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Temporal and Spatial Variations of SST and Ocean Fronts in the Korean Seas by Empirical Orthogonal Function Analysis

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Abstract : In the Korean seas, Sea Surface Temperature (SST) and Thermal Fronts (TF) were analyzed temporally and spatially during 8 years from 1993 to 2000 using NOAA/AVHRR MCSST. In the application of EOF analysis for SST, the variance of the 1st mode was 97.6%. Temporal components showed annual variations, and spatial components showed that where it is closer to continents, the SST variations are higher. Temporal components of the 2nd mode presented higher values of 1993, 94 and 95 than those of other years. Although these phenomena were not remarkable, they could be considered ELNIÑO effects to the Korean seas as the time was when ELNIÑO occurred. The Sobel Edge Detection Method (SEDM) delineated four fronts: the Subpolar Front (SPF) separating the northern and southern parts of the East Sea; the Kuroshio Front (KF) in the East China Sea, the South Sea Coastal Front (SSCF) in the South Sea, and the Tidal Front (TDF) in the West Sea. TF generally occurred over steep bathymetry slopes, and spatial components of the 1st mode in SST were bounded within these frontal areas. EOF analysis of SST gradient values revealed the temporal and spatial variations of the TF. The SPF and SSCF were most intense in March and October; the KF was most significant in March and May.

Key Words : SST, Thermal Fronts, Sobel Edge Detection Method, EOF analysis.

1. Introduction

Satellite-derived measurement of sea surface temperature (SST) is one of the most influential remotely sensed oceanographic parameters (Robinson, 1994) providing a quantitative view of thermal features in the ocean, such as fronts identified by sharp temperature gradients (Deacon, 1982). There have been a lot of research about SST variations in the Korean seas and they contributed to representing conditions of oceanic environment in this region (Gould and Arnone, 2004; Kang, 1984; Park, 1998; Yoon, 2001). In this paper, SST and Thermal Fronts (TF) in the Korean seas were analyzed temporally and spatially from the AHVRR (Advanced Very High Resolution Radiometer) instrument aboard the National Oceanic and Atmospheric Administration (NOAA) series of polar-orbiting environmental satellites, since satellite data are very useful for investigations of long-time variations and wide distributions in SST.

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Ocean fronts occur where two water masses with different properties meet and mix. Formation processes, shapes and locations of ocean fronts vary. Ocean fronts are associated with, or accompanied by, current jets, enhanced variability, strong isopycnal and diapycnal mixing, water mass boundaries, biological ecotones and bioproductivity maxima, acoustical wave guides, marginal ice zones and atmospheric boundary layer fronts (Berkin and Spall, 2002). Many researchers studied ocean fronts using satellite data by various methods and encouraged other researchers to use satellite data in the research of ocean fronts (Berkin, 2002; Chiswell, 1994; Everson *et al.*, 1997; Hickox *et al.*, 2000; Ullman and Cornillon, 2001). By broadening the scope of research area beyond Korean coastal seas, we could extensively study TF affecting Korean oceanic environment. We demonstrated both distributions and variations of SST and TF and also analyzed relations of them.

2. Data and Method

1) Data and Study Areas

The AVHRR MCSST data set contains weekly values of SST available in (approximately) 19×19km grids for the entire globe. A weekly period consists of 8 days so as to give a 1-day overlap between consecutive weekly files. The data containing mask values for areas of no data, sea ice, and land were provided by JPL PO.DAAC (Jet Propulsion Laboratory, Physical Oceanography Distributed Active Archive Center) (NASA/NOAA,1998). The MCSST data set was chosen rather than the newer Pathfinder SST data set as it has a complete and continuous temporal coverage for this period. The study area is 25°~45°N, 117°~142°E (Fig. 1). The area covers the West Sea, the East China Sea, the South Sea and the East Sea influencing on the Korean seas. SST was validated using serial oceanographic data from the National Fisheries Research and Development Institute (NFRDI, Korea). Serial Oceanographic Data (SOD) of only 3 stations in the West Sea (WS), the South Sea (SS), the East Sea (ES) were compared with the most adjacent SST pixels, because NOAA/AVHRR MCSST by JPL PO.DAAC has been previously proved. The correlation coefficients were high above 0.8 (Table 1).

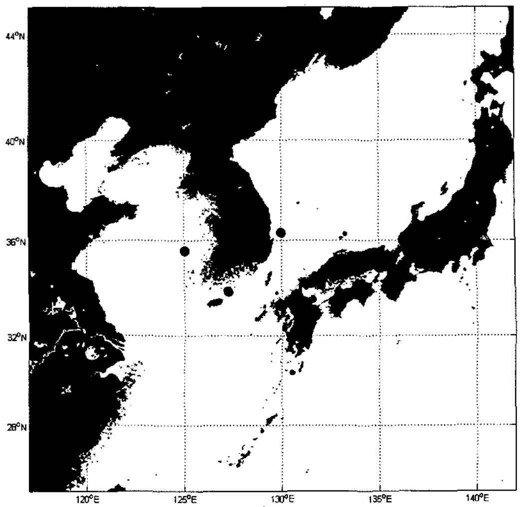


Fig. 1. Study Area (● : serial oceanographic data stations).

2) Sobel Edge Detection Method (SEDM)

In TF regions, isotherms are more closely packed than in adjacent areas. Thus, TF are defined by a steeper

Table 1. Locations and correlations of validation data in Serial Oceanographic Data (SOD) and Satellite MCSST.

		East Sea	West Sea	South Sea
SOD	Locations	St. 103-7 36.30°N 130.00°E	St. 309-7 35.51°N 125.00°E	St. 205-3 34.05°N 127.56°E
	Mean SST	17.26°C	15.31°C	18.61°C
Satellite	Locations	36.29°N 129.99°E	35.59°N 125.06°E	34.01°N 127.52°E
	Mean SST	18.61°C	16.03°C	19.25°C
Correlation coefficients		0.89	0.92	0.89

SST gradient. Sobel filtering can detect edges of TF in the SST gradient and can produce clean results in noisy images because of its high filter weight (Kim and Ro, 2000). This study used the following linear differential equation for the SEDM:

$$\nabla f(x, y) = i(\partial f/\partial x) + j(\partial f/\partial y) = i(Gx) + j(Gy) \quad (1)$$

Gradient magnitude: $[Gx^2 + Gy^2]^{1/2}$,
Gradient Orientation Angle: $\tan^{-1}(Gx/Gy)$

-1	0	1
-2	0	-1
-1	0	1

X direction Mask

-1	-2	-1
0	0	0
1	2	1

Y direction Mask

Applying Sobel Mask, we calculated gradient magnitude and orientation angle and extracted edges of TF when gradient magnitude exceeds threshold (0.3°C) (Budgell, 2003).

3) Empirical Orthogonal Function (EOF) analysis

EOF analysis can describe temporal and spatial variations effectively and simultaneously (Na *et al.*, 1997) and was used to describe SST and TF in this study. The EOF analysis is shown in Eq. (2), where i is mode, $e_i(x)$ presents spatial components and $c_i(t)$ presents temporal components. Gradient values from the SEDM were processed in the EOF analysis of TF.

$$F(x, t) = \sum_{i=1}^{n} e_i(x)c_i(t) \quad (2)$$

3. Results and Discussion

1) SST variations by EOF Analysis

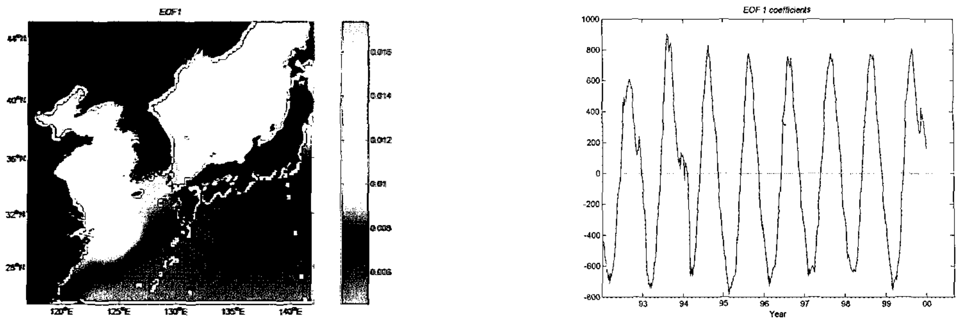
EOF analysis was used to study SST variations in the Korean seas temporally and spatially. The variances of the 1st and 2nd mode were 97.46% and 1.54%, respectively. Spatial components of the 1st mode showed higher variations closer to the continent (Fig. 2a). Temporal components showed annual variations with positive peaks in summer and negative peaks in winter (Fig. 2b). Spatial components of the 2nd mode showed contrasting distributions of positive values in the East Sea and negative values in other seas. Temporal components showed strikingly irregular positive values from 1993 to 1995 (Fig. 3). The period 1993 to 1995 coincided with an ELNIÑO event, so the irregular results may reflect ELNIÑO effects in the region. However, the 2nd mode influence was rather small.

2) Distributions of Thermal Fronts

By using SEDM, we detected significant TF: the Subpolar Front (SPF) in the East Sea as open sea front, the Kuroshio Front (KF) in the East China Sea as continental shelf front, the South Sea Coastal Front (SSCF) in the South Sea as coastal front and the Tidal Front (TDF) in the West Sea as tidal front (Fig. 4). TF in the Korean seas are included in classification of ocean fronts by Yanagi (1987) (Fig. 5). Locations of TF were similar to those of each border dividing the spatial components of the 1st EOF mode applied to SST. Also, TF were located on steep continental slopes; the SPF was in slope from 3000m continent shelf to southern 1000~2000m isobath, the KF was in slope from 100m continent shelf to 500~1000m isobath and the the SSCF was in slope of 20~100m isobath (Fig. 6). The bottom bathymetry seemed to affect locations of TF and these results could be considered as influence of seasonal variations.

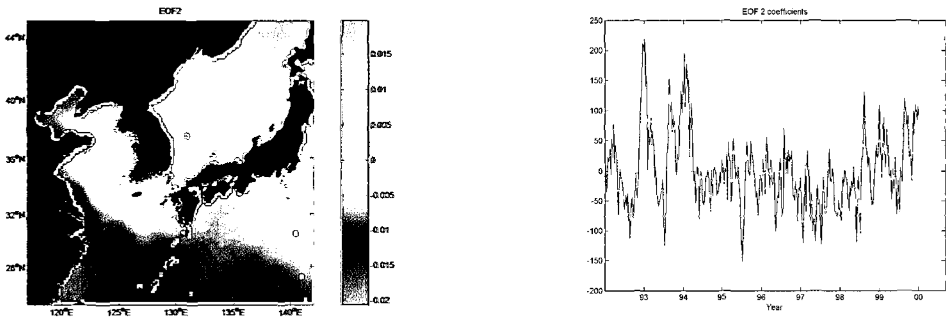
3) EOF analysis of Thermal Fronts

With EOF analysis of TF, we studied temporal variations quantitatively. The variances of the 1st, 2nd and 3rd mode were 64.55%, 22.86% and 12.58%, respectively. SPF, KF and SSCF showed striking negative values in spatial components of the 1st mode, and temporal components showed a negative peak in March with annual variations (Fig. 7). SPF and SSCF



(a) (b)

Fig. 2. (a) Spatial components and (b) temporal components in the 1st mode of SST.



(a) (b)

Fig. 3. (a) Spatial components and (b) temporal components in the 2nd mode of SST.

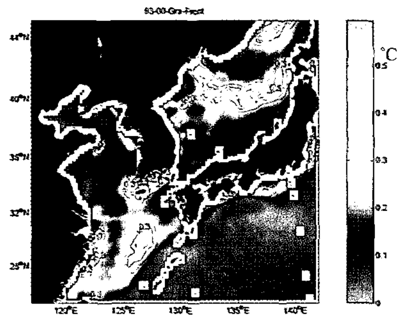


Fig. 4. Distributions of SST gradient values (°C) and Thermal Fronts (red dotted line).

showed negative values but KF showed positive values in spatial components of the 2nd mode (Fig. 8a). As shown in Fig. 8b, values were negative in October and positive in May. SPF showed positive values in spatial components of the 3rd mode and seasonal variations with 2 peaks per year in temporal components (Fig. 9). The times of positive values were March and October.

- Fronts
  - Coastal Fronts
    - Estuarine front
    - Thermal effluent front
    - Themohaline front
    - Tidal front
  - Continental Shelf Front
    - Shelfslope front
    - Coastal upwelling front
    - Coastal boundary current front
  - Open sea Front
    - Western boundary current front
      Warm core front, cold core front
    - Subartic front
    - Subtropical front
    - Doldrum front
    - Polar front

Fig. 5. Classification of ocean fronts (Yanagi, 1987).

In summary, we could know SPF and SSCF were presented in March and October and KF was presented in March and May significantly. TDF in the West Sea

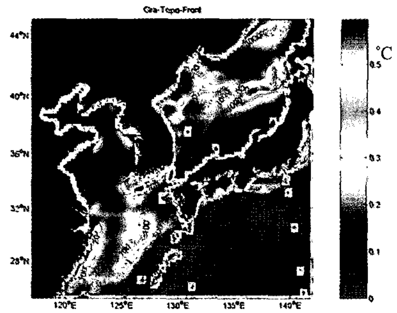
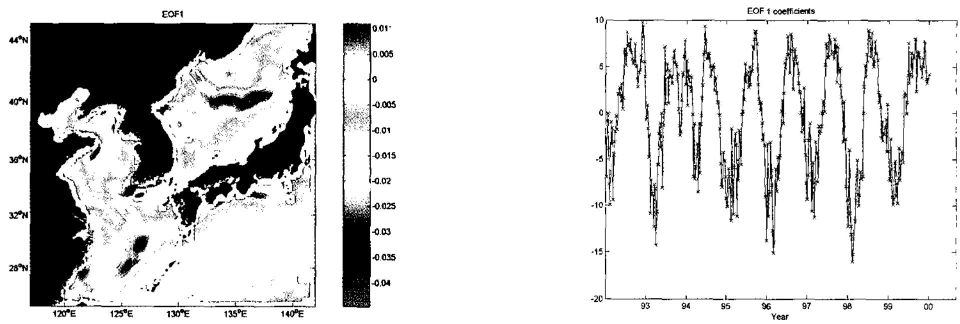
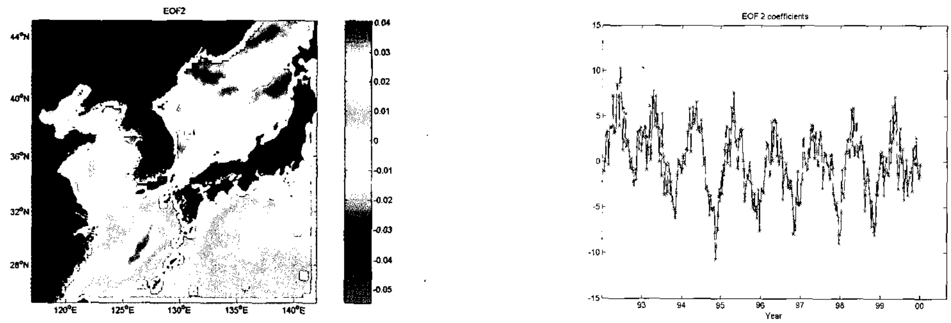


Fig. 6. Distributions of bottom bathymetry and Thermal Fronts (red dotted line) on SST gradients image.



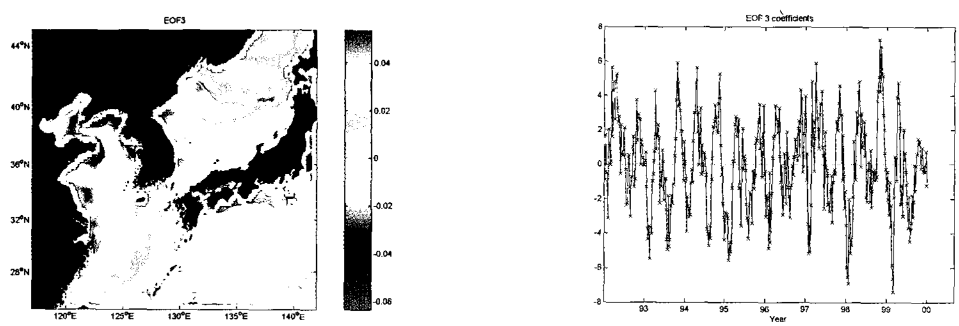
(a) (b)

Fig. 7. (a) Spatial components and (b) temporal components in the 1st mode of SST gradients.



(a) (b)

Fig. 8. (a) Spatial components and (b) temporal components in the 2nd mode of SST gradients.



(a) (b)

Fig. 9. (a) Spatial components and (b) temporal components in the 3rd mode of SST gradients.

could not be analyzed because it appeared weakly.

4. Conclusions

EOF analysis revealed temporal and spatial variations of SST in the Korean seas. The 1st mode was suitable for presenting SST variations in the study area as the variance is 97.6%. It showed that there existed annual variations and that where it is closer to coasts, the variations are higher. The variance of the 2nd mode was not remarkable as 1.54% and spatial and temporal components did not show conspicuous phenomena. But temporal components from 1993 to 1995 when ELNIÑO occurred were higher than those of other years. Thus, it could suggest ELNIÑO effects to the Korean seas.

By using sobel edge detection method, we could find 4 Thermal Fronts (TF) which are included in classification of ocean fronts: the Subpolar Front, the Kuroshio Front, the South Sea Coastal Front and the Tidal Front. Therefore, the study area is efficient to study ocean fronts. Locations of TF were similar to those of each border dividing the spatial components for the 1st EOF mode of SST and at the same time in steep bathymetry. As a result of EOF applied to SST gradients, SPF and SSCF were dominant in March and October and KF in March and May.

This paper presented quantitative temporal and spatial variations in SST from EOF analysis based on satellite data, and showed distributions of TF and figured out the correlation of SST and TF. However, satellite data were so difficult to present the precise threshold for detecting TF. Therefore, researches on objective and correct distribution of TF, and specific TF variations are needed.

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