

The author expresses his sincere gratitude to Jung Chang Hee, professor of the Department of Meteorology, Seoul National University, for his careful direction. He is also grateful to Yi Sok U for the kind guidence and to Han Sang Bok for his helpful advices and criticisms, in preparing this thesis.

REFERENCES CITED

Assaf, G. and A. Hecht., 1974. Sea Straits: a dynamical model. Deep-Sea Res., 21: 947-958

Defant, A., 1961. Physical Oceanography. Pergamon, Oxford, 1: 745pp.

Dietrich, G., 1963. General Oceanography. John Wiley & Sons, Inc., 588 pp.

Hidaka, K., and T. Suzuki., 1950. Secular variation of the Tsushima Current. J. Oceanogr. Soc. Japan. 16:28-31.

Isozaki, I., 1969. An investigation on the variations of sea level due to meteorological disturbances on the coast of Japanese Island(III). On the variation of daily mean sea level. J. Oceanogr. Soc. Japan. 25(2): 91-102

Lee, Chang Ki, 1970. On the currents in the Western Channel of the Korea Strait. Bulletin of Fisheries Research and Development Agency., No 6, pp. 175-232

____, 1974. A study on the currents in the Western Channel of the Korea Strait. Bulletin of Fisheries Research and Development Agency., No 12, pp. 37-106,

Moriyasu, S., 1972. "The Tsushima Current," Kuroshio, its physical aspects, ed. H. Stommel & K. Yoshida. Univ. of Tokyo Press. pp. 353-370.

Neumann. G., 1968. Ocean Currents. Elsevier Publishing Company, Amsterdam., 352 pp.

Proudman, J., 1953. Dynamical Ocaenography. Methuen, London/Wiley, New York, N.Y., 409 pp.

Rossiter, J.R., 1962. "Long-term variations in sea-level," The Sea, ed. M.N.Hill., Interscience, New York-London 1: 590-610

Stommel, H., 1965. The Gulf Stream, 2nd ed. Univ. Calif. Rress, Berkely, Calif.

Sverdrup, H.U., M.W. Johnson, and R.H. Fleming, 1946. The Oceans, their physics, chemistry and general biology, 2nd ed. Prentice-Hall, Englewood Cliffs, N.J., 1087 pp.

Tsuchida, T., 1973. On the relation between the sea level and the oceanographic conditions in the Goto-nada. Oceanography and Meteorology. 20, No. 280.

Whitehead, J.A., A. Leetmaa and R.A. Knox., 1974. Rotating Hydraulics of Strait and Sill flows. Geophys. Fluid Dynamics., 6:101-125

Yi, S., 1966. Seasonal and secular variations of the water volume transport across the Korea Strait. J. Oceanogr. Soc. Korea. 1: 7-13

____, 1967. On the variations of monthly mean sea levels along the coast of Korea. J. Oceanogr. Soc. Korea. 2: 24-33

____, 1970. "Variations of oceanic condition and mean sea level in the Korea Strait." The Kuroshio, ed J.C. Marr. East-West Center Press, Honolulu pp. 125-142