Empirical Orthogonal Function Analysis of Coastal Water Temperatures in the Tsushima Current Region

Seog-Won CHOI and Yong Q. KANG
Department of Oceanography, National Fisheries University of Pusan, Pusan, 608 Korea
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The fluctuations of sea surface temperatures (SST) and their anomalies in the Tsushima Current region are studied by means of empirical orthogonal function (EOF) analysis of the monthly SST data for 30 years (1941-1970) at 8 coastal stations. The overall features of the seasonal variation of SST are described by the first EOF mode, which explains 97.2% of the total variance. Annual ranges of seasonal variation of SST and root-mean-square amplitudes of SST anomalies in the downstream of the Tsushima Current are larger than those in the upstream. The SST anomalies in the Tsushima Current region consist of simultaneous fluctuations, which explain 40.9% of the total variance, and "see-saw" fluctuations of which rise and fall in the upstream are opposite to those in the downstream. The latter second EOF mode explains 19.3% of the total variance. We generated the low-pass (periods longer than 24 months), band-pass (periods between 6 and 24 months) and high-pass (periods shorter than 6 months) SST anomaly series and analyzed them by EOF method. The spatial distributions of the first and second EOF modes of all filtered SST anomalies are similar to each other.

Introduction

Fluctuations of the sea surface temperatures (SST) are dominated by seasonal variations, but annual march of SST does not repeat exactly the same pattern each year. The seasonal variation of SST can be represented by means of harmonic method. Examples of the harmonic anlysis include studies on variation of SST in the neighbouring seas of Korea by Kang and Jin (1984) and in the Japan Sea by Kang (1985a).

The SST anomalies, or departures of SST from multi-year normals, are often studied by means of variance and cross-correlation analyses. Spatial distributions of intensity of fluctuations and space-scales of fluctuations can be studied by means of the variance and cross-correlation analyses, but temporal characteristics of fluctuations are not well posed by means of those analyses.

Empirical orthogonal function (EOF) or eigen-function analysis of time series at many locations is very useful in representing both spatial and temporal characteristics of fluctuations. The EOF analysis has a shortage that its results do not provide an explanation for the associated physical processes, but the EOF analysis is very useful in obtaining an overall view on the spatio-temporal behavior of multiple time series. The EOF analysis was employed in describing oceanic variabilities by many authors. For example, Weare *et al* (1976) and Lie *et al* (1986) studied the spatial and temporal fluctuations of SST in the Pacific and in the south-eastern Yellow Sea, respectively.

In this paper, we present the spatial and temporal characteristics of SST and their anomalies in the Tsushima Current region depicted by the EOF analysis. This paper extends our previous work on the annual and interannual fluctuations of SST in the Tsushima Current and Kuroshio regions studied by the harmonic, correlation and spectral analyses

(Kang and Choi, 1985).

Data and Method

Our study is based on the monthly SST data for 30 years from 1941 to 1970 at 8 coastal stations in the Tsushima Current region shown in Fig. 1. The data was published by Japan Meteorological Agency

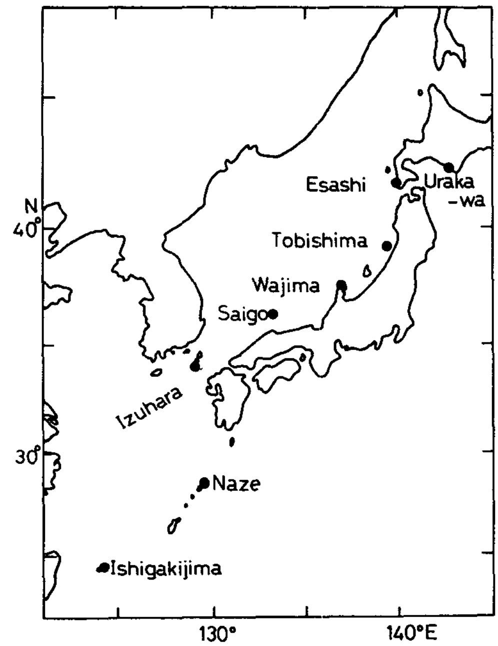

Fig. 1. Locations of coastal stations.

(1976). The time series of SST anomalies are generated by removing monthly normals of SST at each station. The low-pass (periods longer than 24 months), band-pass (periods between 6 and 24 months) and high-pass (periods shorter than 6 months) SST anomaly series are generated by the symmetric convolution filter techniques. We applied Hamming window in order to reduce Gibb's effect, namely, overshootings and wiggles in frequency response function (Kim and Kang, 1984). There is no distortion of phase in the filtered series generated by symmetric convolution filter.

The data sets of actual SST, SST anomaly, low-pass anomaly, band-pass anomaly and high-pass anomaly are analyzed by EOF method. Methematical details of the EOF method can be found in Kutzbach (1967). For an easy understanding of our results, we present the basic ideas of EOF method.

A collection of time series with length n at m locations can be represented by an m by n matrix $F(x,t)$. This set of data is decomposed into various EOF modes by

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

where i is the mode number, $e_i(x)$ is the i-th eigenvector or eigenfunction that satisfies the orthonormality condition, and $c_i(t)$ is the time-dependent coefficients associated with the i-th mode. The eigenvector $e_i(x)$ represents the spatial characteristics of i-th mode, and $c_i(t)$ represents the temporal characteristics of i-th mode. In the EOF method, the multi-dimensional time series $F(x,t)$ is represented by the superposition of spatially and temporally orthogonal functions.

The nomalized eigenvector e can be found by solving an eigenvalue problem

$$Re=\lambda e$$

where R is the m by m covariance matrix of the time series at m locations. There are m eigenvalues associated with m eigenvectors. Since the covariance matrix is symmetric, the eigenvalues are real and positive. It can be shown that the i-th eigenvalue is equal to the variance of the i-th time-dependent coefficient, and the fraction of variance explained by the i-th eigenfunction is equal to the ratio between the i-th eigenvalue and the sum of all eigenvalues.

The time-dependent coefficients represent the temporal characteristic, but their magnitudes are not the same as the physical magnitude, because we applied an orthonormality condition to the eigenvectors. Actual root-mean-square (rms) amplitude $A_i(x)$ of the time series associated with i-th eigenvector at location x can be computed by

$$A_i^2(\mathrm{x})=\lambda_i\, e_i^2(x).$$

One of the main advantages of EOF analysis is its capability to describe both spatial and temporal characteristics of a set of time series at many locations by considering only a few EOF modes with large eigenvalues. However, each mode does not necessarily accompany the corresponding physi-

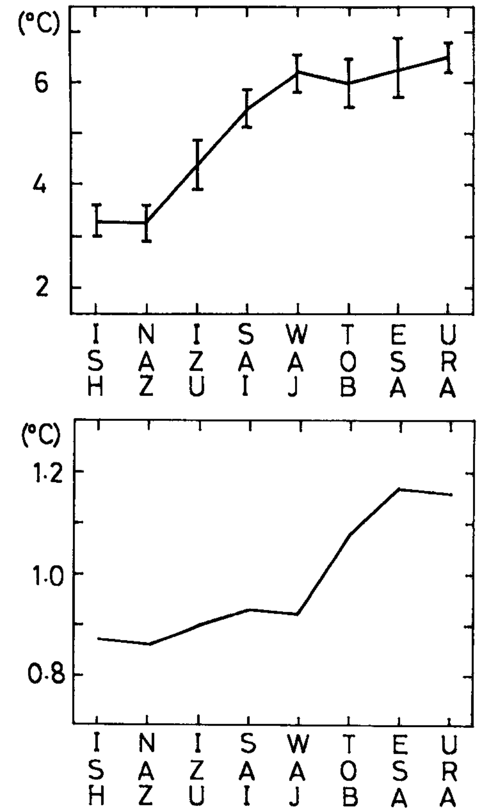

Fig. 2. Spatial distributions of rms amplitudes of SST (upper) and SST anomalies (lower).

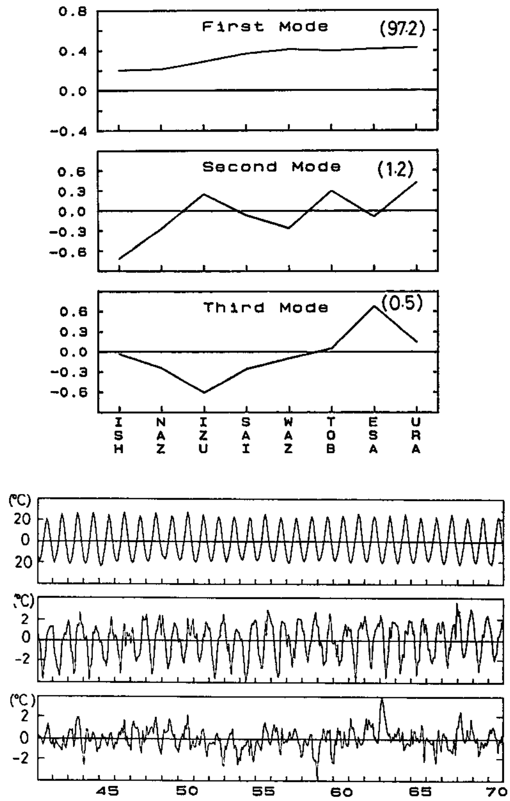

Fig. 3. Eigenfunctions and time-dependent coefficients of the first three EOF modes of SST flucuations at 8 coastal stations in the Tsushima Current region.

cal processes.

Results

The spatial distributions of rms amplitudes of SST and SST anomalies are shown in Fig. 2. The rms amplitudes of both SST and SST anomalies have a tendency to increase with the downstream distance of the Tsushima Current. The rms amplitude of SST is 3.3°C at Ishigakijima and 6.0°C at Esashi. The rms amplitude of SST anomalies is about 0.9°C at Ishigakijima and 1.2°C at Esashi.

The first three modes of eigenfunctions and associated time-dependent coefficients are shown in Fig. 3. The first EOF mode, which explains 97.2% of the total variance, is characterized by a monotonic increase of eigenfunction with downstream distance and also by the annual variation of the time-dependent coefficients. The eigenfunction of the second mode, which explains 1.2% of the total variance, changes its sign depending on stations, and the associated time coefficients are dominated by fluctuations with an annual period.

The first three EOF modes of SST anomalies are shown in Fig. 4. The eigenfunction of the first mode, which explains 40.9% of the total variance, has the same sign at all stations and its magnitude increases with the downstream distance of the Tsushima Current. The eigenfunction of the second mode, which explains 19.3% of the total variance, is positive at upstream stations (from Ishigakijima to Wajima) and negative at downstream stations (Tobishima, Esashi and Urakawa). The first and second EOF mode together explain about two-thirds of the total variance. The corresponding time-

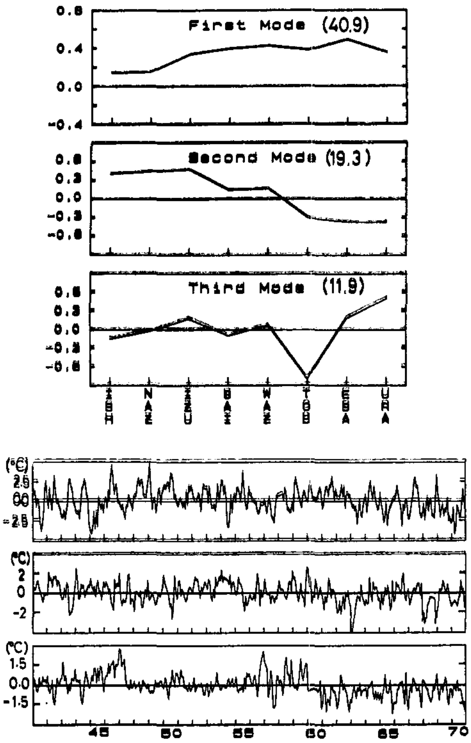

Fig. 4. Eigenfunctions and time-dependent coefficients of the SST anomaly series.

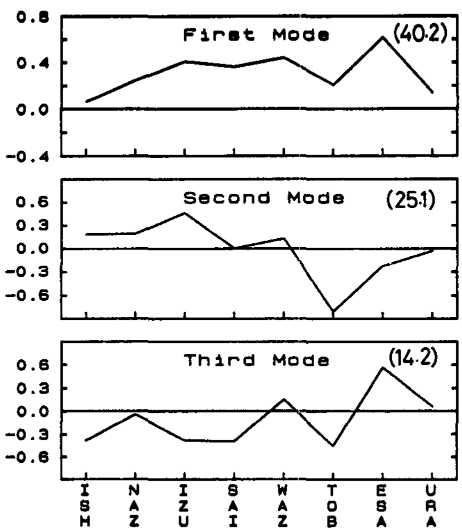

Fig. 5. Eigenfunctions of the low-pass SST anomalies with periods longer than 24 months.

dependent coefficients show irregular fluctuations.

The eigenfunctions of the first three EOF modes of the low-pass (periods longer than 24 months), band-pass (periods between 6 and 24 months) and

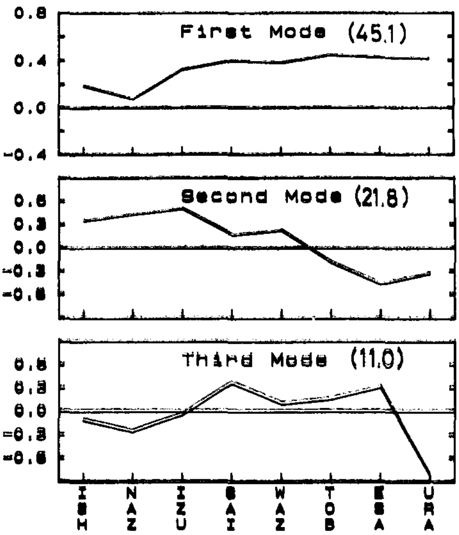

Fig. 6. Eigenfunction of the band-pass SST anomalies with periods between 6 and 24 months.

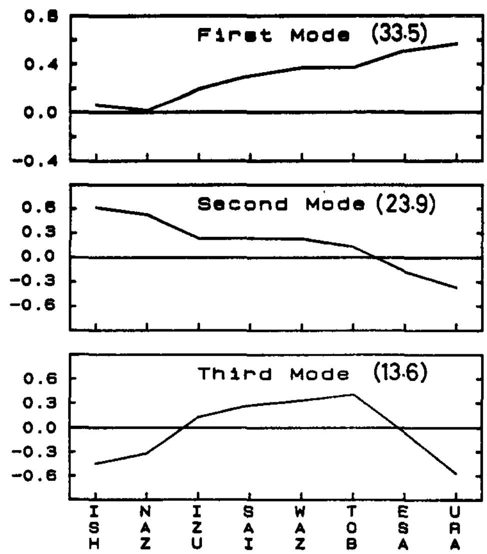

Fig. 7. Eigenfunction of the high-pass SST anomalies with periods shorter than 6 months.

high-pass (periods shorter than 6 months) SST anomalies are shown in Figs. 5, 6 and 7, respectively. The first mode eigenfunctions of the low-pass, band-pass and high-pass SST anomalies have the same sign at all stations and they have a tendency to increase their magnitudes with the downstream distance of the Tsushima Current. The second mode eigenfunctions of all filtered SST anomalies are positive in the upstream and negative in the downstream. In other words, the spatial distributions of the first two EOF modes for all filtered SST anomaly series are similar to each other.

Discussion and Conclusions

The spatio-temporal characteristics of SST fluctuations and SST anomalies for 30 years (1941-1970) at 8 coastal stations in the Tsushima Current region are analyzed by EOF method. The SST anomalies in various frequency bands are studied by EOF analysis of the low-, band- and high-pass SST anomalies.

The actual SST fluctuations in our study area are dominated by seasonal variations of which annual march is almost simultaneous at all stations. An increase of annual range of seasonal variation with downstream distance of the Tsushima Current is cleary represented in the eigenfunction of the first mode. Annual ranges of SST fluctuations in the northern part of the Japan Sea are larger than those near the Korea Strait mainly due to seasonal advections of heat associated with the Asian monsoon (Kang, 1985b).

The spatial distribution of the first mode eigenfunction of SST anomalies (Fig. 4) is similar to that of rms amplitude of SST anomalies themselves (Fig. 2). The SST anomalies associated with the first EOF mode, which explains 40.9% of the total variance, change simultaneously at all stations. This fact suggests that fluctuations of SST anomalies in our study area are spatially correlated. Advections of heat along the Tsushima Current are expected to play a major role in spatial correlation of SST anomaly field.

The eigenfunction of the first EOF mode of high-pass SST anomalies has the same sign at all stations (Fig. 7), and the associated fluctuations of high-pass SST anomalies are spatially correlated. This suggests that the time scales of heat advection in our region by the Tsushima Current is much less than 6 months or the cut-off period of our high-pass SST anomaly series.

The second mode of SST anomalies is characterized by "see-saw" fluctuations. That is, an increase in the upstream is associated with a decrease in the downstream and vice versa. The second mode explains 19.3% of the total variances. Similar "see-saw" fluctuations appear as the second EOF modes for all of the low-, the band- and the high-pass SST anomalies. The fluctuations of SST anomalies in the Tsushima Current region can be summarized as follows. About two-thirds of SST anomalies in the Tsushima Current region can be described by a superposition of "simultaneous" fluctuations and "see-saw" fluctuations. The corresponding temporal fluctuations are irregular. The spatial distributions of "simultaneous" and "see-saw" fluctuations hold true for all of the low-, the band- and the high-pass SST anomalies in our study area.

Acknowledgements

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쓰시마난류역 연안 수온의 경험적 직교함수 분석

최 석 원 · 강 용 균
부산수산대학 해양학과

쓰시마난류역 연안 8개 지점의 30년간 (1941~1970) 표면수온과 이상수온에 대한 경험적 직교함수(EOF) 분석을 통하여 수온의 시공간적 변동을 구명하였다. 본 해역 표면수온 계절변동의 전반적 양상은 전체 변동량의 97.2%를 설명하는 제 1 EOF 모드로 기술된다. 표면수온 계절변동의 연교차는 상류에서 작고 하류에서 크다. EOF 분석에 의하면, 쓰시마난류역 표면이상수온은 전해역이 동시적으로 승강하는 변동 (전체 변동량의 40.9%)과 상류역과 하류역의 이상수온 승강이 반대인 "교차적 변동"(전체 변동량의 19.3%)의 합으로 나타낼 수 있다. 주파수 영역별로 이상수온 변동의 특성을 구명하기 위해 각 관측점의 이상 수온을 종합필터 방법으로 장주기(주기 24개월 이상), 중간주기(주기 6~24개월) 및 단주기(주기 6개월 미만) 영역의 시계열로 분리한 후, 각 주기 영역 이상수온에 대한 별도의 EOF 분석 결과에 의하면, 제 1 및 제 2 EOF 모드의 공간적 분포는 모든 주기 영역에서 비슷하다.