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Empirical Orthogonal Function Analysis of Seawater Temperature in the Southeastern Hwanghae

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東南黃海에서 海水温度의 EOF 分析

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Abstract

Spatio-temporal variabilities of seawater temperature at 0 and 30 m in the southeastern Hwanghae were studied by variance and empirical orthogonal function (EOF) analysis of long records of temperature between 1967 and 1982. The spatial distribution of monthly mean sea surface temperature has a pattern similar to the long-term annual mean which decreases from south to north. On the contrary, the total variance computed from the annual mean of sea surface temperature (SST) increases from south to north. The variance of SST is found to be two times greater thàn that at 30 m in the study area except coastal area south of Kyunggi Bay. The important variance of temperature seems to be closely associated with the seasonal change of temperature because the first and second modes of EOF having a seasonal cycle explain 97.6% and 85.2% of variances at 0 and 30 m, respectively. There is a large difference in temperature between the northern and southern parts of the study area during winter, while the difference becomes very small during summer. This might reflect that in summer the heat gain of sea surface from the incoming radiation is much more important than the heat loss or the oceanic heat advection. In summer coastal waters south of the Kyunggi Bay and around Mokpo are observed to be colder than offshore waters due to tidal mixing.

요약 : 황해 동남해역에서 해면과 30m층 수온의 시·공간 변동성을 1967 - 1982 장기 수온 자료의 variance와 empirical orthogonal function (EOF) 분석으로 연구하였다. 월평균 해면수온의 공간분포는, 남에서 북으로 감소하는 장기 년평균과 유사한 형태를 갖고 있다. 반면에 년평균 해면수온으로 부터 계산한 분산은 남에서 북으로 증가한다. 해면수온의 variance가 경기만 남부해역을 제외한 연구해역에서 30m층보다 2배이상 크다. EOF의 첫째와 둘째 모드가 계절변화를 갖고 있으며 해면과 30m층 variance의 97.6%와 85.2%를 각각 설명하기 때문에 수온의 큰 variance는 계절변화와 밀접한 관계가 있다. 겨울철 조사 해역 북부와 남부사이 수온의 차이가 크나 여름철에는 작아진다. 이것은 여름철 복사에 의한 해면의 열흡수가 열손실이나 해양열이류보다 훨씬 크다는 것을 반영해준다. 여름철에 경기만 남부와 목포주변 연안수가 조석혼합에 의해 외해수보다 수온이 낮게 나타난다.

INTRODUCTION

The Hwanghae (Yellow Sea) is a very shallow and wide basin with its mean depth of about 40 m. The typical pattern of climate controlling sea conditions is the Asian monsoon which is known to be driven by seasonal variation of polar continental air masses and tropical maritime air masses. The Hwanghae Warm Current as a major heat source in the southern part of the Hwanghae is thought to have a large seasonal change mostly due to the monsoon and oceanographic conditions inside the sea. Sea water temperature can be thus expected to have large seasonal and spatial variations.

Sea surface temperature (SST) at coastal stations of the eastern Hwanghae has been known to have a dominant annual periodicity with its amplitude of 5.9-12.5° C (Gong, 1968; Kim, 1983). The large seasonal variation of temperature was also observed in the southeastern Hwanghae from hydrographic data observed in 1968 (Kang, 1971). Kang and Jin (1984) have reported that applying a harmonic analysis to monthly mean SST data the annual amplitude has a range of 7° west of Chejudo to 10.5° in the 307 hydrographic section (Fig. 1). According to temperature-salinity diagram based on the long-term data (1961-1980), sea water temperature in the southeastern Hwanghae has a wide temperature range in summer, being 5.0-30.0° C in August, and a narrower one in winter, being 1.0-18.0° C in February (Lie, 1985). Such a large seasonal variation of sea water temperature should be closely associated with the seasonal change of the incoming radiation and the heat advected by the Asian monsoon and the ocean currents in the area (Kang, 1985; Lie, 1984).

So far studies on the sea water temperature in the Hwanghae have been focused on the seasonal variation of SST using harmonic methods, not on the spatial variability of temperature. For more comprehensive understanding on sea water temperature this paper is intended to investigate temporal and spatial variabilities based on the long-term hydrographic data observed during 1967-1982.

The discussion on the variabilities will be done using temperature data both on the surface and at 30 m because waters below 30 m in the deeper area of the Hwanghae are mainly the Hwanghae Cold Water which has little change of hydrographic properties from one season to another. Data analysis in the paper was done by a simple statistical method to catch general patterns of surface temperature with its monthly variation and also by an empirical orthogonal function method to describe the variability in time and space of temperature.

DATA AND METHOD

To analyze temporal and spatial variabilities of sea water temperature in the southeastern Hwanghae, we used long-term hydrographic data collected regularly by the Fisheries Research and Development Agency of Korea (FRDA). The data considered here were those obtained for a period of sixteen years between 1967 and 1982 at 61 stations on sea surface and 57 stations at 30 m located in the sections 307 to 313 (Fig. 1). Most hydrographic surveys were carried out bimonthly in the first part of February, April, June, August, October and December. When there were more than or equal to two data at a

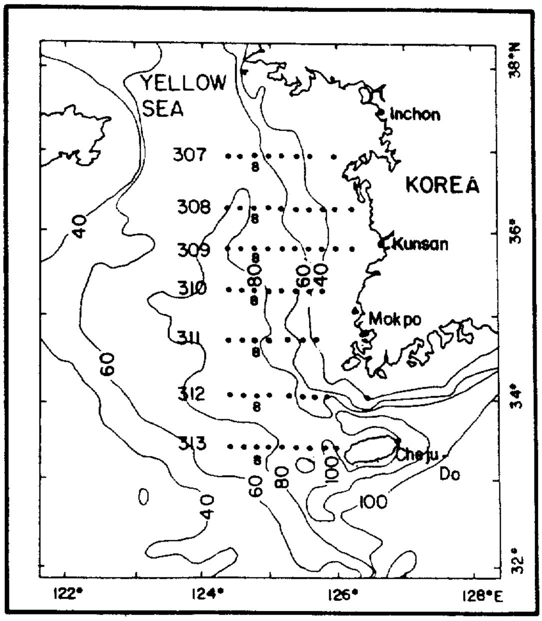


Fig. 1. Hydrographic stations in the study area. Bottom depths are in meters and numbers 307 to 313 indicate the hydrographic sectioins. The number 8 on each section is Station 8.

given station between the sixteenth of the preceeding month and the fifteenth of the following month, we averaged all data to get the representative data in the corresponding month of the year. The total number of data were finally 5,552 on the sea surface and 5,256 at 30 m, so that the missing rates were 5.2% on the sea surface and 3.9% at 30 m, respectively.

The first step of data processing is the preparation of long-term mean temperature and monthly mean sea surface temperature for the entire period of 16 years. For the long-term mean temperatures at both depths we calculated the mean value at each station by averaging all data at the station observed during the whole period. The monthly mean sea surface temperatures were obtained by averaging all observations in the sample months over a 16 year period of 1967-1982 (February, April, June, August, October and December).

The second step of data processing is an application of empirical orthogonal function (EOF) analysis to temperature data observed between 1967 and 1982. Bimonthly temperature data for each station were demeaned by subtracting the long-term annual mean from the data and the variances of the resampled data sets were then calculated. From the resampled data we constructed a 61 × 61 covariance matrix for the sea surface temperature and also a 57 × 57 covariance matrix for the temperature at 30 m. According to the procedure of EOF analysis, eigenfunctions and eigenvalues representing the seasonal cycle were estimated using International Mathematics and Statistics Library (IMSL). Time coefficients were then obtained for a few lowest modes of empirical orthogonal functions.

SEASONAL VARIATION OF SEA SURFACE TEMPERATURE

The horizontal distribution of the long term annual mean sea surface temperature is illustrated in Figure 2 for the whole period of 16 years. This figure can be considered as a basic pattern of sea surface temperature (SST) in the study area. Generally SST decreases from the south to the north and SST in the coastal area is lower than that in the offshore area when comparing temperatures at the same latitude. Isotherms having temperature 16 to 18 ° C are found to be located in the area between the southwest coast of the Korean Peninsula and Chejudo, which represents a strong south-north gradient of temperature. Those isotherms are known to extend from the west to the east along the coast and to form a coastal front in the sea south of the Korean Peninsula seperating coastal water from offshore water which can be observed by infrared satellite images (Hue, 1982; KORDI, 1985; Zheng and Klemas, 1982) and also hydrographic data (Gong, 1971). The annual

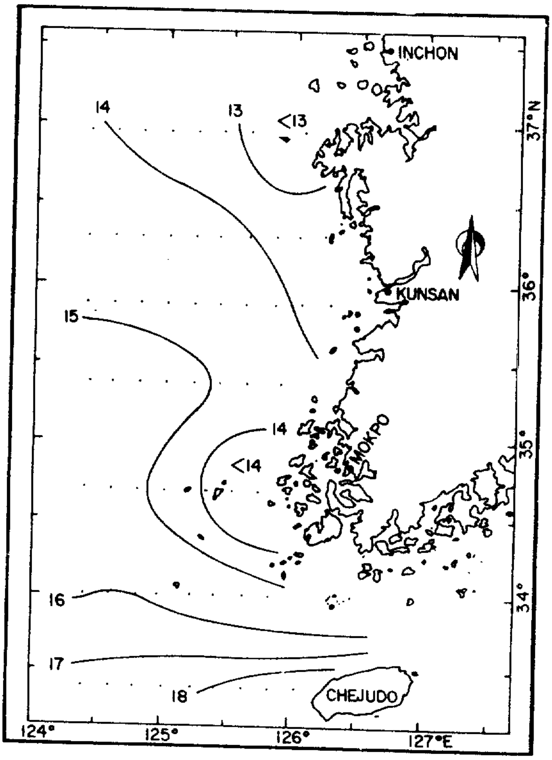
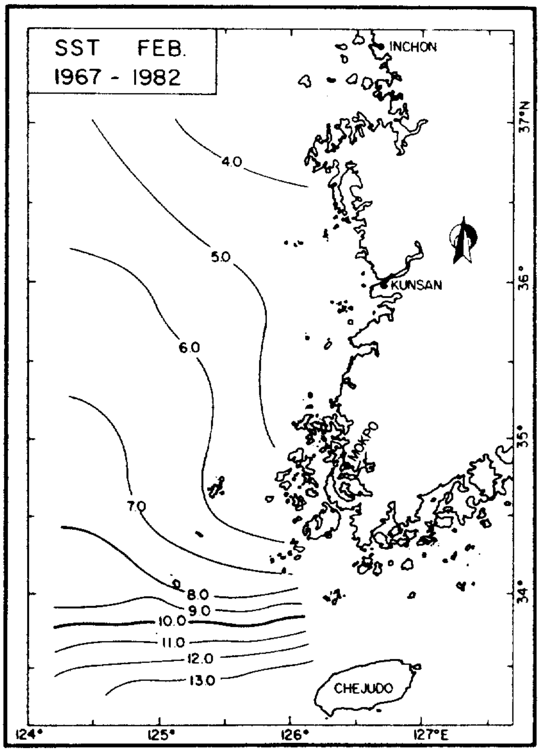
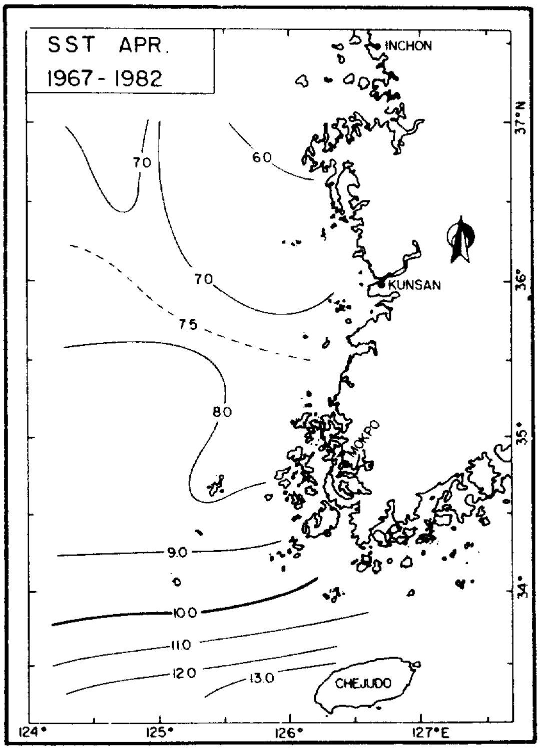


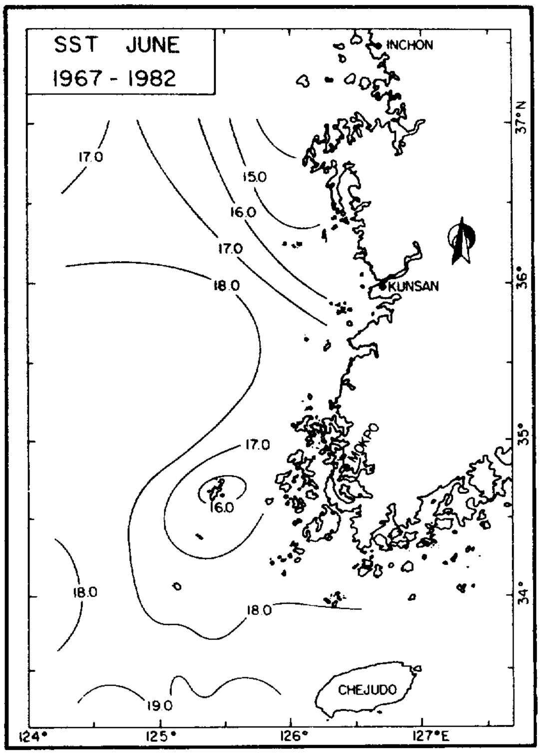
Fig. 2. Long-term annual mean of surface temperature for a period of 16 years from 1967 to 1982.


SST FEB.
1967 - 1982
INCHON
KUNSAN
MOKPO
CHEJUDO
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
12.0
13.0
37°N
36°
35°
34°
124°
125°
126°
127°E

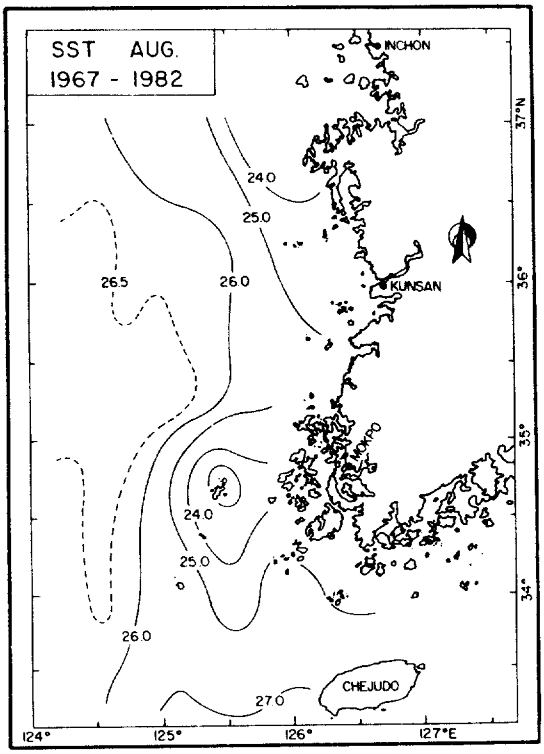
(a)


SST APR.
1967 - 1982
INCHON
KUNSAN
MOKPO
CHEJUDO
7.0
6.0
7.0
7.5
8.0
9.0
10.0
11.0
12.0
13.0
37°N
36°
35°
34°
124°
125°
126°
127°E

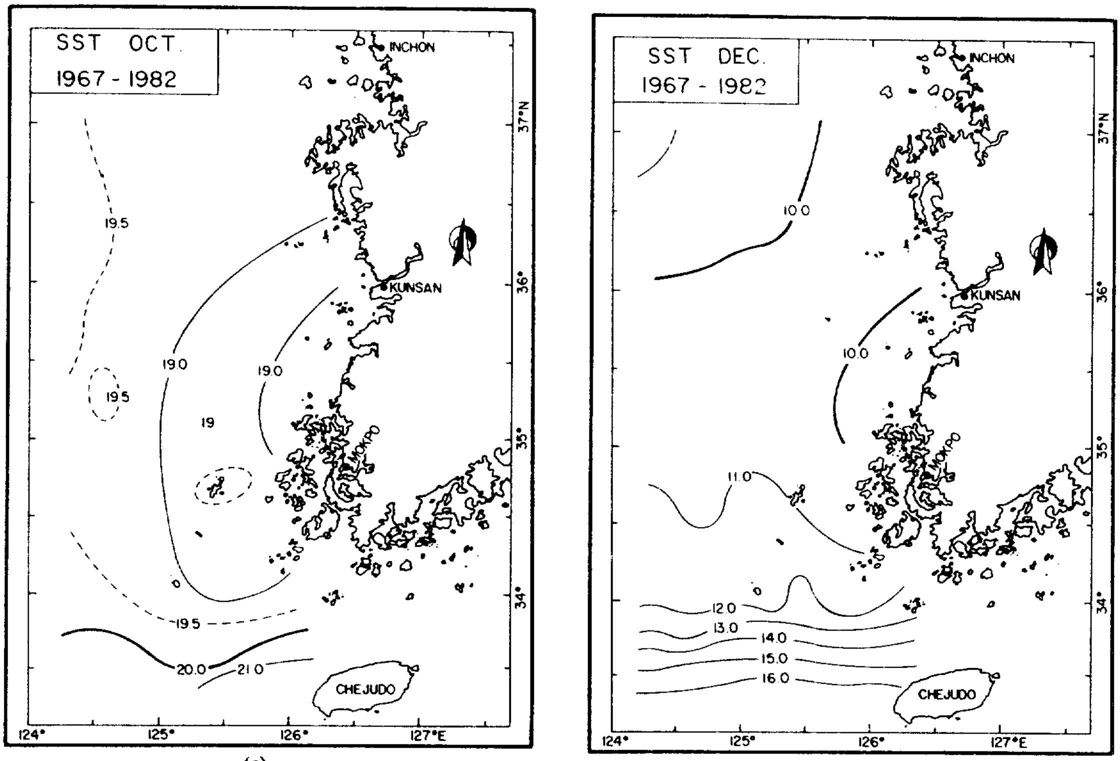
(b)


SST JUNE
1967 - 1982
INCHON
KUNSAN
MOKPO
CHEJUDO
17.0
15.0
16.0
17.0
18.0
17.0
16.0
18.0
18.0
19.0
37°N
36°
35°
34°
124°
125°
126°
127°E

(c)


SST AUG.
1967 - 1982
INCHON
KUNSAN
MOKPO
CHEJUDO
24.0
25.0
26.5
26.0
24.0
25.0
26.0
27.0
37°N
36°
35°
34°
124°
125°
126°
127°E

(d)



(e) (f)

Fig. 3. Long-term monthly means of surface temperature tor a period of 16 years from 1967 to 1982. (a) February, (b) April, (c) June, (d) August, (e) October, and (f) December.

mean SST seems to have the general pattern similar to the monthly mean SST in winter presented in Figure 3.

Monthly mean SST for February, April, June, August, October and December are shown in Figure 3. As indicated in the spatial distribution of the annual mean SST, the monthly mean SST is concordant with the general pattern of the annual mean. All the year round, isotherms west of Chejudo are running from west to east. Temperature difference in mid-winter between the area west of Chejudo and the coastal area located at 37 ° N reaches about 10° C, but in summer it decreases to about 3 °C. Figure 3 also shows that seasonal change of SST is about 12° C west of Chejudo and 20° C in the region between 36° N and 37° N. A strong thermal front running west to east is formed west of Chejudo during winter, which was found to be a thermohaline front extending from surface to bottom (Lie, 1985). Cold coastal water in summer occurs in the regions south of the Kyunggi Bay and west of the southwestern Korean Peninsula. The appearance of such cold water is due to tidal mixing recently reported by Lie et al (1986).

Figure 4 shows the spatial patterns of seasonal variance on the sea surface and at 30 m in the southeastern Hwanghae, which were computed from deviations of the temperature data from the long-term annual mean based on the 16 year data. Variance in the northern part of the study area is much more important than that in the southern part, being two times larger on the surface and four times larger at 30 m. The low variance west of Chejudo is due to the small seasonal fluctuation since in winter waters in the region receives heat from the Hwanghae Warm Current, waters in the

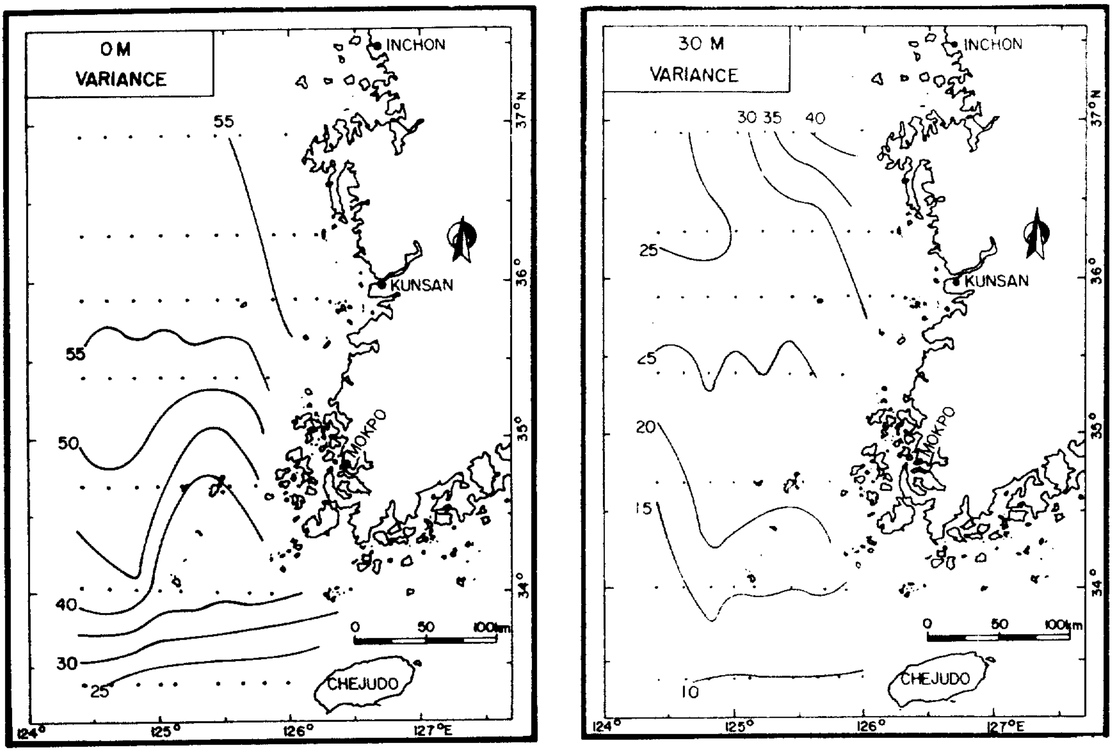


Fig. 4. Variances of water temperature computed from the long-term annual mean over 1967-1982. (a) sea surface and (b) 30 m.

northern part being far from the effect of the warm current. Relatively low variance on the surface in the coastal area and around Hugsando, comparing with that in the offshore area, can be explained by low temperature in summer by tidal mixing. Offshore waters at 30 m have lower variance in comparison with surface waters. This results from the fact that the Hwanghae Cold Water, defined by a temperature less than 10° C and a salinity of 32.0-33.0‰, occupies the lower layer below the thermocline (or halocline) located around 20 m (Lie, 1984; Nakao, 1977). The strong stratification in summer seems to be broken in the coastal area by tidal mixing, so that coastal water is vertically homogeneous, compared with the offshore water.

EMPIRICAL ORTHOGONAL FUNCTION ANALYSIS

Empirical orthogonal function method (EOF) has been broadly employed for the long term oceanographic records over a vast area since only a small number of variables obtained by the analysis can account adequately for the spatial and temporal variabilities of oceanographic and meteorological factors like temperature, sea level, atmospheric pressure, and current (e.g. Davis, 1976; Inoue, 1985; Kundu and Allen, 1976; Weare et al., 1976). In this paper we consider seasonal temperature variations, not non-seasonal ones computed from deviations of temperature from

Table 1. Percents and cumulative percents of total variance explained by the lowest five modes of empirical orthogonal functions.

	MODE	1st	2nd	3rd	4th	5th
SST	Percent	96.6	1.0	0.6	0.4	0.3
	Cumulative Percent	96.6	97.6	98.2	98.6	98.9
30T	Percent	81.8	3.4	2.8	1.4	1.2
	Cumulative Percent	81.8	85.2	88.0	89.4	90.6

the long-term monthly means. Table 1 gives fractions and cumulative percentages of the total variance explained by the lowest five modes of empirical orthogonal functions. The table shows that the five orthogonal functions can describe 98.9% of the total variance on the surface and 90.6% at 30 m. The most important function is the first mode which explains 96.6% and 81.8% of the corresponding variances, respectively.

Figures 5 and 6 presents the spatial distributions of the first two orthogonal eigenfunctions explaining 97.6% of the total variance and their time coefficients on the surface. The same sign of functions over an area considered means that temperature changes in the area are in phase but the opposite sign means that temperature changes are anticorrelated. The spatial pattern of the first EOF explaining 96.6% of the total variance coincides well with that of the variance. The time coefficient indicates the seasonal variation of SST which is maximum in August and minimum in February as can be shown in the monthly

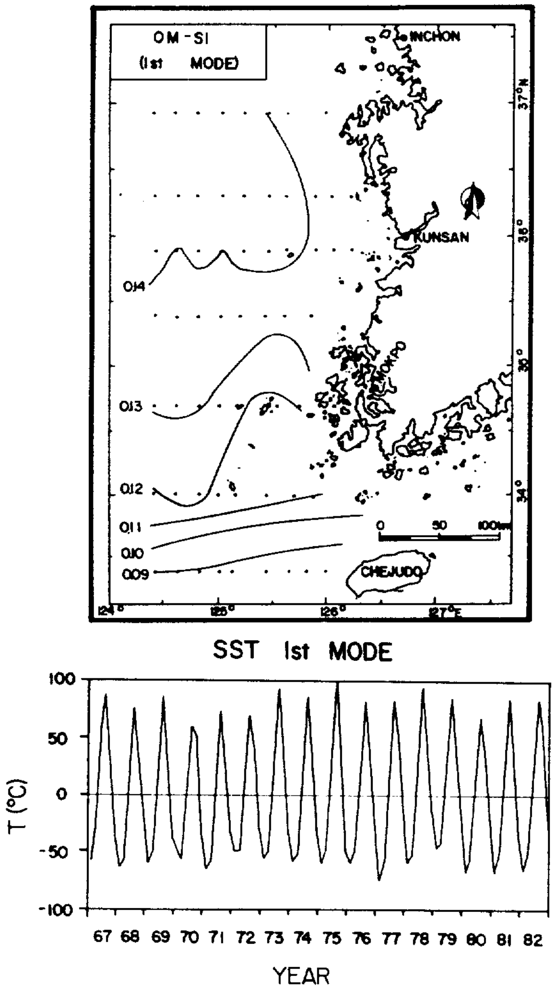


Fig. 5. The first mode empirical orthogonal function, explaining 96.6% of the variance, of SST and its corresponding time coefficient.

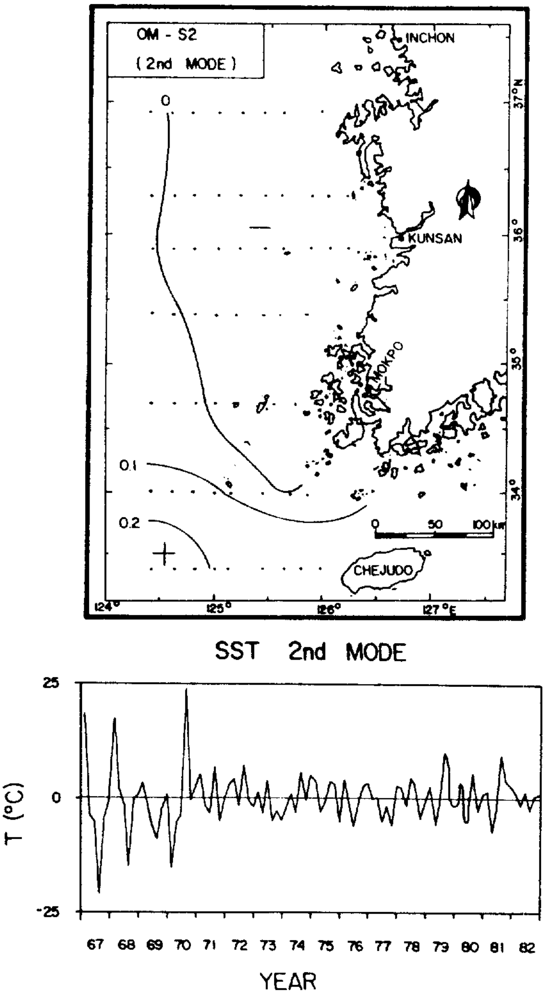


Fig. 6. The second mode empirical orthogonal function, explaining 1.0% of the variance, of SST and its corresponding time coefficient.

mean distributions (Fig. 3). The contribution of a given mode to the temperature deviation from the long-term annual mean for given station and time is the product of the value of the function at the station and the time coefficient at the time. Thus temperature deviations at northern stations are about 1.5 times larger than those west of Chejudo located in the vicinity of the northern boundary of the Hwanghae Warm Current. The second mode of EOF explains 1.0% of the total variance. It is of interest to note that the second mode has negative sign in the northern part and positive in the southern part, while the first mode is of same sign over the whole study area. The boundary of the two regions of opposite signs is parallel to the bottom contour of about 80 m. Such a dominant periodicity as the first mode is not shown. The exceptionally large amplitude of time coefficient occurred in 1967-1970. Although the contribution of the second mode to the variance is small, the pattern seems to seperate shallow water region partly influenced by cold coastal water from deeper water region having relatively warm water. We did not present here eigenfunctions and time coefficients of the other higher modes because of their small contribution to the total variance less than 1%.

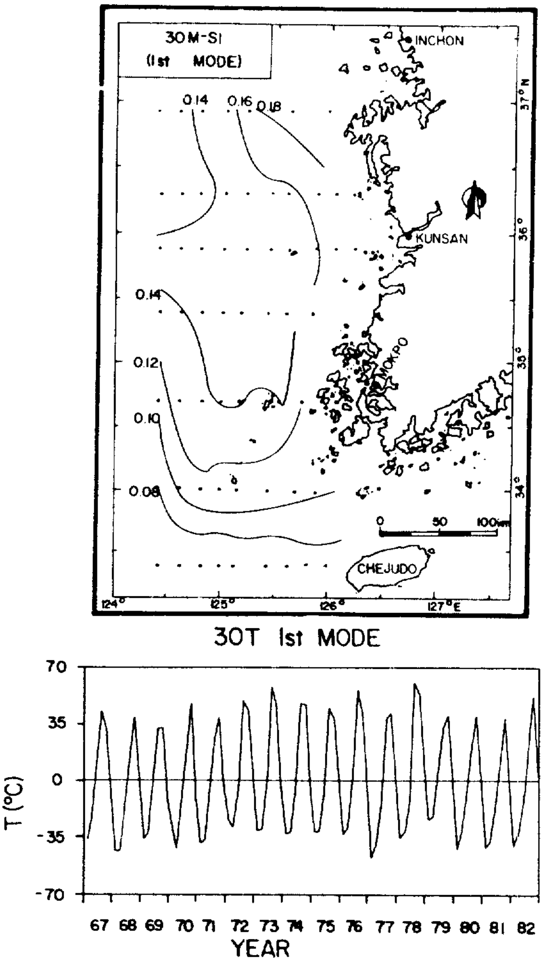


Fig. 7. The first mode empirical orthogonal function, explaining 81.8% of the variance, of temperature at 30 m and its corresponding time coefficient.

Spatial distributions and time coefficients of the empirical orthogonal functions at 30 m are shown in Figures 7 to 9. The spatial pattern of the first mode eigenfunction resemble generally that of the total variance at 0 m. In the region between Kunsan and Inchon, surface coastal water has a little less seasonal variation than offshore water but coastal water at 30 m has a larger variation than offshore water. This is why the offshore water below the thermocline is less sensitive to the air-sea interaction and far from the effect of tidal mixing, compared with the vertically homogeneous coastal water. The same situation could also happen in the shallow coastal area of the southern part including few hydrographic stations when we refer to cold water band along the coast detected by infrared imagery in summer (Lie et al., 1986). The second mode of EOF, explaining 3.4% of the total variance, shows anti-correlation between coastal water and offshore water. Considering that the time coefficient shows a dominant seasonal cycle, the temperature deviation due to the second mode is positive (negative) in the coastal area and negative (positive) in the offshore area in summer (winter). The third mode of EOF, accounting for 2.8% of the total variance, indicates an anti-phase between the northern and southern parts. The

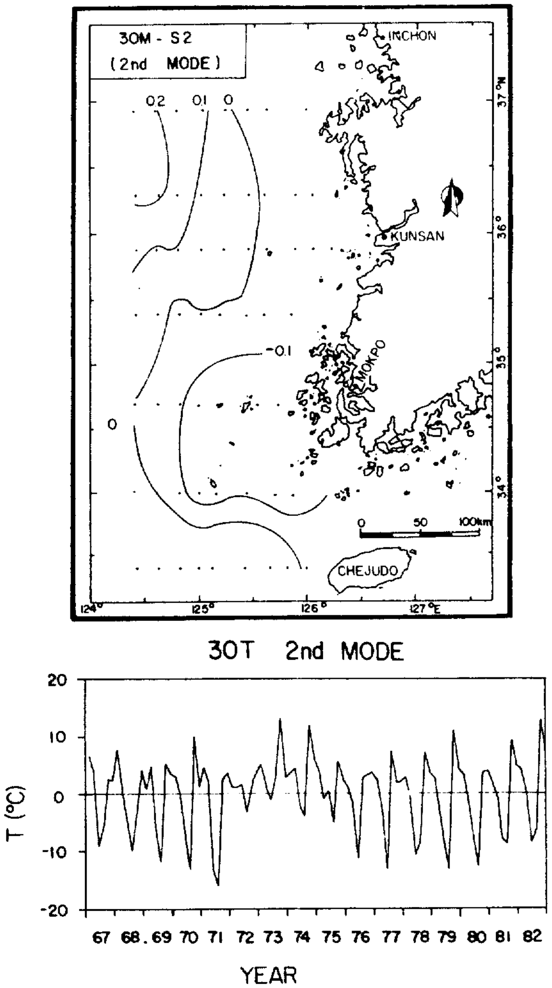


Fig. 8. The second mode empirical orthogonal function, explaining 3.4% of the variance, of temperature at 30 m and its corresponding time coefficient.

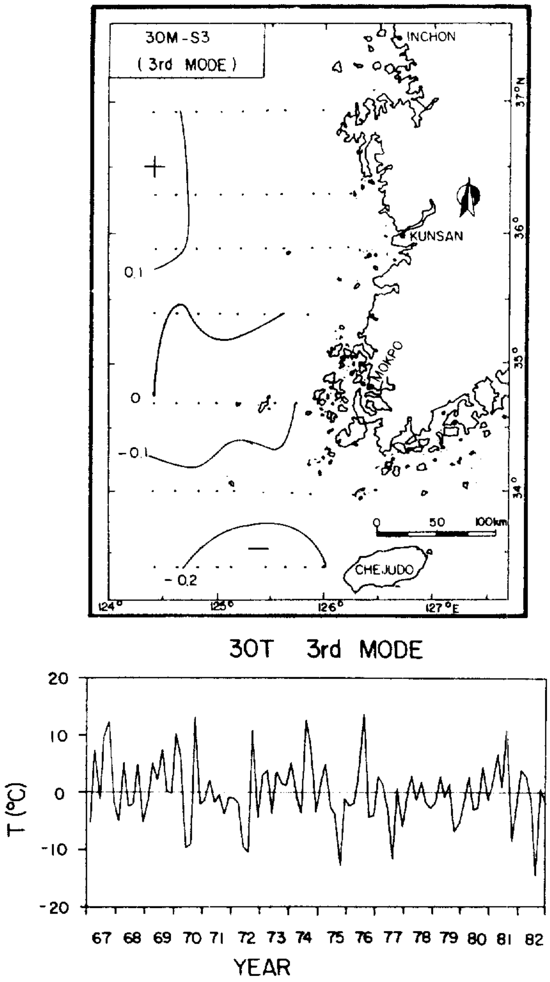


Fig. 9. The third mode empirical orthogonal function, explaining 2.8% of the variance, of temperature at 30 m and its corresponding time coefficient.

corresponding time coefficient shows the semi-annual cycle fluctuations.

DISCUSSIONS AND CONCLUSIONS

Water temperature in the southeastern Hwanghae has a very large variance, specially in the surface layer. The total variance computed from the long-term annual mean increase from south to north in the study area. The variance of SST is found to be two times larger than that of temperature at 30 m over the whole study area with an exception of coastal area south of the Kyunggi Bay. General patterns of the monthly mean SST is concordant with the long-term annual mean. According to the EOF analysis, the important variance is closely associated with the seasonal variation. The first and second modes of EOF explain most of the total variances; 97.6% and 85.2% of the variances on the surface and at 30 m, respectively.

The horizontal distributions of long-term monthly mean SST show that in winter there is a large difference in temperature between the northern and southern parts of the area, while the difference becomes very small in summer. The Asian monsoon is the typical pattern of climate in the Hwanghae such that in winter the strong northerly wind carries cold and dry continental air masses to the sea, while in summer warm and humid maritime air masses are brought into the Asian Continent. In winter when the incoming radiation is small, waters in the southern part gains heat advected by the Hwanghae Warm Current, but waters in the northern part, far from the influence of the warm current (Lie, 1985), losses just heat by the cold northerly wind. Thus such a large difference in temperature is formed in the study area. Meanwhile in summer when the heat gain from the incoming radiation is more important than the heat loss (Kang and Jin, 1983), water temperature has a small difference in the study area except the coastal area.

The east-west gradient of SST is negligible west of Chejudo all the year round because isotherms are running from west to east. However, the monthy mean SST in summer indicates a good contrast of temperature between offshore and coastal areas both south of the Kyunggi Bay and west of Mokpo where the coastal water is much colder than the offshore water (Fig. 3d) and the tidal current is strongest around the Korean Peninsula (Choi, 1980). Lie et al. (1986) have reported that coastal waters in the southwestern corner of the Korean Peninsula are vertically homogeneous, offshore waters being well-stratified. They introduced tidal mixing proposed by Simpson and Hunter (1974) to explain such a vertical structure. The stratified water column has in general high temperature in the upper layer and lower temperature in the lower layer before mixing. After mixing, the water temperature of the water column is colder than the upper layer and warmer than the lower layer provided that no heat is supplied from the outside.

REFERENCES

Choi, B.H. 1980. A tidal model of the Yellow Sea and Eastern China Sea. Rep. Korea Ocean Research and Development Inst. No. BSPI00019, 72 pp.

Davis, R.E. 1976. Predictability of sea surface temperature and sea level pressure anomalies over the North Pacific Ocean. J. Phys. Oceanogr., 5, 240-268.

Gong, Y. 1968. On the seasonal variation of coastal surface water temperature. Bull. Fisheries Research Development Agency, 3, 59-79 (in Korean).

Inoue, M, 1985. Modal decomposition of the low-frequency currents and baroclinic instability at Drake Passage. J. Phys. Oceanogr., 1157-1181.

Kang, Y.Q. 1985. Influences of the Asian monsoon and the Kuroshio on the sea surface temperatures in the Yellow, the Japan and the East China Seas. J. Oceanol. Soc. Korea, 20, 1-9.

Kang, C.J. 1971. On the seasonal variation of the oceanographical conditions in the eastern part of the Yellow Sea. Bull Fisheries Research Development Agency, 8, 9-29 (in Korean).

Kang, Y.Q. and M.S. Jin, 1984. Seasonal variation of surface temperature in the neighbouring sea of Korea. J. Oceanol. Soc. Korea. 19, 31-35.

Kim, B.K. 1983. Periodic and correlation analysis between water temperature and air temperature in the Korean waters. J. Oceanol. Soc. Korea. 18, 55-63 (in Korean).

Kundu, P.K. and J.S. Allen, 1976. Some three-dimensional characteristics of low-frequency current fluctuations near the Oregon coast. J. Phys. Oceanogr., 6, 181-199.

Lie, H.J. 1984. A note on water masses and general circulation in the Yellow Sea (Hwanghae). J. Oceanol. Soc. Korea. 19, 187-194.

Lie, H.J. 1985. Wintertime temperature-salinity characteristics in the southeastern Hwanghae (Yellow Sea). J. Oceanogr. Soc. Japan, 41, 291-298.

Lie. H.J., D.C. Jun, H.J. Kwon, and S.C. Hwang, 1986. Tidal front in the southwest area off Korea. Rep. of Korea Ocean Research and Development Institute. No. BSPE00058-93-1, 106 pp. (in Korean).

Nakao, T. 1977. Oceanic variability in relation to fisheries in the East China Sea and the Yellow Sea. J. Fac. Mar. Sci. Technol. Tokai Univ., Spec. No., 199-367.

Simpson, J.H. and J.R. Hunter, 1974. Fronts in the Irish Sea. Nature, 250, 404-406.

Weare, B.C., A.R. Navato, and R.E. Newell, 1976. Empirical orthogonal analysis of Pacific sea surface temperatures. J. Phys. Oceanogr., 6, 671-678.

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