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Variability of Sea Levels Associated with the Tsushima Current in the Korea Strait

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Time series of barometrically adjusted sea level at Pusan, Izuhara and Hakada are analyzed to study the fluctuations of the Tsushima Current through the Korea Strait. Variability of sea levels and their differences is divided into two parts with respect to the frequency of 0.01 or 0.02 cycles per day(cpd). At lower frequency, both of sea levels and sea level difference(SLD) are coherent and in phase to each other. Pusan has smaller seasonal variations in sea level than other two stations because the effects of geostrophic current and prevailing wind have a negative influence on the seasonal thermosteric contribution to sea level change. Low frequency variability of SLD thus of the Tsushima Current is much greater in the western channel.

For higher frequency parts, SLD in the eastern channel has larger variability and is not coherent with that of the western channel. Sea levels at Pusan and Izuhara are 180° out of phase with SLD in the western and eastern channel respectively, whereas the Hakada level is in phase. This result indicates that eastern channel has a normal response to the along-channel winds and cross-channel geostrophy because Izuhara faces the eastern channel.

Introduction

Sea level data across a strait is useful to monitor the variations in the strength of currents and volume transport through the strait. Yi(1970) and Hahn(1991) calculated the volume transport through the Korea Strait from the hydrographic data by means of the Margule's equation. Lee and Jung (1977) correlated the sea level difference between Pusan and Izuhara with the average geostrophic velocity as well as observed velocity by Lee(1970, 1974) in the western channel of the Korea Strait. In the eastern channel, relation between sea level difference across the strait and current measured using moored current meters was examined by Mizuno *et al.*(1987, 1989). Kaneko *et al.*(1991) also investigated the geostrophic velocity in both channels using towed Acoustic Doppler Current Profiler (ADCP) and CTD observation. Sea level differences between islands are also useful to study the velocity variability of the Kuroshio(Otsuka, 1985; Kawabe, 1988).

Monitoring the current by the sea level data is based on the assumption that the geostrophic condition is satisfied. There have been continuous controversies on the geostrophy in the straits. Shim *et al.*(1984), using the moored-array of current meters and STD data, suggested that the geostrophic estimates of current and volume transport should be made carefully in the western channel of the Korea Strait. KORDI(1990) showed that the average current structure obtained by the towed

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ADCP was in good agreement with the geostrophic velocity in the same channel. By means of the moored current meters in the Striat of Belle Isle about 20 *km* wide and 100 *m* deep between Labrador and New Foundland, Garrett and Petrie(1981) demonstrated that the cross-channel geostrophy enables the flow to be monitored by the sea level observations at both sides.

In the Korea Strait, there have been several studies to establish a statistical relationship between sea level and velocity of the Tsushima Current. Their seasonal or annual variations have also been documented by the previous studies cited above. However, properties of shorter term fluctuations with periods of 5~60 days of sea level and related current should be addressed. In this paper, sea level variability is studied in relation to the variations of current.

Data and Methods

Daily mean sea level data from 1966 to 1987 were excerpted from the results of tidal observation published by the Hydrographic Office of Korea for Pusan and the Japan Maritime Safety Agency for Izuhara and Hakada(Fig. 1). Sea level data at

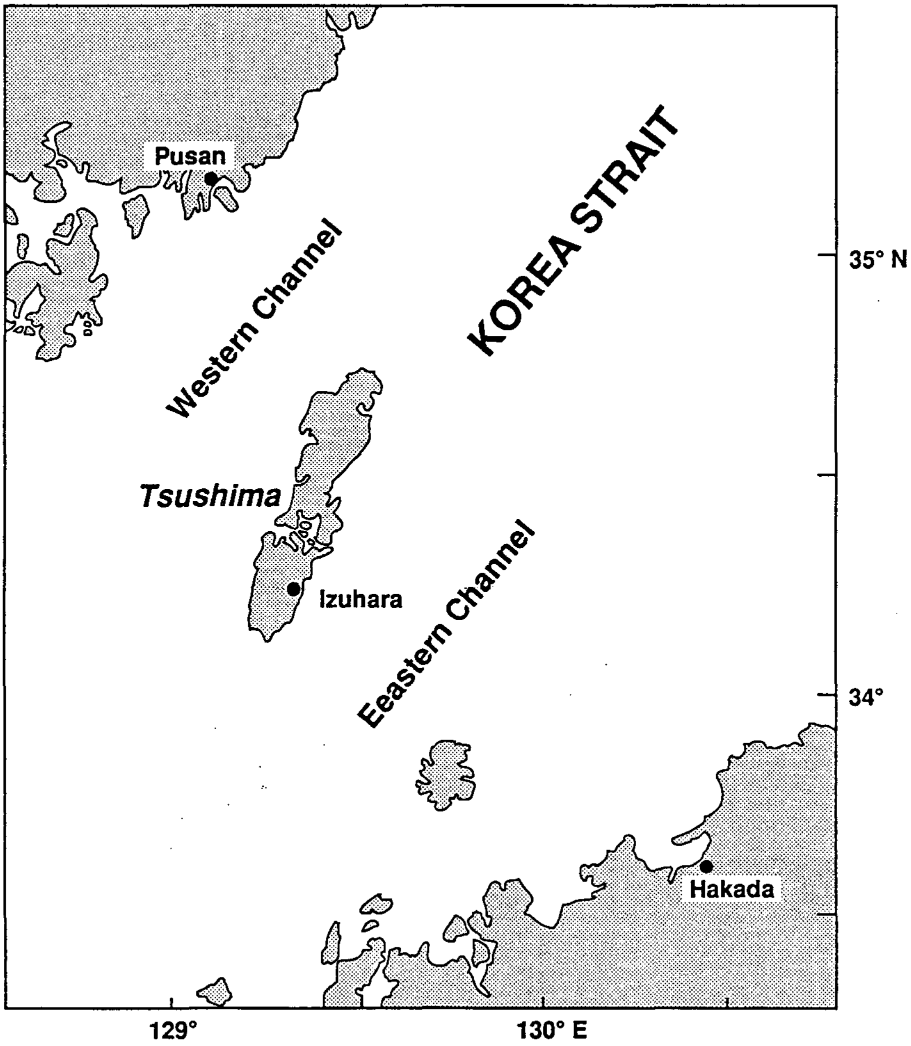

Fig. 1. Location map of the tidal stations in the Korea Strait.

Hakada for the years of 1967, 1968, 1973, 1975, 1985~87 were not available. The available sea level data at Izuhara and Hakada contained many missing data for more than 10 consecutive days. Of these data sets, only those with missing data for less than 6 consecutive days were accepted. Missing data were interpolated linearly. Daily mean sea levels at three locations in the Korea Strait were barometrically adjusted by the daily mean atmospheric pressure at Pusan that is the only data available presently. Barometric adjustment of sea levels at Izuhara and Hakada by the atmospheric pressure at Pusan may cause the error of about 2~3 *cm* at most in general, since they are less than 200 *km* apart from Pusan. Demeaned sea level series were obtained by subtracting the annual mean adjusted sea level for each year. At each location, 10 realizations of annual sea level series were selected for the calculation of the ensemble-averaged autospectra.

Since the main purpose of this study is to investigate the variability of sea levels and their differences in two channels by means of cross spectrum analysis, complete data at all stations are necessary. There were only three years of 1966, 1978 and 1979 in which this required condition was met. The empirical orthogonal function(EOF) analysis, cross correlation and cross coherence analysis were made for these data.

Results and Discussion

Sea Level Variability

From 1966 through 1987, standard deviations of adjusted sea level from the annual means are 0.06~0.09 *m* at Pusan, 0.09~0.11 *m* at Izuhara and 0.10~0.13 *m* at Hakada. Thus the sea level variability is greater in the eastern side of the strait. Fig. 2 shows the time series of three-day moving averaged sea levels at Pusan, Izuhara and Hakada in the year of 1966, 1978 and 1979. In order to include all the time series in a graph, 0.3 *m* and 0.6 *m* were added to the demeaned values of 1978 and 1966 respectively. Since the sea levels at three places cannot be compared by geodetic leveling, demeaned time series in Fig. 2 represent only the relative magnitudes of variation. At Pusan, sea level is relatively higher during winter to spring and lower during summer to fall with respect to the local annual mean compared with other stations. The smallest standard deviation at Pusan is due to this small amplitude of seasonal fluctuations. However, closer examination reveals that the fluctuations with periods of about 10~15 days are generally greater at Pusan than at Izuhara or Hakada. A comparison of the individual peaks and troughs of sea level at three stations reveals that Pusan and Izuhara have the same tendency of variations.

The results of the empirical orthogonal function (EOF) analysis of sea levels are summarized in Table 1. The first and the second mode can explain about 90% and 6~9% of the total variance respectively. The same sign of the eigenvectors of the first mode indicates that the sea level fluctuations are in unison. Hakada has the largest value of eigenvector and Izuhara has similar magnitude while those of Pusan are smaller by the factor of two in 1978 and 1979. The smallest eigenvector of the first mode at Pusan is related to the smallest seasonal variation. The second and the third mode with eigenvectors of different signs represent the

Table 1. Results of the empirical orthogonal function analysis for adjusted sea level at Pusan, Izuhara and Hakada.

1966			Eigenvectors		
	Eigenvalue	Percentage	ϕ_{PS}	ϕ_{IZ}	ϕ_{HA}
model 1	0.0313	89.18	0.41	0.63	0.66
model 2	0.0031	8.83	-0.86	0.03	0.51
model 3	0.0007	1.98	0.30	-0.78	0.55

1978			Eigenvectors		
	Eigenvalue	Percentage	ϕ_{PS}	ϕ_{IZ}	ϕ_{HA}
model 1	0.0238	91.62	0.33	0.65	0.68
model 2	0.0018	6.94	-0.77	-0.23	0.59
model 3	0.0004	1.44	0.54	-0.72	0.43

1979			Eigenvectors		
	Eigenvalue	Percentage	ϕ_{PS}	ϕ_{IZ}	ϕ_{HA}
model 1	0.0301	92.04	0.36	0.64	0.67
model 2	0.0020	6.09	-0.74	-0.23	0.63
model 3	0.0006	1.87	0.56	-0.73	0.39

components of fluctuation that are out of phase. The absolute values of the second-mode eigenvector are greatest at Pusan and smallest at Izuhara. Fig. 3 is an example of the decomposed time series of sea level in 1978. First two modes are presented because the contribution of the third mode is very small. Evidently the seasonal variations are contained in the first mode.

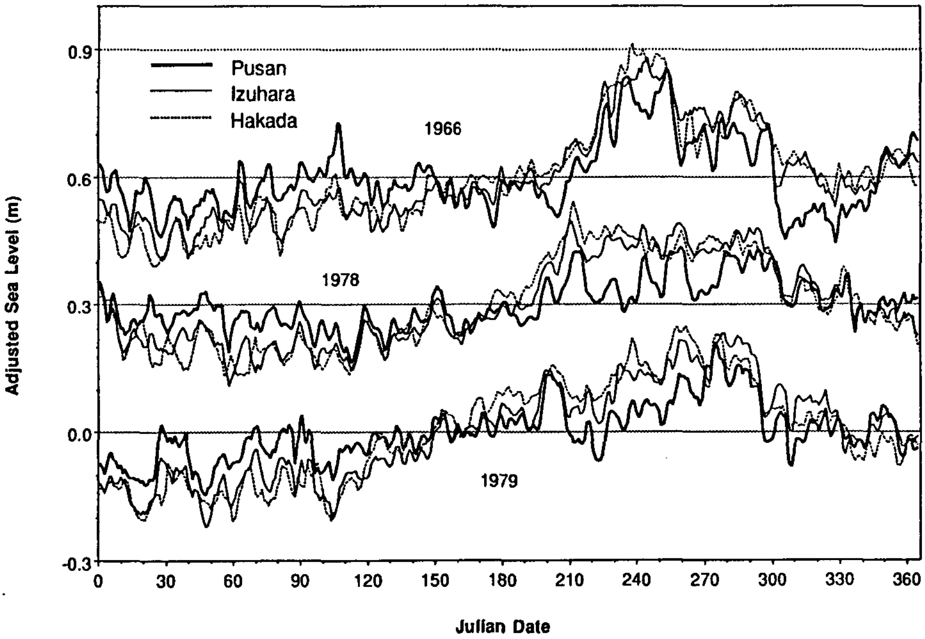

Fig. 2. Time series of 3-day moving averaged sea level at Pusan, Izuhara and Hakada.

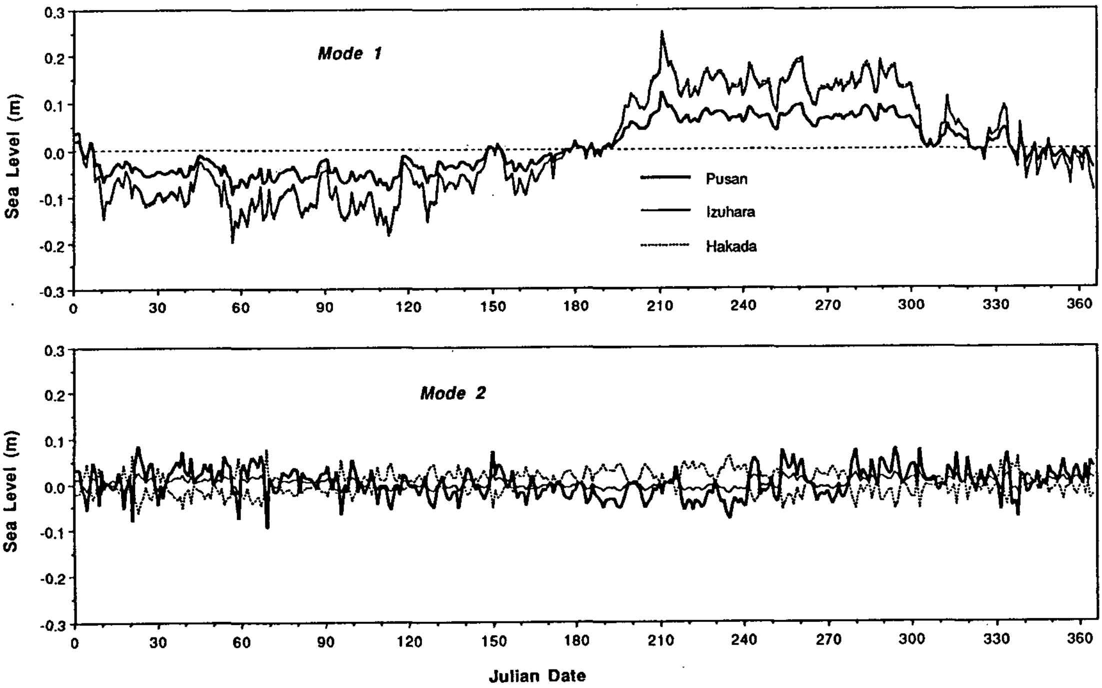

Fig. 3. Decomposed time series of sea level by EOF in 1978.

Fig. 4 shows the autospectra of sea level. In this case, ensemble-average method was applied to the same frequencies after computing raw spectral density for annual time series of 10 years. The first peak at low frequency corresponds to the annual cycle. At Pusan, low-frequency variability with longer period than 100 days is smallest whereas the higher frequency components are greatest. Significant peaks near the 0.07 cycles per day(cpd) may be due to the semimonthly tidal oscillation.

Correlation coefficient of sea levels between Pusan and Izuhara is 0.79 in 1966 and 0.87 in 1979. For the eastern channel, Izuhara-Hakada coefficient is always higher than 0.92. This significant correlation is investigated in the frequency domain by means of the coherence analysis(Fig. 5). Because the graphs for individual years have virtually the same feature, only the averaged values for three years are shown. Left parts of the Fig. 5 are graphs of coherence squared(upper) and phase in degree (lower) between Pusan and Izuhara. Sea levels at

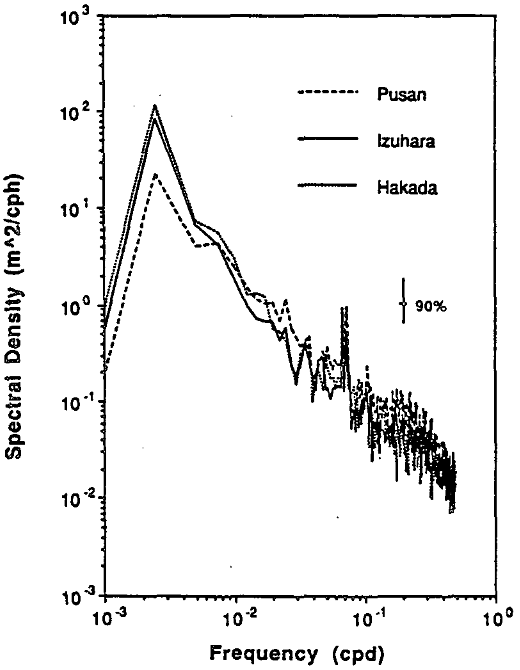

Fig. 4. Autospectra of sea level at Pusan, Izuhara and Hakada.

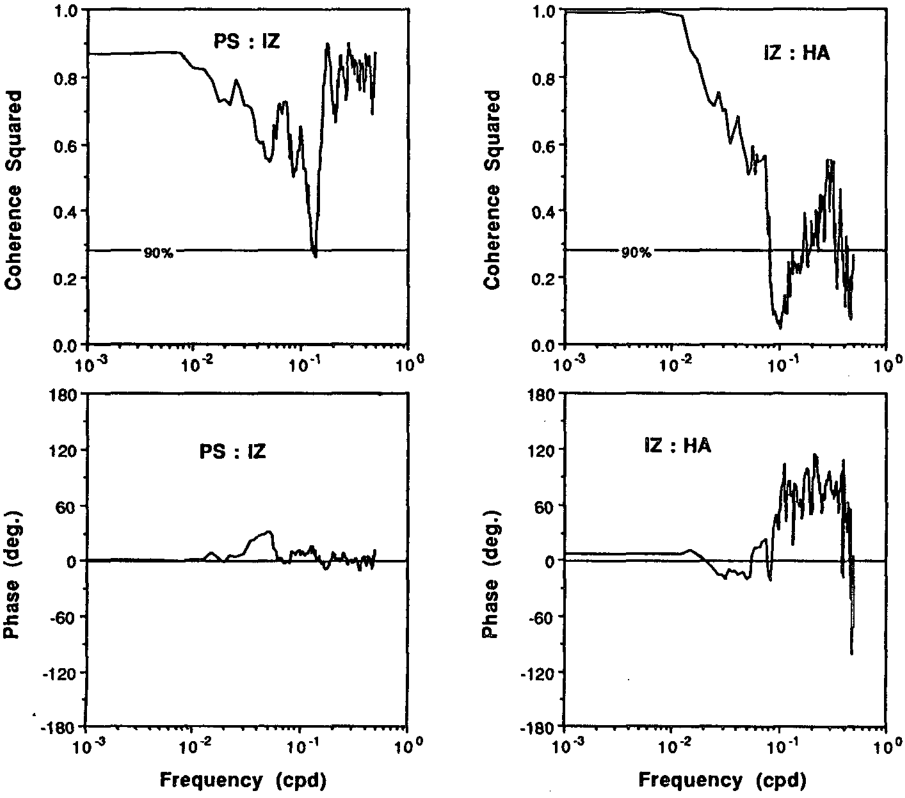

Fig. 5. Coherence and phase of sea levels at Pusan, Izuhara and Hakada.

two stations are significantly coherent at almost all the frequency except for the narrow band near 0.15 cpd. Confidence limit for the phase estimate depends on the coherence squared as well as the degrees of freedom. Positive(negative) phase less than 90° means that the first(second) time series leads the second(first) one. Phase graph indicates that the sea level fluctuations are fundamentally in phase as can be seen in Fig. 2. Therefore, sea levels fluctuate simultaneously at both locations because of the seasonal thermosteric effect. The smallest spectral density of Pusan may be due to the seasonal changes in the strength of the Tsushima Current and prevailing monsoon wind that have negative effects on the thermosteric variations. For example, intensification of the current and southerly winds in summer will reduce the thermosteric rising of sea level at Pusan. Since Izuhara is located on the eastern side of Tsushima, the same result may be expected. However, the island system with a length scale of about 70 *km* does not seem to be sensitive to those negative effects having seasonal period. Lee(1983) showed that the daily mean sea level variability along the southeast coast of Korea is susceptible to longshore wind in summer. Using the monthly mean sea level data, Kang and Lee(1985) showed that the west coast has larger amplitude of sea level variations than the east coast because of both seasonal monsoon wind and thermosteric effect. These two factors have a negative effect on the thermosteric rise of sea level at Pusan thus reduce the seasonal variation. Coherence between Izuhara and Hakada(right part of Fig. 5) in the eastern channel is close to unity at lower frequency than 0.08 cpd and small positive phase less than 10° indicates that Hakada leads slightly Izuhara. For example, phase lag for the annual variation is about a week. Low coherence near 0.1 cpd is a common feature.

At higher frequency than 0.2 cpd they are marginally coherent, and positive phase lag also means that Hakada leads Izuhara as pointed out in Fig. 2 although it contains the increased error due to the low coherence. Coherence analysis for both channels commonly demonstrates that the sea levels are incoherent in the period of 5~10 days. More detailed study is necessary to explain this phenomenon. It should also be noted that the coherence at the semimonthly tidal frequency is not very high.

Variability of Sea Level Difference

Sea level difference(SLD) across the strait can be used as an indicator of average current velocity. Time series of SLD in western(Izuhara-Pusan) and eastern channel(Hakada-Izuhara) are shown in Fig. 6. The numbers at the vertical axis are meaningless because 0.2 and 0.4 *m* were added to the series of 1978 and 1966 for effective presentation. In order to suppress the extraordinary spikes three-day moving average was taken again. Although sea levels vary in the same manner(Fig. 2), SLD does not. In the western channel, SLD has larger amplitude of annual variation compared to the eastern channel. However, short term variability is greater in the eastern channel. In the western channel, there is a distinct increase in SLD from spring to summer as also demonstrated by Kawabe(1982). In the eastern channel, on the other hand, such a tendency is much weaker. It is noticed that mirror images between the two series are not uncommon. This means that SLD's in both channels vary frequently in opposite ways. Relative importance of this component can be assessed by EOF analysis of SLD.

EOF analysis of SLD(Table 2) reveals that the

Table 2. Results of the empirical orthogonal function analysis for sea level difference in the western and eastern channel of the Korea Strait.

1966			Eigenvectors	
	Eigenvalue	Percentage	ϕ_W	ϕ_E
model 1	0.0048	71.90	0.98	0.19
model 2	0.0019	28.10	-0.19	0.98

1978			Eigenvectors	
	Eigenvalue	Percentage	ϕ_W	ϕ_E
model 1	0.0038	71.90	0.98	0.22
model 2	0.0016	28.10	-0.22	0.98

1979			Eigenvectors	
	Eigenvalue	Percentage	ϕ_W	ϕ_E
model 1	0.0039	63.56	0.99	0.16
model 2	0.0022	36.44	-0.16	0.99

concurrent first mode explains only 64~72% of the total variance whereas the out-of-phase second mode possesses up to 36%. Absolute magnitude of eigenvectors implies that the first mode variability is dominated by the western channel and the second mode by the eastern channel. Since SLD can be a measure of current velocity, these results of EOF analysis are interpreted as follows. When the Tsushima Current gets stronger in both channels simultaneously, current is predominantly intensified in the western channel. Close investigation of Fig. 6 reveals that this phenomenon occurs chiefly in summer to fall. There is also considerable portion responsible for the opposite-way variations in which the current gets stronger dominantly in the eastern channel when it becomes weaker in the western channel. Fig. 6 also shows that this occurs mostly in winter. More detailed observations are needed to clarify if the Tsushima Current is stronger in the eastern channel during winter.

Band-averaged autospectra of SLD are shown in Fig. 7. The results for three years commonly illustrate that SLD in the western channel has much greater energy at lower frequency than 0.02 cpd but smaller at higher frequency compared to the eastern channel. In the frequency band of 0.01~0.02 cpd there is a rapid decrease of the spectral density in the western channel. From the time series, EOF analysis and the autospectra the following interpretation is possible. The seasonal variation with period longer than 100 days of the Tsushima Current is predominant in the western channel whereas the temporal variability with higher frequency is greater in the eastern channel. It has

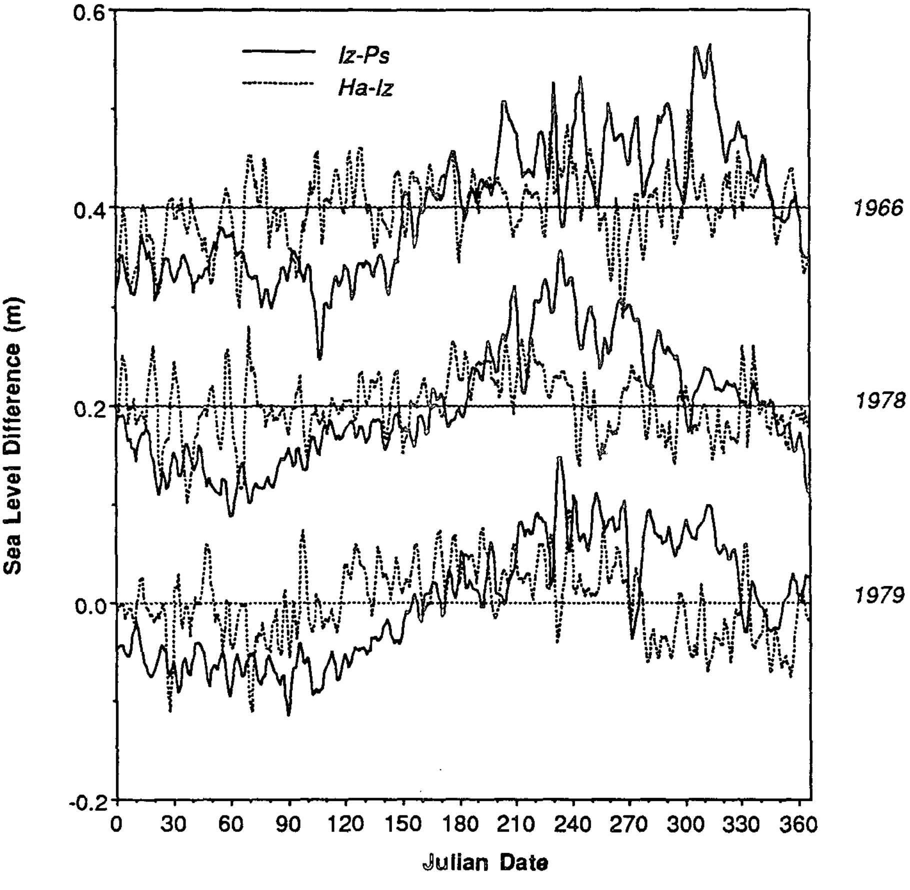

Fig. 6. Time series of 3-day moving averaged sea level difference in the western(Iz-Ps) and eastern(Ha-Iz) channel of the Korea Strait. 0.2 and 0.4 *m* were added to the series of 1978 and 1966 respectively.

been known that the Tsushima Current is stronger in the western channel than in the eastern channel. But it is not easy to explain why the short-term variability appears greater in the eastern channel. As discussed before, response of Tsushima to long-term wind variations may not be large. For the wind forcing of high frequency, both sides of Tsushima with small horizontal length scale may respond in opposite way. Because the only tidal station faces the eastern channel, short-term SLD can be larger across the eastern channel.

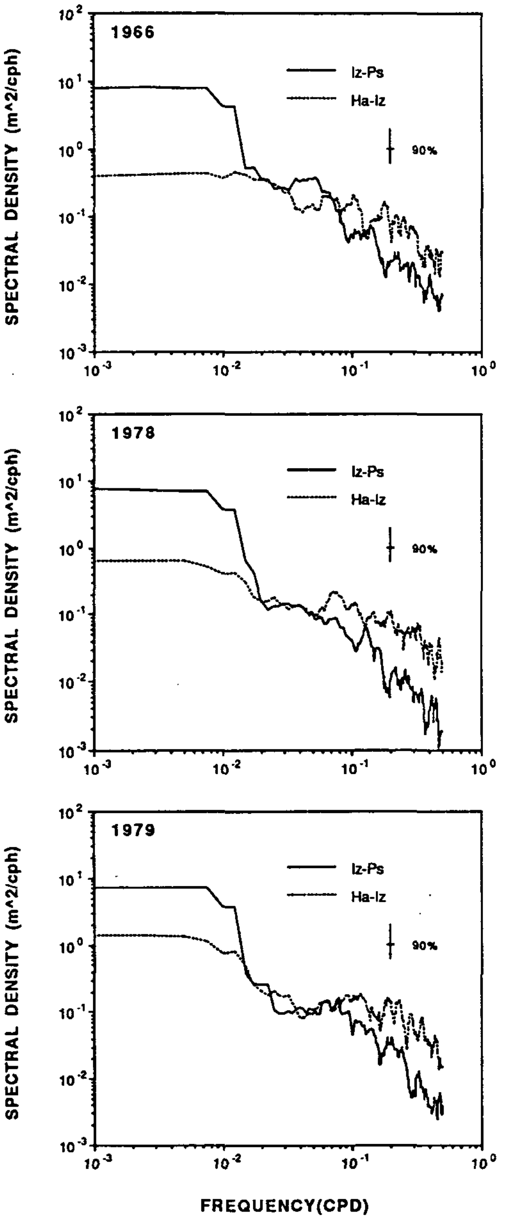

Fig. 7. Autospectra of sea level difference.

Cross-spectrum of SLD(Fig. 8) shows that there is a significant coherence only at low frequency of seasonal period. Phase relation suggests that SLD in the eastern channel leads that in the western channel at annual period by about a month. This means that the intensification or weakening of current begins earlier in the easternh channel. At higher frequency temporal variability of SLD for both channels is incoherent with each other. This lack of coherency and the greater short-term variability of SLD in the eastern channel are discussed again in the next section.

Coherence of Sea Level and SLD

Coherence analyses of SLD and sea level at both

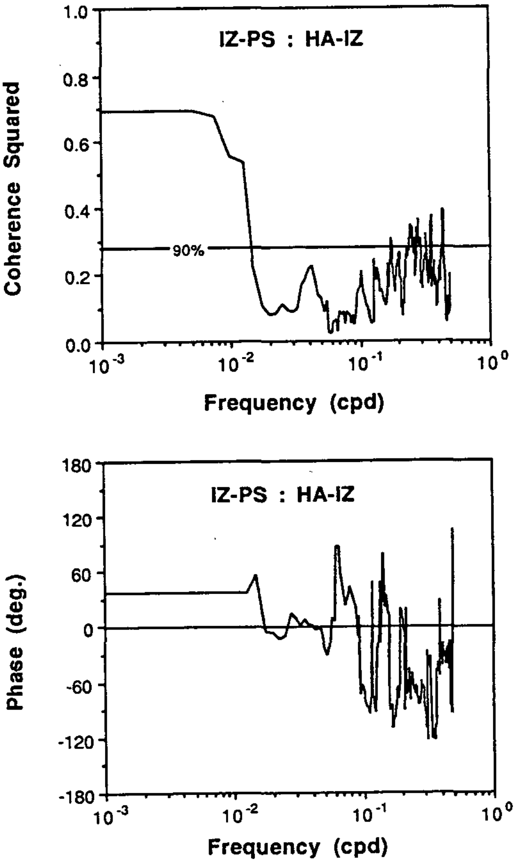

Fig. 8. Coherence and phase between sea level differences.

sides of each channel were made in order to study the phase relationship. As the Tsushima Current gets stronger SLD is also expected to increase correspondingly. Stommel(1967) proposed that the sea level drops along the Florida coast when the Florida Current becomes strong from Key West to Miami. There may be three ways for SLD to increase. First is the concurrent but differential increase of sea level at both sides. Second is the sea level change in opposite direction. Third is the major fluctuations in sea level occurring at one side only. Time series of sea level at three stations(Fig. 2) precludes the third possibility. EOF analysis of sea level(Table 1) reveals that the first way(first mode) is predominant and would be responsible for the low-frequency variation. A question remains though. If the two ways are possible, which one is relevant to the different time scales of current(or SLD) fluctuations?

Fig. 9 shows the results of the coherence analysis between sea level at Pusan or Izuhara and SLD in the western channel in 1966(left part), 1978(central part) and 1979(right part). Phase lags are represented by the scatter plots at coherent frequencies only in order to avoid the confusion. Positive (negative) phase less than 90° means that the first (second) time series leads the second(first) one by $|\varphi|$, where $|\varphi|$ is the absolute value of the phase. Phase larger than 90° indicates that there is an inverse coherence, *i.e.,* the increase of a series leads or lags behind the decrease of the other by $180° - |\varphi|$. Low-frequency oscillations of both sea level and SLD are significantly coherent with each other except at Pusan in 1966. There are irregular distributions of coherent bands at higher frequency than 0.01 cpd. Phase graphs reveal a striking feature. Phase lags are very small at low frequency while they have a tendency to distribute near ±180° at high frequency that is more distinct at Pusan than at Izuhara. Although Izuhara has somewhat greater coherence and smaller phase lag than Pusan in the low frequency band, phases at both places are close to zero. Therefore, long-period sea level fluctuates in unison at both sides but to a less extent at Pusan as explained already and this difference is a cause of SLD. Seasonal variation of thermosteric effect causes the sea levels to rise in summer and drop in winter simultaneously

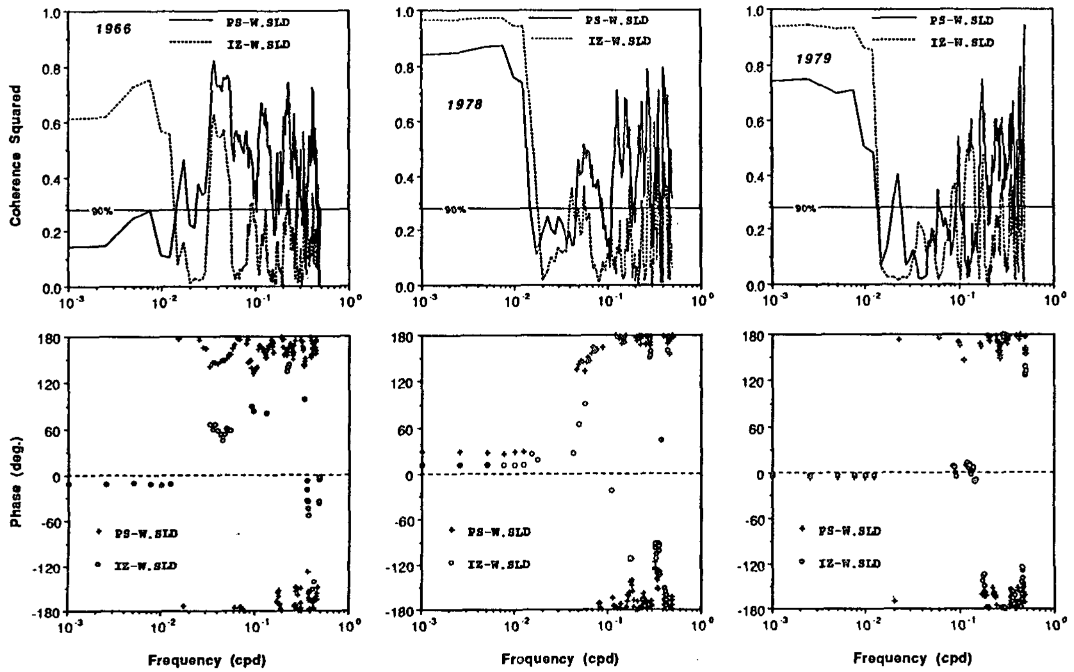

Fig. 9. Coherence and phase of sea level at Pusan/Izuhara *vs.* sea level difference in the western channel(Iz-Ps).

at both sides. SLD is produced by the geostrophic effect of the Tsushima current which is strongest in summer and monsoon effect as elucidated by Kang and Lee(1985). As a result, low-frequency SLD also fluctuates in phase with sea levels.

At higher frequency, sea level drops at Pusan to a greater extent than at Izuhara as SLD increases (180° out of phase which is less obvious) with the strength of the Tsushima Current. Because the overall thermosteric effect due to the heating and cooling of the water column is negligible for short period of fluctuation, dynamic effect may be predominant for sea level change. However, there are some difficulties to interpret this result because the tidal station is on the eastern side of the Tsushima islands. Since the Tsushima lies a little obliquely in the strait, there might be sea level slope along the coast of the islands to some extent. Furthermore, sea levels may have different response at both sides to the longshore wind and geostrophic current. If there is an additional tide gauge on the western side, we would get more correct results.

The same technique is applied to the eastern channel in Fig. 10. Coherence and phase relations of the sea level at Izuhara *versus* SLD have virtually the same result as Fig. 9 for the western channel. Phase relation of 180° is evident in the high frequency band. However, Hakada no longer has phase of 180° with SLD in the eastern channel. Coherence is generally significant except for a few frequency bands between 0.01 and 0.1 cpd. SLD appears to lead the sea level variation at Hakada by about 60° at low frequency and by lesser degree at higher frequency. At high frequency, SLD seems to lead the sea level at Hakada. In summary, higher frequency oscillation of sea level is 180° out of phase with SLD at Izuhara while in phase at Hakada. This seems to be a normal response for a channel flow since the along-channel wind and cross-channel geostrophy will cause the sea level to rise and fall in opposite direction on both sides of a channel. Mizuno *et al.*(1989) found out that the current in the eastern channel is coherent in 0.3~0.4 cpd range with the northeast component of wind which is the along-channel direction. Consequently, greater spectral density in the eastern

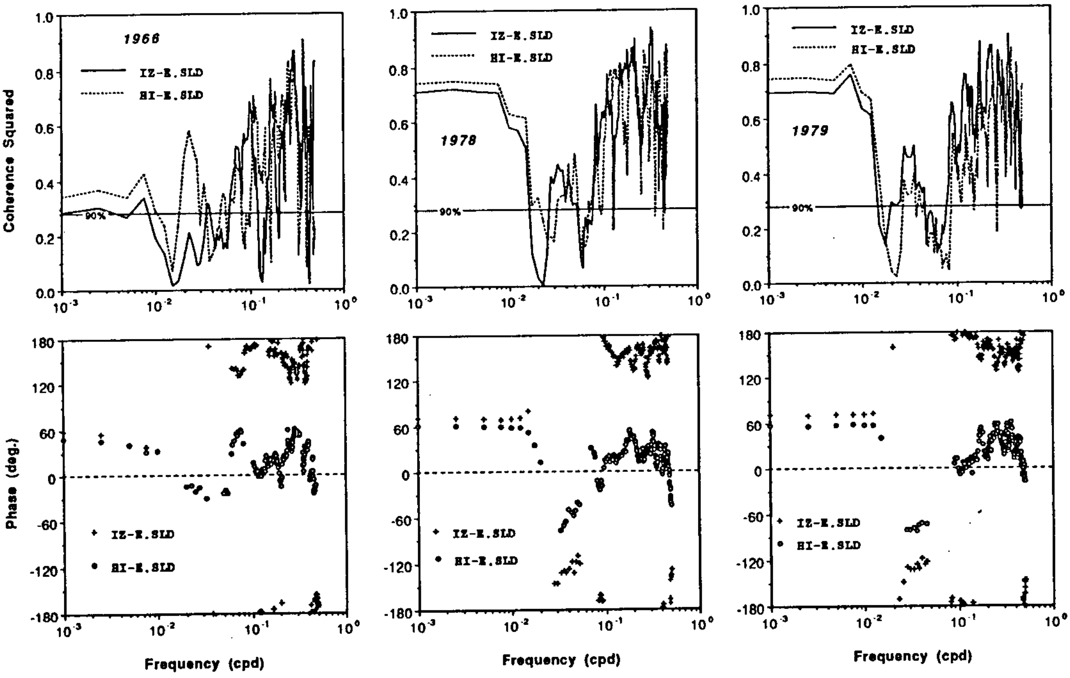

Fig. 10. Coherence and phase of sea level at Izuharta/Hakada *vs.* sea level difference in the eastern channel (Ha-Iz).

channel is also associated with the fact that Izuhara faces the eastern channel. For SLD of the western channel, both of Pusan and Izuhara have 180° phase relation. It is noted that, at high frequency, Izuhara sea-level is more coherently related with SLD in the eastern channel(Fig. 10) than the western channel(Fig. 9).

Summary

Variability of sea level and SLD in the Korea Strait is investigated in time and frequency domain to study the fluctuations of the Tsushima current and related sea level oscillation. With respect to the 0.01 or 0.02 cpd, spectral properties of sea level and SLD fluctuations can be separated into lower-frequency and higher-frequency parts.

For the lower frequency part, sea levels and SLD in both channels vary in phase with each other but Pusan has the smallest magnitude of sea level variation. Without strong current and wind, seasonal variation of the thermosteric effect may yield similar amiplitudes of sea level change. Not only the geostrophic effect of the Tsushima Current but monsoon has the negative influence on the seasonal fluctuations of sea level at Pusan and additive result on the eastern side of a channel thus generates SLD. Spectral density of SLD is much higher in the western channel manifests that the seasonal variation of the Tsushima Current overwhelms that of the eastern channel. Sea level differences in both channels are coherent only at low frequency. Since Izuhara faces the eastern channel where the Tsushima Current is much weaker, the geostrophic effect may be different from that of Pusan.

At higher frequency, variability of SLD appears to be greater in the eastern channel. This does not mean that the current variability is stronger in the eastern channel. Sea levels at Pusan and Izuhara are essentially 180° out of phase with SLD in the western channel but the coherence is considerably lower at Izuhara. Therefore, sea level is expected to drop dominantly at Pusan as the current gets stronger. In the eastern channel, the Izuhara level is about 180° out of phase whereas the Hakada level is approximately in phase with SLD. This result is regarded as normal for channel flow and implies that sea level drops at Izuhara and rises at Hakada as the current becomes strong thus increases SLD in the eastern channel. This phenomenon can be explained by the temporal variation of synoptic scale wind and the fact that Izuhara faces the eastern channel in addition to the geostrophic effect. For the wind parallel to the direction of the channel, sea level will rise on one side while it will fall on the opposite side in the absence of the thermosteric influence for the temporal time scale. The geostrophy also enhances the same effect in summer. Across the eastern channel this process is obvious. If there is an additional tidal station on the west coast of the Tsushima islands, western channel would yield the similar result.

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대마난류와 관련된 대한해협 해수면의 변동

이재철 · 조규대 · 김순영 · 김호균 · 심태보*
부산수산대학교 해양학과
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대한해협을 통해서 흐르는 대마난류의 변동을 연구하기 위하여 부산, 이즈하라, 하카다 해수면의 시계열 자료를 분석하였다.

해수면 및 해수면차의 변동성은 0.01~0.02 cpd 를 중심으로 두 부분으로 구분된다. 저주파에서 해수면과 해수면차는 상관성이 높으며 위상차는 작다. 부산 해수면의 계절변화 폭은 다른 두 곳보다 작은데 이것은 지형류 효과와 계절풍의 영향이 밀도의 계절변화 효과를 상쇄하기 때문이다. 대마난류의 세기와 관련이 있는 해수면차의 변동은 동수도에 비해 서수도에서 매우 크다.

고주파 부분에 있어서 동수도의 해수면차는 그 변동성이 서수도에 비해 크고 양수도의 해수면차는 서로 상관성이 없다.

부산과 이즈하라의 해수면은 각각 서수도와 동수도에서의 해수면차와 180° 위상차가 나는 반면에 하카다에서는 같은 위상을 가진다. 이 결과는 이즈하라가 동수도쪽에 위치함으로써 동수도의 해수면은 바람과 지형류 효과에 대해 정상적인 반응을 한다는 것을 나타낸다.