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Variability of Sea Levels at Mukho and Ullungdo off the East Coast of Korea

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Variability of sea levels at Mukho and Ullungdo and sea level difference(SLD) associated with current is investigated. Time series of adjusted sea levels at both places have very similar pattern of change. Two components appear to contribute to the correlation between sea level and SLD. Low frequency thermosteric effect causes the sea level to rise and fall at the same time. Geostrophic effect of major currents is responsible for the sea level change in opposite ways at both sides. Two contributions have a cancelling effect for sea level change at Mukho while they are additive at Ullungdo. Characteristics of time series in frequency domain are divided into two parts with respect to 0.01 cycles per day(cpd). At Mukho, the cancelling effect yields small values of coherence for low-frequency bands whereas the dominant geostrophic influence may be responsible for the phase relations of about ±180° between sea level and SLD at higher frequency. Bimonthly dynamic height difference(DHD) between Mukho and Ullungdo is very significantly correlated with SLD. This result suggests that DHD thus the average velocity of current through the Mukho-Ullungdo section can successfully be diagnosed by the sea level records at both locations. For the annual variations, maximum SLD occurs at Mukho-Ullungdo section about 40 days later than the Korea Strait.

Introduction

East Korea Warm Current(EKWC) flows northward after branching from the Tsushima Current and meets the North Korea Cold Current(NKCC) at 38~39°N. EKWC forms the polar front after leaving the coast at this latitude. Meandering of EKWC and a large warm water mass near Ullungdo are permanent features off the east coast. This warm water is referred to as the Ullung warm lens(Cho *et al.*, 1990) or Ullung warm eddy(Seung *et al.*, 1990). Kang and Kang(1987, 1990, 1991) studied the thermal structure and its spatial and temporal variations off the east coast related with this permanent warm water mass. Na(1988) and Na and Han(1988) suggested that the wind stress distribution be favorable for the formation of the warm core near Ullungdo.

The warm water mass around Ullungdo is because EKWC usually passes through the cross section between the east coast and Ullungdo then deflects to the right. Yi(1967) proposed that the large variance of monthly mean sea level at Ullungdo might be associated with the path variations of EKWC. Chu(1991) suggested that the condition of EKWC can be monitored by means of the tidal records at the east coast and Ullungdo. In principle, geostrophic effect of EKWC will be reflected in the tidal records. However, since the distance between the east coast and Ullungdo of about 150 *km* is much larger than the baroclinic Rossby radius, some eddies or meanders of EKWC may compli-

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cate the situation. Because Ullungdo is a small island, the response of sea level to winds may be quite different from that of the east coasts. In this study the time series of daily mean sea levels at Mukho and Ullungdo(Fig. 1), their differences and bimonthly hydrographic data are analyzed to investigate the variability of sea levels is relation to EKWC.

Data and Method

Daily mean sea level data at Mukho and Ullungdo from 1982 through 1989 was adjusted barometrically using the corresponding local atmospheric pressure data. Time series of sea level difference(SLD) were obtained by subtracting the adjusted sea levels at Mukho from the those at Ullungdo. Annual time series for eight years were selected. From these time series, autospectra, coherence squared and phases were computed. Using the bimonthly hydrographic data of 1982~88 by the National Fisheries Research and Development Agency, dynamic height anomaly was calculated along the Line 105 between Mukho and Ullungdo and the Line 207 in the Korea Strait. Since the primary interest was to compare the difference in hights of the total water column across the sections, dynamic

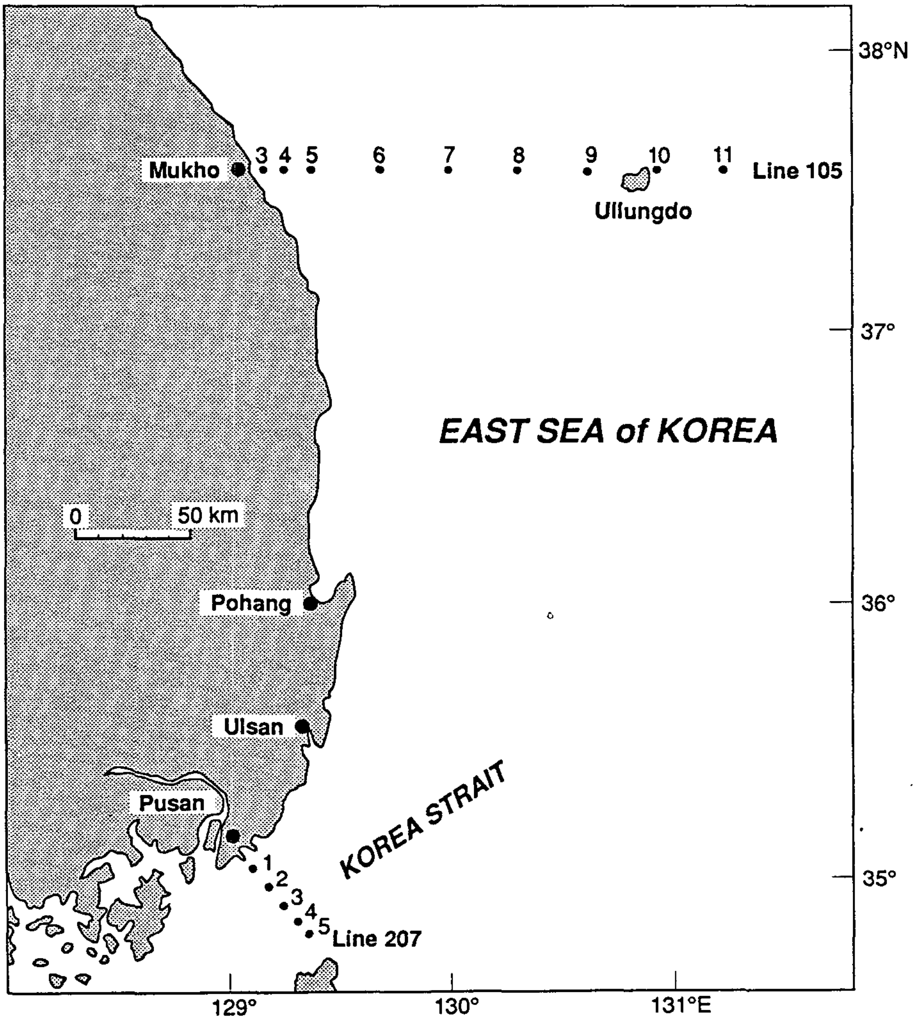

Fig. 1. Location map showing the tidal stations and positions of hydrographic observation.

height anomaly was integrated from the bottom or the deepest level available to the surface. From St. 6 to St. 11 of Line 105 where the water depth exceeds 500 *m*, dynamic height anomaly was integrated from 500 *m* to the surface because the data was not available in deeper layers. Dynamic height difference(DHD) was obtained from the dynamic height anomalies between two stations. With respect to the date of hydrographic observations, five-day mean SLD's were calculated for the comparison with the DHD at both cross-sections. This SLD and DHD data were used for computing the correlation coefficients.

Results and Discussion

Variability of Sea Level

Fig. 2 is the three-day moving averaged time series of daily mean sea level adjusted barometrically at Mukho(solid line) and Ullungdo(dashed line) for eight years from 1982 through 1989. To present all the time series in one graph, integral multiple of 0.3 *m* was added to the demeaned annual data from the lower part. Therefore, the values from -0.3 to 2.4 at the ordinate of Fig. 2 are meaningless. Since the annual mean was subtracted from the individual time series, Fig. 2 represents only the relative magnitudes from the local annual mean values so that the sea levels at two locations cannot be compared absolutely. Both stations have similar pattern of variations to each other. Sea level is low in February to April and high in August to October. At first glance the seasonal variation is clearly greater at Ullungdo as pointed out by Yi(1967). Maximum sea level appears to occur in August to September at Mukho while in September to October at Ullungdo. In 1985, sea level was extraordinarily low in March to April. It is remarkable that even shorter term fluctuations take place concurrently at both places.

Sea level difference(SLD) was obtained by subtracting the adjusted sea level at Mukho from that of Ullungdo. Absolute values of SLD are not meaningful since the sea levels at both sites cannot be related geodetically. Time series of SLD is shown in Fig. 3. Three-day moving average was not taken in this case so that several unusual spikes on the SLD curves were not removed. The time of hydrographic observations on the Line 105 is marked by the crosses on each curve to illustrate the state of SLD during the observations. SLD representing the strength of EKWC is generally small in March to April and large in September to October. Abrupt changes in SLD are not uncommon. With respect to the annual means, very small SLD occurred at the end of July and August in 1982, in July of 1985 and in September of 1983, 1984, 1987 and 1988. SLD was extraordinarily large in June to July of 1987. Since the sea levels change in unison at both places(Fig. 2), SLD is produced by the difference in magnitude of change.

Statistics of the adjusted sea level and SLD is given in Table 1. Because the sea levels at both places cannot be compared geodetically, annual

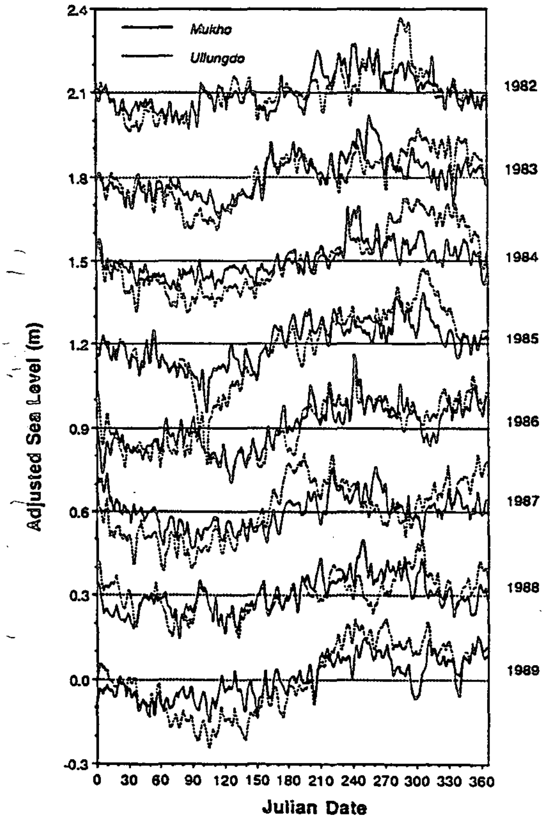

Fig. 2. Time series of adjusted sea level with 3-day moving average at Mukho and Ullungdo.

Table 1. Mean ± standard deviation of sea levels at Mukho and Ullungdo and their differences (*cm*).

	Mukho	Ullungdo	SLD
1982	-2.5 ± 7.0	-1.2 ± 8.4	1.3 ± 5.7
1983	-0.2 ± 7.6	0.8 ± 9.1	1.0 ± 6.2
1984	0.0 ± 6.5	-0.7 ± 11.3	-0.7 ± 7.9
1985	-1.8 ± 8.1	3.7 ± 12.5	5.5 ± 7.1
1986	1.0 ± 8.6	-7.5 ± 9.2	-8.5 ± 5.0
1987	0.9 ± 6.7	-2.1 ± 10.6	-3.0 ± 8.4
1988	0.1 ± 7.1	1.0 ± 7.3	0.9 ± 6.1
1989	2.6 ± 7.7	5.6 ± 12.5	3.0 ± 7.6

mean values of sea level are calculated from the demeaned values of total time series for eight years. As a result, annual means of sea level and SLD are meaningful only for their year-to-year variations. Average standard deviation is 7.6 *cm* at Mukho and 10.9 *cm* at Ullungdo for the whole period of 8 years. Each annual data has ranges of 6.5~8.6 and 7.3~12.5 *cm* at Mukho and Ullungdo respectively. Annual mean of SLD varying from -8.5 *cm* in 1986 to 5.5 *cm* in 1985 has a range of 14 *cm*. Standard deviation of SLD is 7.9 *cm* on the whole and varies from 5.0 *cm* in 1986 to 8.4 *cm* in 1987. Sea levels in 1986 have two unusual features. First, the annual mean value is high at Mukho(1.0 *cm*) while very low at Ullungdo(-7.5 *cm*). Second, the standard deviation is of the similar magnitude for sea level but it is the smallest for SLD. One of the plausible explanation may be that the EKWC did not pass the section of Line 105 and/or the southward flow of NKCC was stronger than other years. More detailed investigation about this result is not made in the present study. Same trend also appears to continue in 1987 but larger variability at Ullungdo results in the greatest standard deviation of SLD.

Fig. 4 shows the autospectra of sea level and SLD where the eight annual realizations were ensemble-averaged at each frequency. The first significant peaks represent the annual variations. Significant peak at about 0.07 cycles per day(cpd) corresponds to the semimonthly tidal component. Evidently the sea level variability is greater at Ullungdo for frequencies lower than 0.03 cpd. SLD has the similar trend of variability to those of sea level.

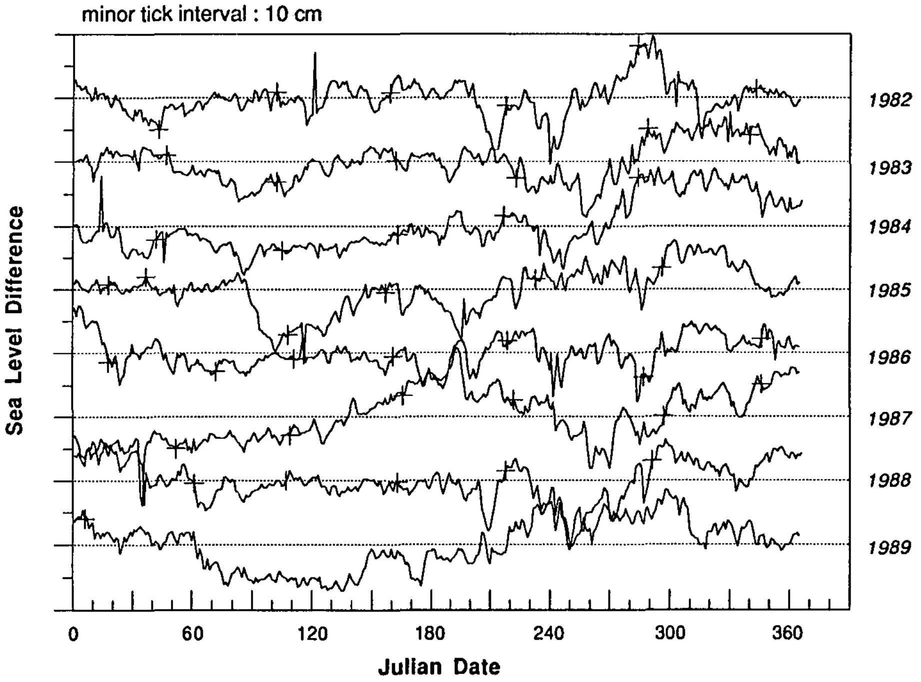

Fig. 3. Time series of sea level difference between Ullungdo and Mukho.

Correlation of sea levels and sea level *vs.* SLD is shown in Table 2. Sea levels at both sites are correlated significantly with each other. Sea level *vs.* SLD is generally significant at Ullungdo but not at Mukho. This result simply indicates that the greater variability at Ullungdo is much more responsible for the SLD. It is a characteristic feature that Mukho is negatively correlated with SLD when Ullungdo has low correlation coefficient less than

Table 2. Correlation coefficients of sea levels at Mukho (MH) and Ullungdo (UL) and their differences.

	MH : UL	MH : SLD	UL : SLD
1982	0.74	-0.15	0.55
1983	0.74	-0.14	0.56
1984	0.73	0.22	0.83
1985	0.85	0.36	0.80
1986	0.85	-0.15	0.40
1987	0.62	0.00	0.78
1988	0.64	-0.41	0.45
1989	0.82	0.33	0.81

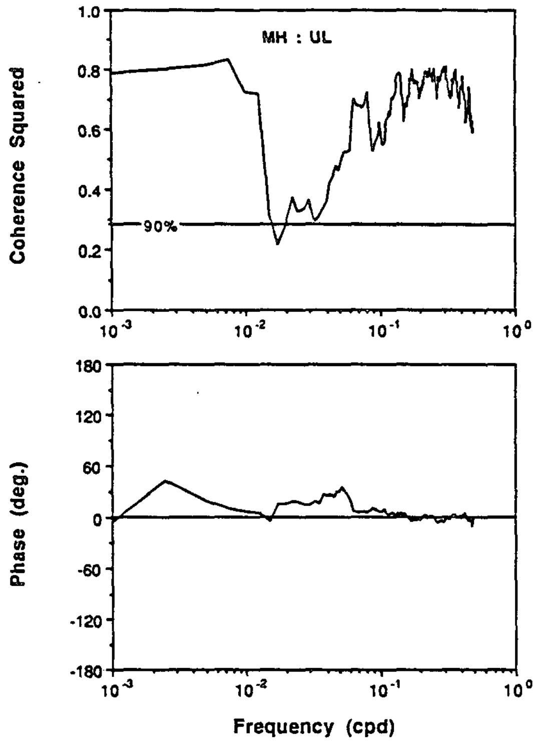

Fig. 5. Coherence and phase relation of sea level between Mukho and Ullungdo.

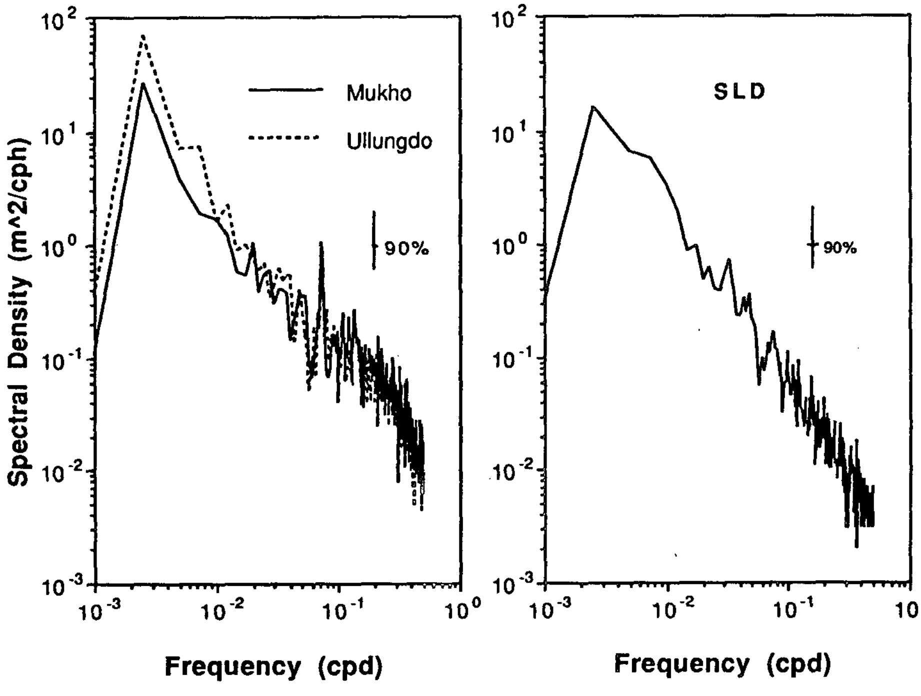

Fig. 4. Autospectra of sea level at Mukho and Ullungdo(left) and SLD(right).

0.6. Whenever Mukho has a positive but small coefficient Ullungdo has a large value. Therefore, the characteristics of sea level variability may be classified into two cases. First, the increase of SLD is caused by the sea level oscillations in the opposite direction at both sides that will yield negative correlation. Second, sea levels fluctuate concurrently but SLD is predominantly caused by the larger amplitude at Ullungdo that will yield positive correlation. Relative dominance of the two contributions will affect the sign as well as the magnitude of the correlation coefficient. More detailed analysis should be made in the frequency domain.

To examine the correlation in the frequency domain, cross-spectral analyses have been carried out. Fig. 5 shows the relation of sea levels at both places. Since the coherence squared and phase have virtually the same feature every year, only mean values are plotted. Sea levels are significantly coherent at almost all the frequencies except for a band of about 0.015～0.04 cpd corresponding to periods of 25～67 days. Negative(positive) phase whose absolute value |φ| is less than 90° means that the first(second) time series leads the second (first) one by |φ|. Phase graphs demonstrate that the sea levels at both places fluctuate almost concurrently at all frequency.

Relations between sea levels and SLD are shown

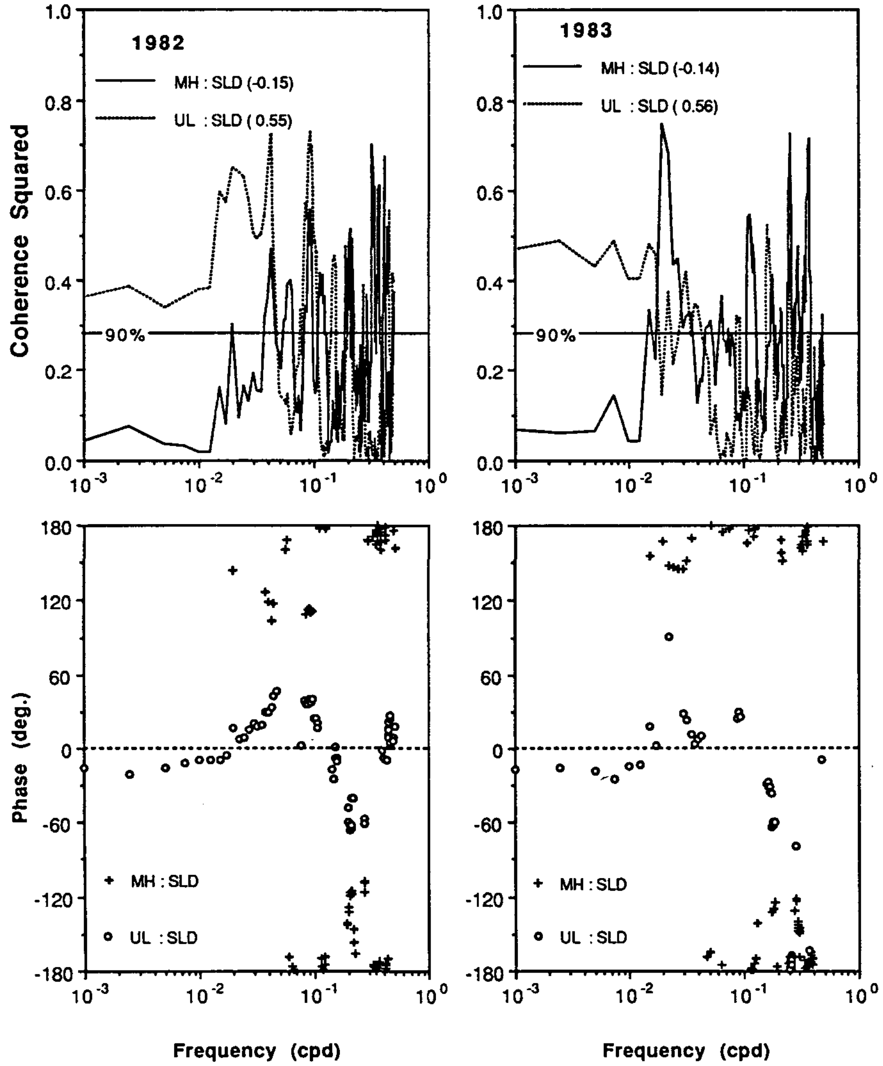

Fig. 6a. Coherence and phase between sea level and SLD.

in Fig. 6. The numbers inside the parentheses in the legend of upper part are the correlation coefficients presented in Table 2. For the phase graphs in lower parts, only significant values were plotted to avoid confusion. All the individual cases are shown because the averaging of the ±180° may result in the misleading values close to zero. 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° − | φ | . By the phase relations, the result can be divided into two parts with respect to about 0.01 cpd as is true for the Korea Strait by Lee *et al.*(1991). For Mukho *vs.* SLD, phases are small at lower frequency whereas they are scattered near ±180° at higher frequency. Consequently, Mukho has two components of normal(positive) correlation at low frequency and inverse(negative) correlation at higher frequency. These two contributions are expected to have a cancelling effect for the overall correlation coefficient in the time domain. For the low frequency part, Mukho is always less coherent with SLD than Ullungdo. It should be noted that the correlation coefficient is negative when the coherence squared at low-frequency is not significant as in 1982, 1983 and 1986. In 1985 and 1989 low-freque-

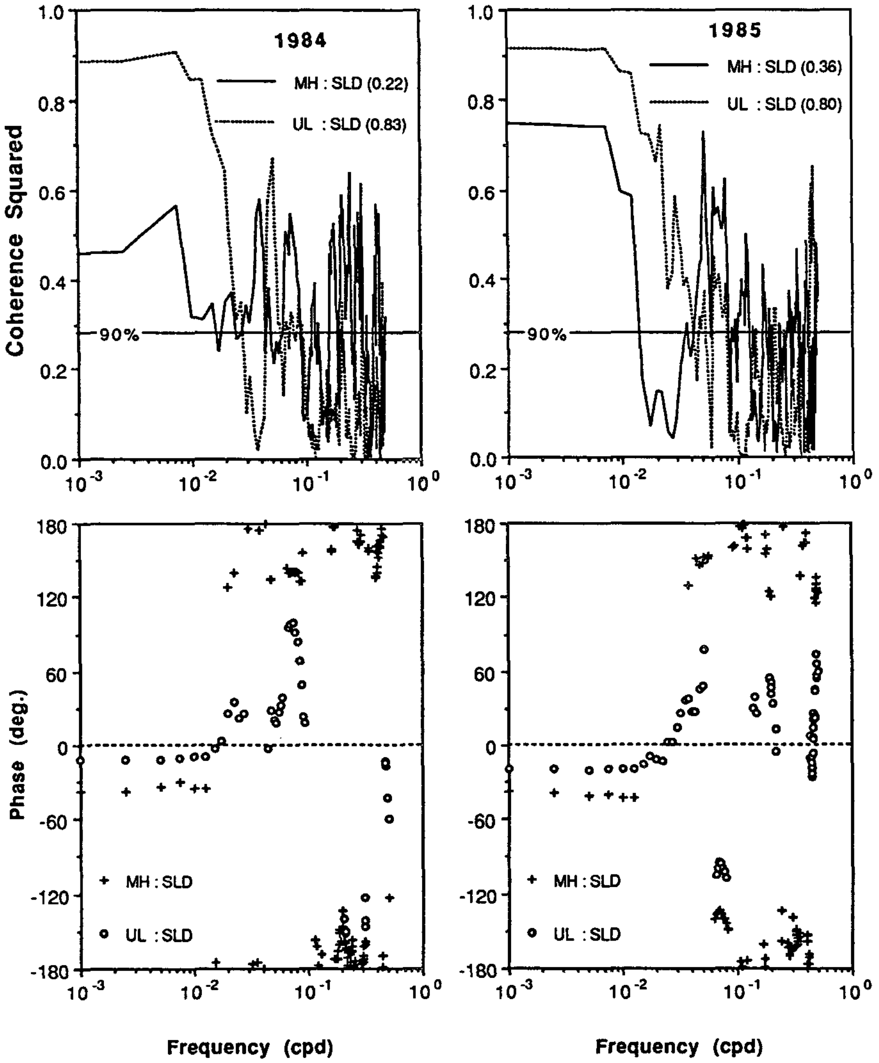

Fig. 6b. Coherence and phase between sea level and SLD.

ncy coherence is significant and correlation coefficient is relatively high. In 1987, however, zero correlation is the result of the equal contribution of low-frequency coherence in phase and the high-frequency coherence out of phase. In 1988, high-frequency contribution was more dominant although the low-frequency coherence was somewhat significant.

Ullungdo always has greater coherence than Mukho in low-frequency band. Whenever the coherence squared is low at Mukho, it is also relatively low at Ullungdo. Phases are also smaller than those at Mukho. Therefore, sea level at Ullungdo is basically in phase with SLD for all frequency bands. However, at higher frequency, phase lag of Ullungdo is fairly large.

Interpretations of the results are as follows. Variability of sea level at Mukho and Ullungdo consists principally of overall thermosteric influence and geostrophic sea level slope due to the currents flowing through the section between two locations. The former is mostly effective for low-frequency variability related to the seasonal changes whereas the latter may be important for all frequencies. The former is responsible for the in-phase while the latter for ±180° out-of-phase relations of sea level

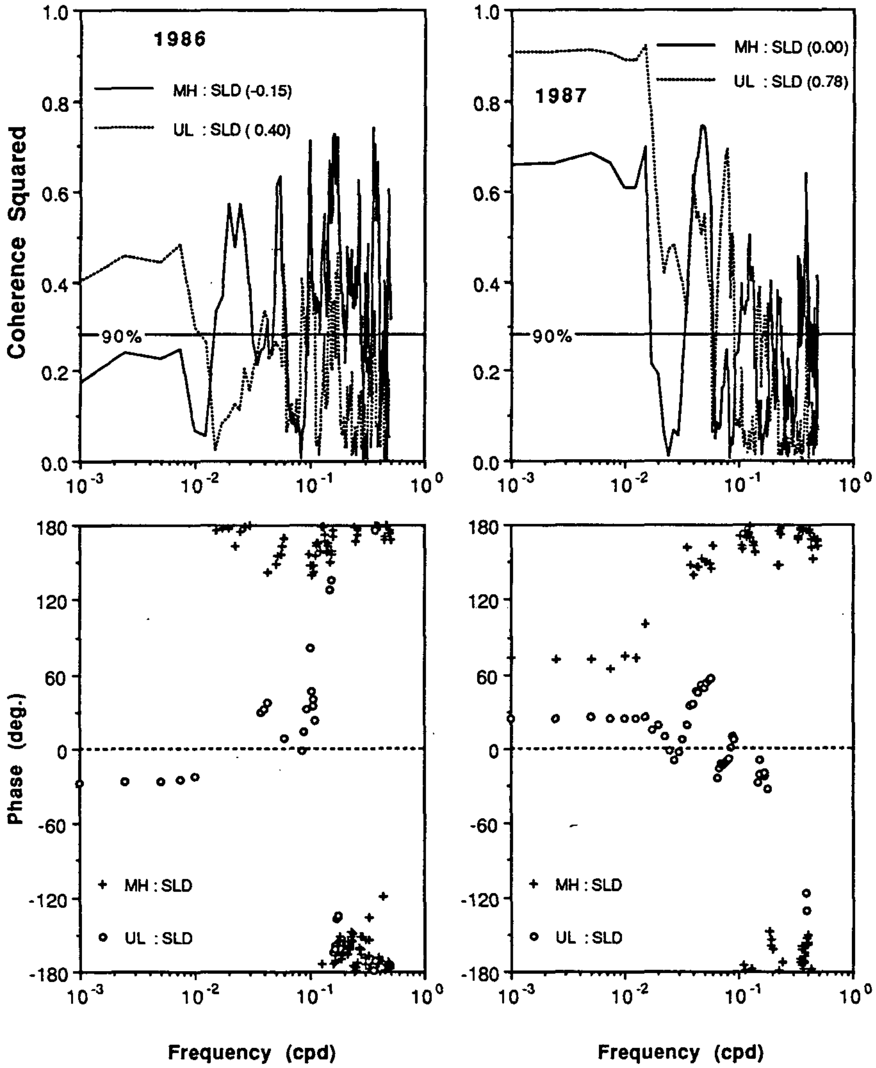

Fig. 6c. Coherence and phase between sea level and SLD.

vs. SLD. Thus the geostrophic effect accompanies sea level drop at one side and rise at the other side whereas the thermosteric influence causes concurrent variations at all places. The two components have a cancelling effect at Mukho while they are additive at Ullungdo because major current flows northward. Since the thermosteric effect is important in the low-frequency bands only, additive superposition of two components yields greater coherence at Ullungdo. For high frequency part where the seasonal thermosteric effect is negligible, only geostrophic influence can account for the phase relation that is smaller at Ullungdo and close to ±180° at Mukho. If the distance between two stations were not so large and geostrophic effects were predominant, phase would approach zero at Ullungdo while ±180° at Mukho to a greater extent. One of the factors important for the sea level variability is the influence of wind. In the strait or channel it is easier to interpret the results in terms of wind. However, because Ullungdo is a small island, it is not simple to explain the response of coastal sea level to wind. In this region it may be more appropriate to consider the wind stress curl as Na(1988) suggested.

Relation with Dynamic Height Anomaly

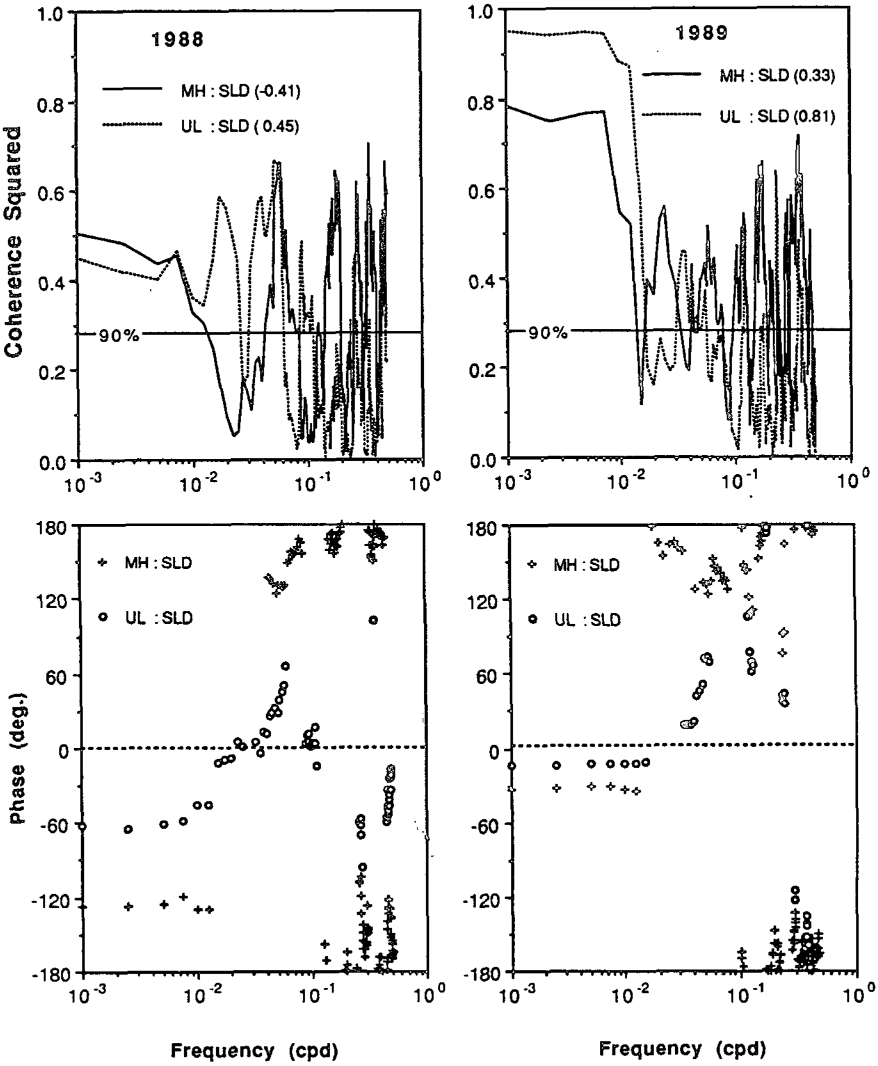

Fig. 6d. Coherence and phase between sea level and SLD.

Fig. 7 shows the distribution of dynamic height anomalies for the whole data available. If the dynamic height anomaly is referred to equal depth at all stations, distribution of dynamic height would be related directly to the state of surface current through the cross section. In the present study we want to compare total dynamic height anomaly for the whole water column as far as possible. Therefore, integration was taken from the bottom, *i.e.*, roughly 50 *m* at St. 3,250 *m* at St. 4 and 380 *m* at St. 5. From St. 6 to St. 10 dynamic height anomaly was referred to 500 *m* depth because the observation was scarce at deeper level. Rapid increase in dynamic height between St. 3 and St. 5 is due to the depth change to a considerable extent. Consequently it is not plausible to simply interprete that the northward current is strongest near the coast. Monotonic increase from St. 6 to the offshore direction corresponds to the northward flow everywhere in the section. More complicated curves are possibly associated with meander, eddy or return flow near Ullungdo. Dynamic height is generally minimum in February and maximum in October.

Relationship between dynamic height anomaly and sea level is represented in Fig. 8. As mentioned before, daily mean sea level was averaged for five days with respect to the date of hydrographic observation marked by crosses on the SLD curves in Fig. 3. Dynamic height near the tidal station appears to be correlated significantly with mean sea level. Correlation coefficient is 0.73 at Mukho and 0.90 at Ullungdo. When the daily mean sea level data are used instead of five-day average values, correlation coefficient becomes somewhat lower, *i. e.*, 0.62 at Mukho and 0.88 at Ullungdo(not shown). Therefore, dynamic height anomaly can be inferred approximately from the daily mean sea level by the relation fitted by the least squares method.

Dynamic height difference(DHD) between Station 10 near Ullungdo and other stations are related with Ullungdo-Mukho SLD in Fig. 9. SLD values also were averaged for five days. SLD is most significantly correlated with DHD between St. 10 and St. 3 or 4. Fig. 10 shows that the correlation coefficient between SLD and DHD of St. 10 minus St. 3 is 0.86 and the equation of the least squares fit is SLD=-0.361+0.766 DHD. This result suggests that DHD thus average current velocity through the section of Line 105 can be diagnosed by the sea level records at both places. Since the hydrographic data is restricted to bimonthly period, it is not certain if this relation will hold true for shorter

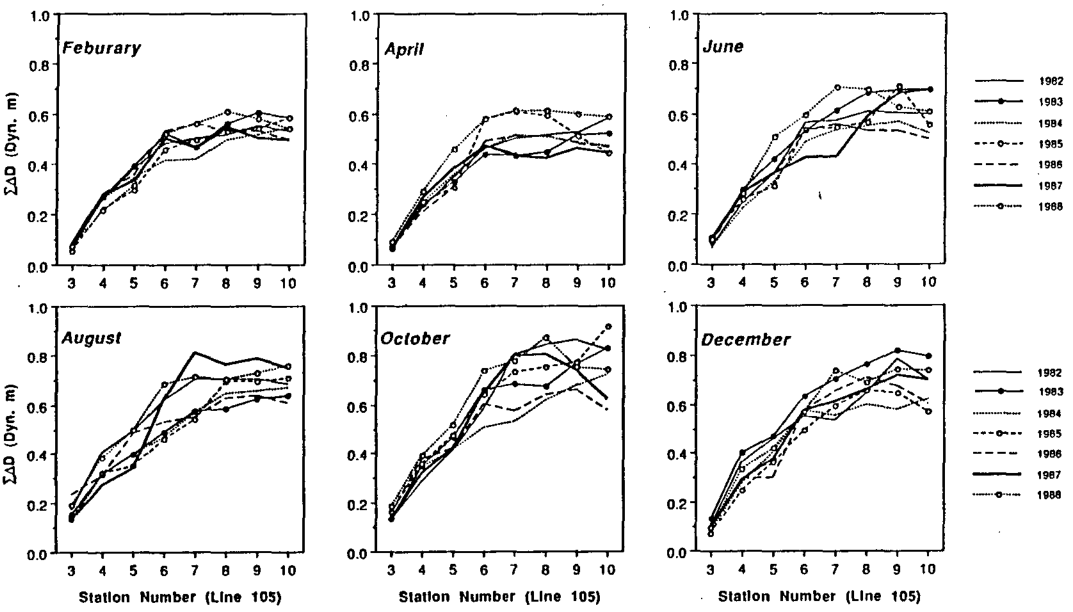

Fig. 7. Distributions of dynamic height anomaly at Line 105.

period. In order to verify this relation including the high-frequency variability, long-term mooring of current meters would be required.

Time series of bimonthly DHD at Line 105 and SLD(also averaged for 5 days) are compared with DHD at Line 207 in the Korea Strait(middle part) in Fig. 11. Small absolute values of SLD are not meaningful as mentioned before. At Line 105, both of SLD and DHD vary in approximately the same fashion. DHD at Line 207 has similar seasonal variations to those of Line 105. However, the time of maximum DHD is different; it generally occurs in August at Line 207 while in October at Line 105. In 1986 through 1988 discrepancies from the general result are due to the anomalous fluctuations of SLD as discussed previously(Fig. 3). In spite of rough result due to the observation interval of two

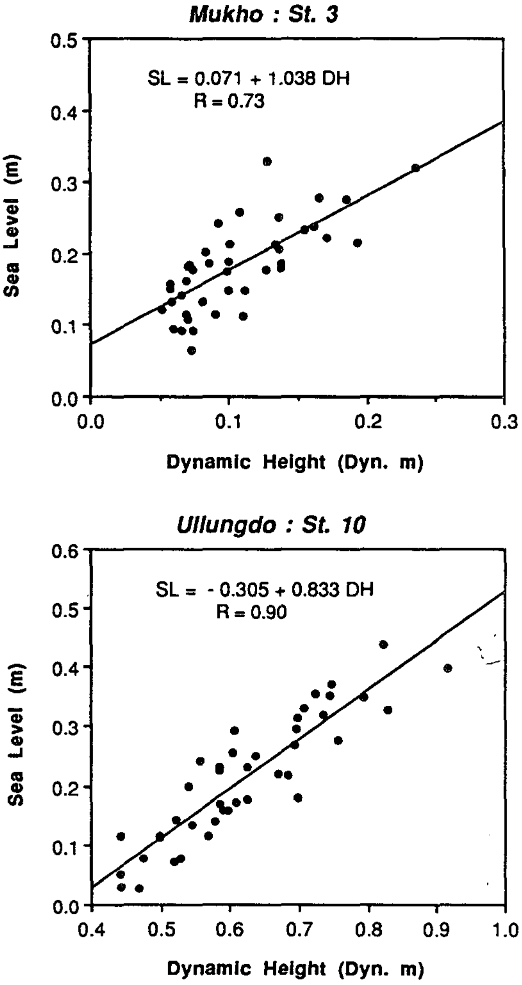

Fig. 8. Correlation coefficients of SLD at Mukho and Ullungdo with dynamic height anomaly at St. 3 and St. 10 respectively.

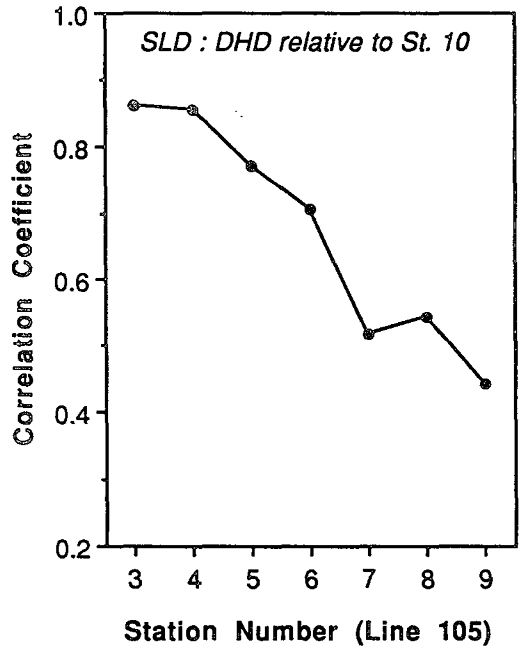

Fig. 9. Correlation coefficients of SLD with dynamic height difference(DHD) between St. 10 (Ullungdo) and other stations.

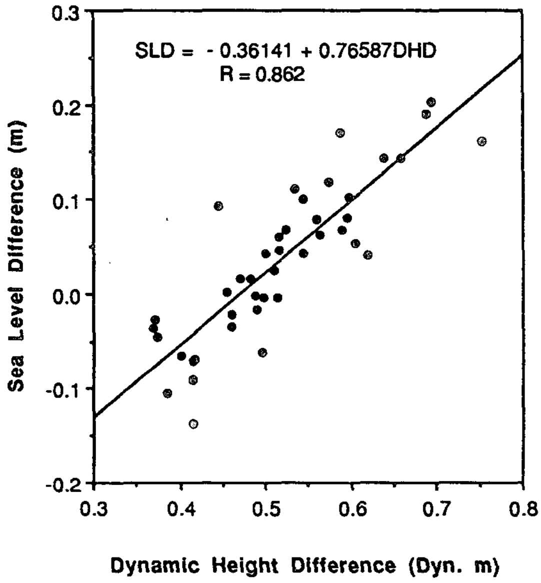

Fig. 10. Least squares fitting between SLD and DHD.

months, it appears evident that the time of maximum strength of currents is delayed at Line 105 considerably compared to the Korea Strait. Minimum DHD occurs in Febraury or April at two sections. Phase relations of SLD at the two cross sections are further explored by the coherence analysis of daily mean level data(Fig. 12). Only the results for two years of 1984 and 1986 are presented. Coherence between SLD's in the Korea Strait(Izuhara-Pusan) and those of Line 105(Ullungdo-Mukho) are commonly significant at low frequency. At frequencies higher than 0.01 cpd distributions of coherent bands are irregular, but it is noticeable that they are not coherent at semimonthly tidal frequency of about 0.07 cpd. Phases for the insignificant coherence were excluded again to avoid probable confusion. It should be noted that the unit of phase lag is days. At lowest frequency corresponding to the annual period SLD change in the Korea Strait leads that of Line 105 by about 40 days. At 0.005~0.01 cpd(200~100 days of period) Korea Strait leads Line 105 by 10~20 days. At higher frequencies, phase lag becomes much smaller.

Conclusions

Variability of sea levels at Mukho and Ullungdo and sea level difference(SLD) is investigated. Main purpose of this study is to answer two questions; What is the characteristics of the sea level variability at Mukho and Ullungdo ? Is it possible and relevant to monitor the strength of EKWC by means of daily mean sea level ? Three-day moving averaged sea levels at both places fluctuate very similarly to each other. However, both of cross correlation analysis in time domain and coherence analysis in frequency domain show that two components of thermosteric and dynamic effects have considerable influence on the variability of sea level and SLD. Variability of sea level and SLD in frequency domain can be classified into two parts with respect to 0.01 cpd according to the phase relationship. Thermosteric component of variation is influential at lower frequency and contributes to the positive correlation between sea level and SLD. Dynamic (geostrophic) component causing sea levels to vary in the opposite directions at both sites is effective

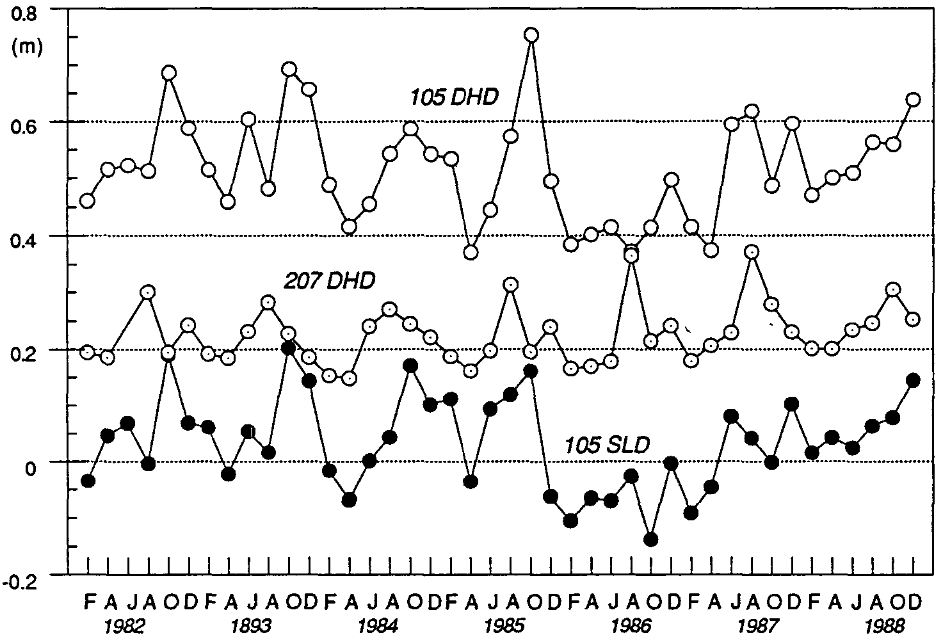

Fig. 11. Variations of bimonthly SLD and DHD in the Ullungdo-Mukho section(Line 105) and the Korea Strait (Line 207).

at all frequency and contributes to the negative correlation. Two contributions have a cancelling effect at Mukho and additive at Ullungdo for the correlation between sea level and SLD. As a result, not only sign but magnitude of correlation coefficient at Mukho depends on the relative dominance of a contribution over the other. Thermosteric contribution is responsible for small phase lag at low frequency between SLD and sea levels of both places. Dominant geostrophic contribution at higher frequency appears to result in the sea level-SLD phase relation of ±180° at Mukho and much smaller values at Ullungdo.

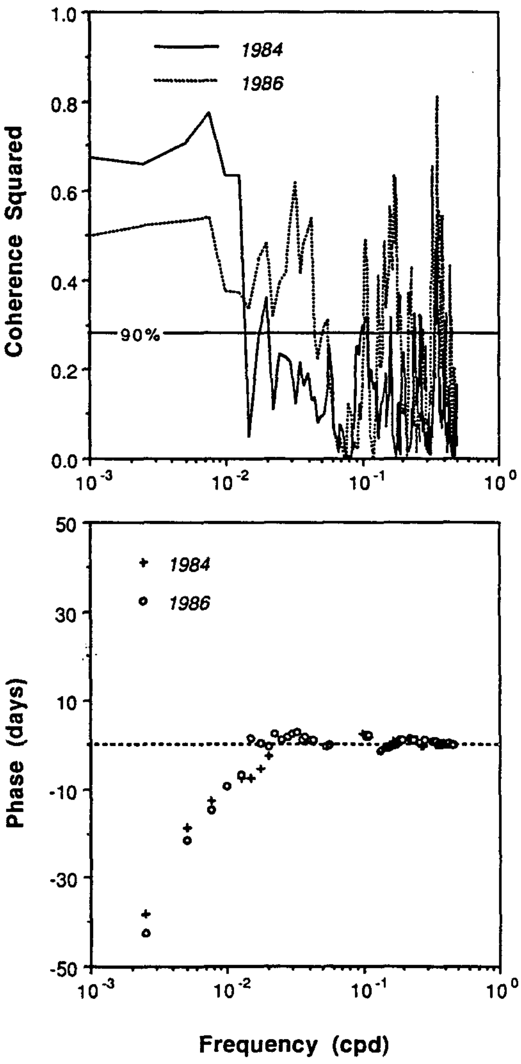

Fig. 12. Coherence and phase(in days) of SLD between the Korea Strait and Ullungdo-Mukho.

Correlation coefficient between bimonthly dynamic height difference(DHD) across Line 105 and five-day averaged SLD is 0.86 and the two variables are related by the equation SLD=-0.361+0.766 DHD. This result suggests that DHD thus the average velocity of current through the Mukho-Ullungdo section can successfully be diagnosed by the sea level records at both locations. Coherence analysis of SLD's of Ullungdo-Mukho and Izuhara-Pusan in the Korea Strait reveals that the annual variations of SLD at Mukho-Ullungdo section lag behind those of the Korea Strait by about 40 days.

Acknowledgments

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Variability of Sea Levels at Mukho and Ullungdo off the East Coast of Korea

한국 동해 묵호와 울릉도의 해수면의 변화

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묵호와 울릉도에서의 해수면 및 해류와 관련된 해수면차에 대하여 연구하였다. 기압보정된 두 곳의 해수면의 시계열자료는 매우 유사한 변화 양식을 보여준다. 해수면과 해수면차의 상관관계에는 두가지 성분이 기여를 하는데 저주파의 밀도효과는 양쪽의 해수면이 동시에 상승 · 하강하도록 하고 지형류 효과는 서로 반대방향으로 진동하도록 한다. 두가지 효과는 묵호에서는 서로 상쇄되는 반면에 울릉도에서는 더해진다.

주파수 영역에서의 시계열의 특성은 0.01 cpd를 중심으로 두 부분으로 나뉜다. 묵호에서는 저주파수에서 두가지 효과가 상쇄됨으로써 상관성이 낮은 반면에 고주파수에서는 지형류 효과가 우세하여 해수면과 해수면차 사이에 180°의 위상차가 생긴다.

묵호와 울릉도 사이의 역학고도의 차와 해수면차는 상관성이 높은데, 이는 묵호−울릉도 사이의 평균유속이 양쪽의 해수면 자료를 통하여 성공적으로 파악될 수 있음을 시사하는 것이다.

연변화에 있어서 묵호−울릉도의 해수면차의 최대치는 대한해협보다 약 40일 늦게 나타난다.