Spatio-temporal Variability in Sea Surface Temperatures for the Yellow Sea based on MODIS Dataset

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Abstract – The spatio-temporal variabilities in sea surface temperature (SST) were analyzed using a time series of MODIS datasets for four separate regions in the Yellow Sea (YS) that were located along a north-south axis. The space variant temporal anomaly was further decomposed using an empirical orthogonal function (EOF) for estimating spatially distributed SST. The monthly SSTs showed similar temporal patterns in each region, which ranged from 2.4°C to 28.4°C in the study years 2011 to 2013, with seasonal cycles being stronger at the higher latitudes and weaker at the lower latitudes. Spatially, although there were no significant differences among the four regions ($p < 0.05$) in any year, the geographical distribution of SST was characterized by an obvious gradient whereby SST decreased along the north-south axis. The monthly thermal difference among regions was largest in winter since the SST in the southeast was mainly affected by the Yellow Sea Warm Currents. The EOF1 mode accounted for 56% of the total spatial variance and exhibited a warming signal during the study period. The EOF2 mode accounted for 8% of the total variance and indicated the warm current features in the YS. The EOF3 mode accounted for 6% of the total variance and indicated the topographical features. The methodology used in this study demonstrated the spatio-temporal variabilities in the YS.

Key words – Yellow Sea, sea surface temperature, currents, empirical orthogonal function analysis

1. Introduction

The Yellow Sea (YS) is a semi-enclosed marginal sea that has a mean water depth of 44 m. There is a north-south oriented trough (> 70 m deep) in the central area, and the

bathymetric contours on both sides of the trough are generally parallel to the coastline (Fig. 1). During winter (December–February), the Yellow Sea Warm Current (YSWC) enters the YS from the southeast and advances to the north (Teague and Jacobs 2000; Lie et al. 2009; Yu et al. 2010) and the Yellow Sea Cold Water Mass (YSCWM; 122°–125°E, 34°–37°N) becomes entrenched at the bottom of the sea during the summer (June–August) (Ho et al. 1959; Yu et al. 2006; Zhang et al. 2008; Mei et al. 2016). These water masses represent the two most important physical oceanographic features in the YS. In addition, a southward coastal flow is present during winter along the eastern and western boundaries of the YS (Uda 1934, 1936) and corresponds to the development of the northward YSWC in the central sea area (Wei et al. 2016; Xu et al. 2016).

Sea Surface Temperature (SST) is one of the more important oceanic and atmospheric variables and has been widely used in a variety of studies intended to develop an understanding of ocean dynamics, as well as of the physical and biogeochemical processes occurring in the upper layers of the sea. The importance of SST variability in the YS has been addressed by numerous satellite-based studies (Lin et al. 2005; Shi and Wang 2012; Tseng et al. 2000; Wei et al. 2010; Yeh and Kim 2010). This literature also reports that the complex spatial and temporal variabilities in SST are associated with features such as the thermal or tidal fronts, coastal waters, and currents, etc. that are described above. Recently, several analyses of SST datasets have considered the spatial and temporal distributions of SST in order to examine seasonal and annual SST variability

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and the warming signal in the YS. These studies used the empirical orthogonal function (EOF) method (Yeh and Kim 2010; Park et al. 2015), which is also widely used in other disciplines (Alvarez and Pan 2016; Hu and Si 2016). These earlier studies of SST variability consider the YS as an area in its entirety and focus on relatively long time series variations. The SST exhibits strong variabilities since it is affected greatly by the heterogeneity of hydrographic features in the YS described above. In contrast, in this present study, we seek to compare detailed spatio-temporal patterns of SST in the YS by investigating several separate regions of the YS over a relatively short time-scale.

Therefore, we carried out such an investigation that utilized a time series of SST datasets obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor onboard the Aqua satellite of NASA. We compared the differences in spatial and temporal variabilities for four separate geographical regions in the YS and examined the relation between SST and the regional processes reported by Park et al. (2015) by using the EOF analysis method. The main objectives of this study were to (1) compare the spatial and temporal patterns of the SST in the four regions and (2) investigate the spatial patterns of dominant temporal SST variability by EOF decomposition in the study area.

2. Data Source and Methods

Data source

The MODIS level-3 thermal Infra-red (TIR) (11 micron) daytime monthly composites SST measured by the Aqua satellite of NASA for the years 2011–2013 were downloaded from the ocean color website (<http://oceancolor.gsfc.nasa.gov/cgi/l3>) and processed at 4 km resolution based on the algorithm theory of Brown and Minnett (1999). In order to examine spatial and temporal differences in SST variability from the northern to the southern boundaries of the YS, we defined four separate regions lying along a north to south axis (Fig. 1). The exact positions of these regions were all located in the central part of the YS as related to its western and eastern boundaries, since the SSTs in coastal waters are affected greatly by discharge from rivers and other water sources (Park et al. 2015). The area of each region was bounded by a rectangle (2 by 1) oriented along a west to east axis. The four regions were designated as Regions 1 to 4 and the upper left corners of these regions had the following geographical coordinates: Region 1, 122°E and 39°N; Region 2: 123°E

Fig. 1. Study area with four defined geographic regions (numbered rectangles) in the Yellow Sea

and 37°N; Region 3: 122°E and 35°N; and Region 4: 123°E and 33°N.

Empirical orthogonal function (EOF) analysis

To simplify and quantify the complex variability in the monthly SST from 2011 to 2013 throughout the YS, the spatial SST datasets were decomposed into their dominant modes using EOF analysis (Kelly 1988; Lagerloef and Bernstein 1988). Since the input map time series should not have missing data in order to conduct the EOF analysis, we first used the monthly SST datasets that had the fewest number of pixels without data (due to cloud cover, etc.) in the study area. Then, for the pixels where data was missing, data was inserted based on an interpolation that used the mean of the valid measured SST values of the time series.

All of the SST datasets were adjusted by removing the temporal average of the 36 monthly datasets. This was expressed as:

$$I'(x, t) = I(x, t) - \frac{1}{N} \sum_{t=1}^N I(x, t) \quad (1)$$

where $I'(x, t)$ is the set of all adjusted monthly datasets, $I(x, t)$ represents the set of all monthly datasets; and N is the number of all monthly datasets. Using EOF analysis, the 36 adjusted monthly datasets produced the temporal variance.

Alternatively, the spatial average of each monthly dataset was removed as follows:

$$I'(x, t) = I(x, t) - \frac{1}{M} \sum_{x=1}^M I(x, t) \quad (2)$$

where M is the total number of pixels of each dataset. The spatial variance could then be examined using the EOF analysis.

The spatially or temporally adjusted $I'(x, t)$ datasets were used to calculate the autocovariance of each dataset and the covariance between datasets. An eigenvector $a_n(t)$ was then obtained to decompose $I'(x, t)$ as follows:

$$I'(x, t) = \sum_{n=1}^N a_n F_n(x) \quad (3)$$

The time-varying amplitude function, $a_n(t)$, was calculated by the projection method using the formula:

$$a_n(t) = \sum_{t=1}^M I'(x, t) F_n(x) \quad (4)$$

In Eqs. (3) and (4), $F_n(x)$ is the spatial amplitude function

of each EOF mode that was used to make a comparison of the dominant hydrographic distribution patterns in the YS.

In order to test the significance of the EOF modes, we used the methods described by North et al. (1982). The error produced in a given EOF (e_j) was calculated as:

$$e_j = \lambda_j \left(\frac{2}{N} \right)^{0.5} \quad (5)$$

where λ_j is the eigenvalue for the j^{th} EOF; and N is the degrees of freedom. When the difference between neighboring eigenvalues satisfied $\lambda_j - \lambda_{j+1} \geq e_j$, then the EOF modes represented by these two eigenvalues were statistically significant.

3. Results and Discussion

Temporal variations of SST patterns

The monthly mean SST and the SST anomalies in each of the four regions of the YS for each study year (2011, 2012 and 2013) are presented in Fig. 2 and Fig. 3, respectively. The monthly anomaly at a given pixel was calculated as the difference between the mean monthly SST minus the total mean SST for the entire study period of 36 months. The SST and the SST anomalies in each region both show similar monthly temporal patterns during the three study years.

Fig. 2. Monthly temporal distributions of SST (°C) in the four study regions

Fig. 3. Changes in monthly mean SST anomalies ($^{\circ}\text{C}$) in the four regions during three study years (2011–2013)

Table 1. Monthly SST ($^{\circ}\text{C}$) statistical characteristics for each of the three study years (2011–2013)

		The whole year				Summer				Winter			
		Mean	Max.	Min.	<i>CV</i>	Mean	Max.	Min.	<i>CV</i>	Mean	Max.	Min.	<i>CV</i>
Region 1	2011	12.30	23.73	2.43	8.53	20.12	22.25	18.20	2.92	5.20	6.45	3.18	11.22
	2012	13.21	26.05	2.61	7.95	22.72	23.94	20.99	1.90	4.97	6.69	1.86	16.65
	2013	13.07	26.26	2.76	10.25	22.94	25.52	20.51	3.42	5.71	7.48	4.09	10.89
Region 2	2011	13.87	23.78	5.30	4.76	21.02	22.16	19.71	1.87	7.93	9.58	4.94	7.53
	2012	15.07	27.10	5.92	5.18	24.55	25.93	22.33	2.64	6.91	9.49	3.33	9.50
	2013	15.05	27.53	6.07	4.69	23.85	25.13	21.24	2.91	8.02	8.19	5.94	4.56
Region 3	2011	15.04	24.68	7.22	4.51	22.35	24.27	20.33	2.73	9.98	12.32	7.46	7.73
	2012	16.55	26.01	7.58	4.49	24.72	25.86	22.83	1.81	9.84	11.84	7.05	7.76
	2013	16.38	28.41	7.97	4.34	24.84	26.61	23.25	2.35	10.02	11.57	8.17	6.99
Region 4	2011	16.87	26.62	8.37	5.31	23.63	25.62	22.17	2.31	11.27	15.21	8.00	10.45
	2012	17.39	27.44	8.79	5.87	24.97	26.25	23.34	2.16	10.72	13.48	8.54	7.99
	2013	17.59	28.24	8.52	4.18	24.98	26.07	23.91	1.58	11.73	15.14	9.72	10.87

Maximum (Max), minimum (Min), coefficient of variation (*CV*)

Generally, for each year, the monthly mean SST increased from the northern to the southern regions. The SST ranged from 2.4°C to 28.4°C , with seasonal cycles being strongest at the highest latitude (Region 1) and weakest at the lowest latitude (Region 4) (Table 1 and Fig. 2). The maximum SST values occurred between July and August while lower values occurred between February and March in each region. The highest 3-year SST ($\sim 28^{\circ}\text{C}$) was observed in Region 4 in August 2013, while the lowest 3-year SST ($\sim 2^{\circ}\text{C}$) was observed in Region 1 in February 2011. The seasonal variation in SST was affected mainly by the net sea surface heat flux; however, ocean circulation and mixing also influenced the temporal and spatial variations in SST (Zhai et al. 2010). For example, during winter, the SST in Region 4 was $\sim 11^{\circ}\text{C}$ on average and was affected by the YSWC while, during summer, the SST in Region 2 and 3 were $\sim 23^{\circ}\text{C}$ and 24°C due to the effects of the YSCWM, which were stronger during summer.

The monthly time series SST data also revealed a characteristic monthly cycle of the SST coefficient of variation (*CV*), which

was calculated as the ratio of standard deviation (STD) to mean SST and expressed as a percentage, in each of the four regions (Fig. 4). Most of the SST variability, characterized by the *CV* displayed in Fig. 4, could be attributed to the annual cycle. The values were higher between January and March and were lower between July and October in most regions of the three study years. This annual cycle was the opposite of the seasonal cycle for the monthly SST variations. The STD of SST in each region showed similar variation trends to those of the *CV* (Fig. 4). This was due to the efficient mixing of sea surface water layers in the YS by wind-induced and convective processes due to the presence of the YSCWM during the summer, which reduced variability; while in the absence of the YSCWM during the winter, the mixing was less efficient and variability was increased (Chu et al. 2005). For the entire study period, the mean SST *CV* in Region 1 had the highest value (8.9%) while values in the other three regions were all lower. This is consistent with the generally accepted view that variation during seasonal cycles would

Fig. 4. Temporal distributions in the *CV* and *STD* (black lines) of mean SST (°C) in the four regions during the three study years (2011–2013)

be stronger at the highest latitude (Region 1), where the seasonal fluctuations of the solar radiation were also greater than in regions closer to the equator (Esbensen and Kushnir 1981).

Spatial variations in SST patterns

The monthly SST in each year was temporally averaged to produce information about their respective seasonal (Fig. 5) and annual (Fig. 6) SST in the YS. The SST exhibited a sinusoidal seasonal cycle in which a persistent seasonal warming trend from winter to summer occurred in each year (Fig. 5). This demonstrated that there was a coherent pattern that was also shared by the variations in the monthly SST anomalies (Fig. 3). Spatially, the mean SST always followed the order of Region 1 < Region 2 < Region 3 < Region 4 in each year. This was partly the result of the decreasing solar radiation with increasing latitude (Esbensen and Kushnir 1981). Another reason was that Region 2, Region 3 and Region 4 were all in the area affected by the YS water currents whereas Region 1 was closer to the north coastal water current. There were obvious differences in the temperatures between Region 1 and Region 4 in both the spring and winter; these differences

were 5.3°C and 5.9°C respectively. In contrast, the difference was weak in the summer and fall between Region 1 (2.6°C) and Region 4 (3.8°C), since the YSWC in the south east of the YS begins to form in winter and diminishes during summer.

The spatial distributions of the annual SST during each of the three study years (2011–2013) are shown in Fig. 6. In 2011, the SST in the YS ranged from 2.4°C to 26.6°C with a mean SST of 14.5°C. In 2012, the SST in most areas ranged from 2.6°C to 27.4°C with a mean of 15.6°C. In 2013, the SST ranged from 2.8°C to 28.4°C with a mean of 15.5°C. In each year, the isotherms were generally parallel to the isobaths, running in the southwest-northeast direction. Three cold areas were evident, i.e., in the coastal waters to the west, east and north, which were influenced by the coastal water current. Two warm areas were also observed in the central and south-east YS that were related to the YS warm currents. There were no significant differences among the four regions ($p < 0.05$) in any study year. However, the geographical distribution of SST was characterized by an obvious gradient whereby SST increased from the northern to the southern parts of the YS, with the 3-year mean SST increasing from about 12.9°C in Region 1 to 17.3°C in Region 4.

Fig. 5. Spatial distributions of seasonal SST (°C) in the three study years (2011–2013)

Empirical orthogonal function (EOF) analysis of SST

The variance contribution and cumulative variance of the first six EOF modes are presented in Table 2. The North test showed that only the first three modes passed the significance

test in our study. Therefore, in this paper, only the first three modes were discussed. The EOF1 mode accounted for 56% of the total spatial SST variance (Table 2). The SST anomalies in the EOF1 mode for the entire study area were all positive

Fig. 6. Spatial distributions of annual SST (°C) in the three study years (2011–2013)

Table 2. Variance contributions (%) of the first six empirical orthogonal function (EOF) modes

EOF	EOF1	EOF2	EOF3	EOF4	EOF5	EOF6
Variance contribution	55.91	7.57	6.35	3.75	2.81	2.71
Cumulative variance contribution rate	55.91	63.48	69.83	73.58	76.39	79.10

Fig. 7. EOF analysis of monthly SST anomalies (°C)

(Fig. 7a), but they were not uniformly distributed throughout the entire study area. These findings were consistent with those of previous studies carried out in the YS (Zeng et al. 2006; Wang et al. 2009; Park et al. 2015). The center of the

SST anomalies was located in an area with the geographical coordinates of about 35°–37°N and 124°–126°E, which was mainly affected by the YS coastal waters. When the time coefficients were positive, it indicated that the SST increased in

the entire study area; negative coefficients indicated that the SST decreased. In our study, the EOF1 time coefficients had positive values in the warm water seasons (August–October) and negative values during the cold water season (January–May) in years 2012–2013 (Fig. 8a). Negative values occurred in the warm season in the year of 2011, which suggested that the summer of 2011 was relatively cold as compared to the

Fig. 8. Time-varying amplitude functions corresponding to Fig. 7 for three modes derived from the spatial variance EOF analysis

summers in the years of 2012 and 2013. These results were consistent with that shown in Table 1. It indicated that the EOF1 mode was related to the SST inter-annual variations. The signal reflected that the EOF1 mode was not only influenced by the solar shortwave radiation energy and by the air temperature at the sea surface, but was also probably affected by the weather conditions (Park *et al.* 2015). The time coefficient of the EOF1 mode demonstrated the warming signal (Fig. 8a). This finding was consistent with earlier results published by Park *et al.* (2015). Park *et al.* (2015) indicated that there was a warming trend in the years 1981–2009. Our study focused on the years 2011–2013, which was a much shorter time series than that of Park *et al.* (2015). Consequently, we could not conclude that the SST in the YS had continued to increase from 1981 until 2013. More recent datasets should be used for further investigations. The STD calculated from the 3-year time series of SST is presented in Fig. 9, and is similar to the eigenvector map of the EOF1 mode presented in Fig. 7a. The highest STD value ($\sim 1.2^{\circ}\text{C}$) occurred in an area bounded by $35\text{--}37^{\circ}\text{N}$ and $124\text{--}126^{\circ}\text{E}$.

The EOF2 mode (accounting for 8% of the total variance) presented a feature that had a more north-south orientation (Fig. 7b). There was an opposite variability between the waters in the southeast, which were closer to the warm currents and

Fig. 9. Annual mean STD of SST ($^{\circ}\text{C}$) over the three study years (2011–2013)

that exhibited a positive variation in SST, and a negative variation in the central waters; i.e., indicating that the two regions had opposing trends. The EOF2 mode could be explained by the influences of the YSWC in the southeast and of the YSCWM in the central waters of the YS. The time coefficients were positive, which indicated an increase in SST in the southeast area and a decrease in the central area of the YS. Conversely, when the time coefficients were negative, it indicated a decrease in SST in the southeast area and an increase in the central area (Fig. 8b).

The SST variations in the EOF3 mode (accounting for 6% of the total variance) alternated with positive and negative values occurring in the spatial pattern (Fig. 7c). The positive values occurred in the southern YS, while the negative values occurred in the northern YS. The spatial distribution of the EOF3 mode was similar to the SST presented in Fig. 10. The time coefficients exhibited greater inter-annual variation than they did for the seasonal cycles. The EOF3 mode could be explained by the influence of the sea floor topography. The time coefficient of the EOF3 mode showed high positive values in June/2011, September/2012, July/2013 and December/2013 (Fig. 8c), which were in contrast to the spatial distribution of the EOF3 in the northern YS. Probably in the summer, the YS experienced cooling events in the coastal

waters of the northern YS. The SST anomalies exhibited larger seasonal variations in the shallower waters than those in the deeper waters. Since the coastal water had a low thermal capacity, the SST was easily changed in these areas by the weather conditions such as the occurrence of monsoon rains and atmospheric oscillations, etc.

4. Conclusion

In this study, MODIS SST datasets were used to study the detailed heterogeneity of SST by dividing the YS into four geographical regions. The SST in the region exhibited similar monthly temporal patterns in the three study years (2011, 2012 and 2013). The seasonal cycles showed the general trend that it was stronger at higher latitude (Region 1) and weaker at lower latitude (Region 4). Spatially, the maximum thermal difference between higher latitude (Region 1) and lower latitude (Region 4) was unequal and was larger in summer and winter, mostly because of the influence of the physical environments. Close to Region 4 the SST was mainly affected by the YSWC, which was stronger in winter than in summer. The spatial distribution of annual SST had isotherms that were generally parallel to the isobaths, which ran in a southwest-northeast direction. Although there were no significant differences among the four regions ($p < 0.05$) in any year, the geographical distribution of SST was characterized by an obvious gradient whereby temperatures decreased from the southern to the northern parts of the YS.

The remarkable feature from EOF1 was a manifest distinction in the spatial patterns of the eigenvector map, which was similar to the overall SST STD pattern in the YS. The center of the SST anomalies was located in an area with the geographical coordinates of about 35° – 37° N and 124° – 126° E. The time coefficient of the EOF1 increased during the study period. The EOF2 mode accounted for 8% of the total variance, and indicated the importance of the features of the different currents occurring in the YS. The EOF3 mode accounted for 6% of the total variance and indicated the influence of the sea floor topography. The results of this study can improve our understanding of spatio-temporal variability in SST in the YS. In future studies, datasets with more combined sources collected over longer time series should be used in order to more accurately determine the seasonal cycles and the inter-annual variability in the YS.

Fig. 10. Annual mean SST ($^{\circ}$ C) over the three study years (2011–2013)

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