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Analysis of Surface Water Temperature Fluctuation and Empirical Orthogonal Function in Cheonsu Bay, Korea

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Abstract : *Surface water temperature of a bay (from the south to the north) increases in spring and summer, but decreases in autumn and winter. Due to shallow water depth, freshwater outflow, and weak current, the water temperature in the central to northern part of the bay is greatly affected by the land coast and air temperature, with large fluctuations. Water temperature variations are large in the north-east coast of the bay, but small in the south-west coast. The difference between water temperature and air temperature is greater in winter and in the south-central part of the bay than that in the north to the eastern coast of the bay where sea dykes are located. As the bay goes from south to north, the range of water temperature fluctuation and the phase show increases. When fresh water is released from the sea dike, the surrounding water temperature decreases and then rises, or rises and then falls. The first mode of empirical orthogonal function (EOF) represents seasonal variation of water temperature. The second mode represents the variability of water temperature gradient in east-west and north-south directions of the bay. In the first mode, the maximum and the minimum are shown in autumn and summer, respectively, consistent with seasonal distribution of surface water temperature variance. In the second mode, phases of the coast of Seosan~Boryeong and the east coast of Anmyeon Island are opposite to each other, bordering the center of the deep bay. Periodic fluctuation of the first mode time coefficient dominates in the one-day and half-day cycle. Its daily fluctuation pattern is similar to air temperature variation. Sea conditions and topographical characteristics excluding air temperature are factors contributing to the variation of the second mode time coefficient.*

Key Words : *Cheonsu bay, Surface water temperature, Seasonal fluctuation, River water discharge, EOF analysis*

1. Introduction

Cheonsu Bay is located in the middle of the Yellow Sea of the Korean peninsula (36° 23'~36° 37' N, 126° 20'~126° 30' E). It is a semi-closed inner bay surrounded by coasts of Boryeong city, Hongseong-gun, Seosan city, Taean-gun, and islands of Anmyeon, Hyoja and Wonsan. The width of the south entrance of the bay is about 5 km. The width of the bay at Juk Island is about 9 km. The length of the bay is about 35 km north-south. Cheonsu Bay is a shallow sea bay with a maximum depth of 30 m at the entrance with a depth of 10 to 25 m (average depth of the bay: 10 m). The concentration of suspended matter in the sea water is high throughout the year (Fig. 1).

Since Cheonsu Bay is geographically isolated from the open sea, it exhibits high biological productivity as a spawning ground and nursery for marine organisms. In addition, fresh water flowing from the northern and eastern sea dikes of the bay, offshore

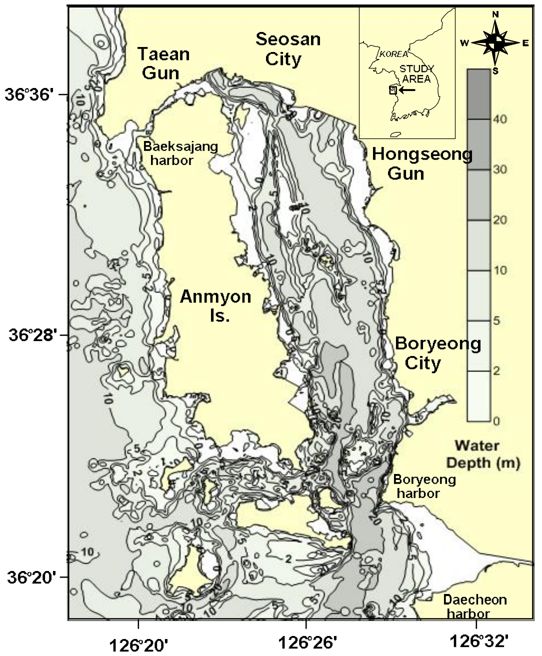

Fig. 1. A map of bottom topography for the study area in the west coast of Korea. Contours denote water depth in meters.

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seawater mainly flowing through the southern inlet, and seawater exchange between these water masses influence creatures living in this sea area greatly. Sea dikes affecting the Cheonsu Bay include Seosan District A (Ganwol Lake) constructed in 1983, Seosan District B (Bunam Lake) constructed in 1985, and Hongsung and Boryeong sea dikes constructed in 1999 and 2000. These sea dikes can reduce water area in the Cheonsu Bay, thus decreasing the flow rate and the transport volume of tidal current. In addition, a large amount of fresh water intermittently discharged from sea dikes A and B in Seosan District in summer can change sea conditions for the surrounding area.

Studies on waters of Cheonsu Bay due to freshwater discharge have been conducted regarding eutrophication (Kim et al., 2005; Park et al., 2006), generation of hypoxia layers due to summer stratification (Lee et al., 2012b; Jung et al., 2015), changes in plankton cluster (Lee et al., 2012a; Lee et al., 2014), and water quality (Kim et al., 2005; Park et al., 2013). The surface water in the inner bay, which is affected by freshwater discharge, is more active in the formation of stratification due to high temperature and low salinity in summer and vertical mixing due to surface layer cooling in winter than surrounding offshore water (Choo and Yoon, 2015). This phenomenon also affects seawater circulation in the bay (Jeong et. al., 2020) where sea surface level rises in summer. Thus, surface water flow along the slope while the bottom layer has a baroclinic flow opposite to the surface layer (Cho, 2005).

As such, the Cheonsu Bay area has a large influence from fresh water and a closed topographic structure in which mixing with the offshore water is limited. The effect of the atmospheric such as air temperature is relatively large. Park and Kim (2012) have investigated horizontal and vertical distributions of water temperature and salinity in waters of Cheonsu Bay through CTD surveys conducted in summer and winter seasons during the spring and neap tide. They have found that vertical mixing is active in the winter season due to convection caused by surface cooling, with water temperature and salinity distribution around the sea dike and other sea areas showing large differences during the rainy season when freshwater discharge increases in summer season.

The water temperature in Cheonsu Bay changes temporally and spatially. Therefore, if the water temperature time series of a certain sea area is averaged over a seasonal (a certain time) period, there is a temporal change in water temperature, but not in spatial distribution. In addition, only the standard deviation or variance of water temperature in each sea area can be used to determine the size of fluctuation in the space (sea area), while it is difficult to know the temporal change. As such, seasonal fluctuations or tidal fluctuations with relatively remarkable periodicity in water temperature in each sea area can be identified by periodic analysis or harmonic analysis. However, it is difficult to effectively grasp changes in water temperature due to geographic, hydraulic, and intermittent fluctuations.

Empirical Orthogonal Function (EOF) analysis of water temperature time series at various points in the sea area has been used as a useful method to determine characteristics of changes in the ocean or weather because it is easy to understand their temporal and spatial fluctuations. By EOF analysis, abnormal temperature fluctuations in Europe and the Atlantic Ocean (Grimmer, 1963), sea level pressure, temperature, and rainfall in North American waters (Kuzbach, 1967), and surface water temperature in the Pacific Ocean (Weare et al., 1976) have been investigated. It has been pointed out that seasonal fluctuations in the Northwest Pacific Ocean are greater than those in other places and that fluctuations in abnormal water temperature fluctuate severely in the sea area where El Niño occurs. Lie et al. (1986) have investigated temporal and spatial fluctuations of the surface and 30 m depth water temperature in the southeastern Yellow Sea of Korea. Choi and Kang (1987) have investigated the distribution of surface water temperature fluctuations in coasts of Korea and Tsushima Current region by EOF analysis. Chang et al. (2005) have analyzed sea variability related to El Niño in the equatorial surface waters by EOF analysis of sea surface temperature. Min and Kim (2006) have analyzed long-term fluctuations of surface water temperature in east and west coasts of Korea and causes of such fluctuations by EOF analysis. Wie et al. (2014) have analyzed the progress of global warming by EOF analysis of vertical sea water temperature. Oh et al. (2012) have analyzed temporal and spatial fluctuations of ocean water temperature through EOF analysis of satellite water temperature data around the Korean Peninsula.

Previous studies on Cheonsu Bay have mainly investigated circulation in the bay, changes in water quality, and marine life communities, focusing on the effect of freshwater runoff from the sea dike through short-term observations and numerical experiments. To more accurately grasp changes in the sea condition of Cheonsu Bay, water temperature fluctuations due to outflow of river water and intermittent large amounts of fresh water, atmospheric effects due to shallow water depth must be identified, and long-term continuous water temperature monitoring data should be studied.

Therefore, long-term continuous water temperature monitoring survey was conducted for one month per season for one year to understand the temporal and spatial water temperature variability across the bay including the north-south inlet waterway of Cheonsu Bay in the present study. Using observed water temperature time series, distribution of water temperature by season or sea area and causes of fluctuations were investigated through time series and EOF analysis.

2. Materials and methods

To investigate the distribution of surface water temperature and its fluctuation characteristics at 50 monitoring stations in Cheonsu Bay shown in Fig. 2, long-term continuous observations of water temperature were conducted in August 2011 (summer), November 2011 (fall), February 2012 (winter), and May 2012 (spring) for one month. Station locations were arranged with appropriate spacing so that the entire area of Cheonsu Bay was covered. To understand the temperature effect of the influent outside the bay and heat source of nearby rivers, stations (St.20, 50, 45, 38) were set inside Seosan A, B, Hongsung and Boryeong sea dikes known to be main sources of river inflow for the Cheonsu Bay. Water temperature was measured by placing a water temperature meter at a depth of 50 cm (surface layer). The water temperature meter was moored in a structure such as a sea route or aquaculture farm in Cheonsu Bay, or in a styrofoam buoy of ∅540 mm × 890 mm made manually. The instrument used for water temperature measurement was a small precision temperature measurement equipment (Magic-T100, GnC Bio Co.) with a resolution of 0.005°C (± 0.02°C accuracy). Continuous time series data of water temperature measured every 1 minute were obtained after calculating an hourly mean value to remove internal and external noise.

Meteorological data (Korea Meteorological Administration, 2011-2012) of air temperature at 10-minute intervals measured simultaneously with water temperature monitoring at Daecheon Port AWS (Shinheuk-dong, Boryeong-si) in the south of Cheonsu Bay and Seobu AWS (Iho-ri, Seobu-myeon, Hongseong-gun) near St.48 were converted into mean data every hour and used for analysis. Data of freshwater flowing into Cheonsu Bay included those from Seosan A (Ganwol) and B (Bunam), Hongsung and Boryeong sea dikes, and river water discharge from Daecheon river (2011-2012, Korea Rural Community Corporation, Boryeong City Facility Management Corporation, Hyundai E&C). Tidal data measured at the survey station in Boryeong Port (36° 24' 23" N, 126° 29' 10" E) at the southern entrance of Cheonsu Bay were also used. Some periods of continuous water temperature measurement were excluded from data analysis because data abnormalities were found due to equipment failure. Data could not be obtained at some stations due to loss of equipment during the observation period (especially in summer). Obtained data were used for statistical analysis and spatial distribution of mean water temperature and variance. Short period fluctuations (40 hours or less) within the time series gave errors of the overall pattern of fluctuations of surface water temperature.

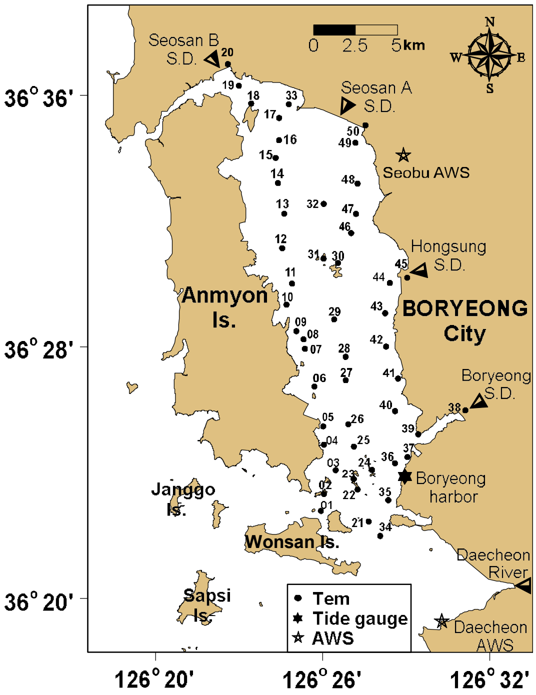

Fig. 2. Temperature monitoring, tide observation, and auto weather system (AWS) stations in the study area around Cheonsu Bay. Seosan A, B, Hongsung and Boryeong S.D. are locations where sea dikes exist.

Water temperature fluctuations in Cheonsu Bay can be affected by periodic tidal phenomena, seasonal fluctuations due to air temperature changes (Park et al., 2013), and river inflow (Lee, 1994; Park et al., 2013). The amplitude and phase of 34 constituents (including M_2, S_2, K_1, and O_1) were obtained from tidal data by harmonic analysis (Foreman, 1978; Pawlowicz et al., 2002). After grasping components of water temperature fluctuations due to these tidal changes, the tidal effect was removed from the water temperature time series data. Fluctuations of surface water temperature in Cheonsu Bay might include short-term fluctuations such as inertia cycles (19 to 21 hours) or quasi-inertia cycles (1.7 days fluctuations due to internal waves) along with fluctuations due to tide (0.5 days, 1 day). These temporary short-term fluctuations in the time series were removed using a 40-hour low-pass filter. One-year and half-year periodic analyses were performed using the least squares method (Kang, 2000) to identify seasonal fluctuations in time series of water temperature and atmospheric elements. The annual mean and annual range of the time series are obtained by harmonic fitting of the time series by

$$T(t) = T_o + T_1 \cos(\omega t - \phi_1) + T_2 \cos(2\omega t - \phi_2) \quad (1)$$

where t is the time in time series, T_o is annual average, T_1, T_2 are annual and semi-annual amplitudes, respectively, ω is annual angular frequency, ϕ_1 and ϕ_2 are annual and semi-annual phases, respectively.

To efficiently understand seasonal and spatial variability of surface water temperature, EOF analysis was performed. In the EOF analysis, there were n time series data points for four seasons at m water temperature monitoring points in Cheonsu Bay. Thus, water temperature time series $T(x,t)$ could be expressed with a matrix $m \times n$. Time series data can be decomposed into several EOF modes as shown in equation (2).

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

where $e_i(x)$ is the eigenvector corresponding to the i-th mode eigenvalue with orthonormality condition and $c_i(t)$ is the time dependent coefficient accompanying the i-th mode eigenvalue. Thus, $e_i(x)$ and $c_i(t)$ represent spatial and temporal variability of water temperature in the i-th mode. Although EOF analysis is one method that can effectively present the temporal and spatial variability of the water temperature time series matrix, it cannot specify the physical meaning of each eigenvector. However, since observed water temperature data could be extracted and reproduced as a function of several EOF major modes, if the distribution of the water temperature variance is compared with the spatial distribution of the EOF eigenvector and temporal fluctuation of time series is reviewed as a periodic fluctuation of the time coefficient by EOF analysis, it is possible to understand causes of seasonal and spatial fluctuations of surface water temperature in Cheonsu Bay.

3. Results

3.1 Seasonal fluctuation of water temperature

Fig. 3 shows horizontal distributions of mean surface water temperature by season (monthly). The water temperature in winter (January~February) ranged from 1.8 to 4.6°C throughout the bay. It gradual decreases from the south to the middle and north of the bay, falling below 2.0°C in the shallow water depth of the northern bay.

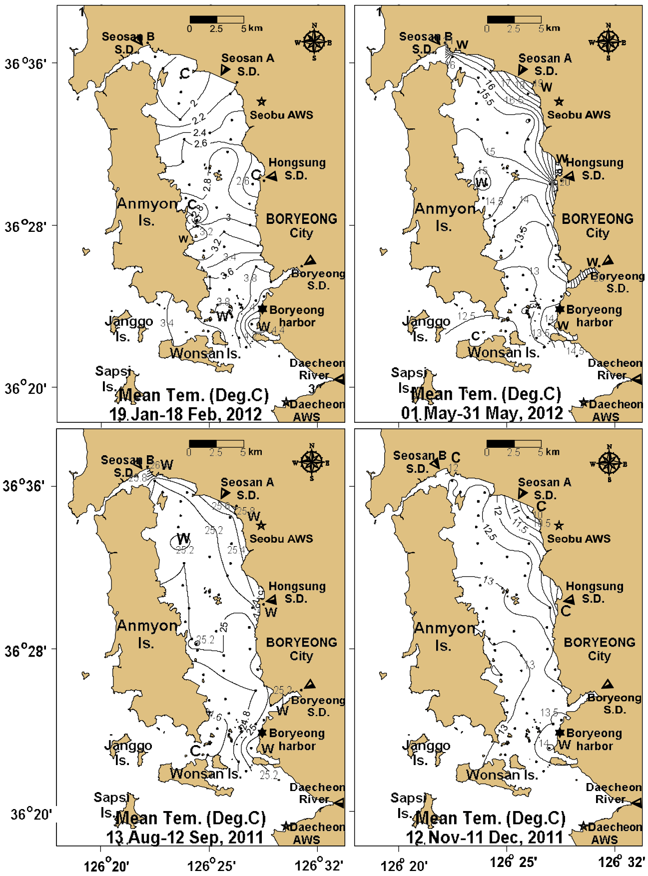

Fig. 3. Monthly means of surface water temperature for each season in Cheonsu Bay. Seosan A, B, Hongsung and Boryeong S.D. show stations where Seosan-B, Boryeong, Hongsung and Seosan-A sea dikes are located.

Stations in the sea dike were lower than the minimum water temperature in the bay. Sometimes data were unavailable for analysis due to freezing below 0°C. Unlike the decrease in water temperature in winter, the water temperature gradually increased in spring (May) from the south to the middle and north of the bay. The water temperature in the bay was in the range of 12.5 to

16.0°C. However, it was in the range of 19.5 to 21.0°C in sea dikes located along the coast of Seosan~Hongseong~Boryeong (hereinafter referred to as Seosan~Boryeong), which was 5.0~7.0°C higher than that in the bay. The highest water temperature was at Seosan B sea dike in the north of the bay. The surface water temperature of Cheonsu Bay in summer (August~September) excluding four stations of the sea dike ranged from 24.4 to 25.4°C. The lowest water temperature was from Anmyeon Island to Wonsan Island. The highest was around the Boryeong thermal power plant (St.35) near Boryeong Port. The water temperature increased from the south to the north of the bay. It was the highest in Seosan A, B, Hongsung, and Boryeong sea dike areas along the Seosan~Boryeong coast. The maximum water temperature was 26.6°C at the Seosan B sea dike (St.20) in the north of the bay, which was 1.0°C higher than the surrounding water temperature in the bay. In autumn (November~December), the temperature in the southern part of the bay was 13.0 to 13.5°C. It decreased to 12.0°C as it went toward the middle and northern coasts. The water temperature ranged from 9.5 to 11.5°C in the sea dike, about 2.0 to 3.0°C lower than that in the bay. Seosan A sea dike (St.50) had the lowest water temperature at 9.5°C.

Fig. 4 shows horizontal distribution of water temperature variance for each season. Variance refers to the degree to which the water temperature at a given station fluctuates over the season. The time when the water temperature variance was the greatest was in autumn (3.0~7.0 in the bay and 7.3~10.9 in the sea dike).

The variance gradually increased from the south of the bay to the shallow northeast coast near Seosan A sea dike. In spring, the entire bay had a variance of 2.0~3.2, smaller than that in autumn. In the spring season, the shallow north-northeast coast had a greater variance than other sea areas. The variance ranged from 0.2 to 0.6 in the bay, 2.0 to 3.2 in the sea dike in summer, and 0.4 to 0.8 in the entire bay in winter. Excluding the coast of Seosan~Boryeong (areas of sea dikes), the variance in summer and winter was very small compared to that in spring or autumn. Throughout the year, excluding winter season, the variance was generally large in the Seosan~Boryeong coast and small from the south of the bay to the east coast of Anmyeon Island.

Fig. 5 shows annual changes in surface water temperature in the south (St. 21), central (St. 29), north (St. 17), and Seosan A sea dike coast (St. 48) of Cheonsu Bay and the air temperature around these points (Daecheon Port, Seobu-myeon, and Hongseong-gun). Annual fluctuation curves of water temperature and air temperature in the figure were obtained from harmonic analysis. The lowest and the highest air temperatures usually appeared in late January and late July, respectively. However, surface water temperature in Cheonsu Bay was generally the lowest in mid-February but the highest in mid-August. Thus, fluctuations in air temperature and surface water temperature were about 15 days apart. From mid-August to mid-March (water temperature decreases), surface water temperature was higher than air temperature. From late March to early August (water temperature rises), it was lower than the air temperature. The air temperature during water temperature increase period (June-July) was 2.5~3.5°C higher than the water temperature, while the air temperature during water temperature decrease period (December-January) was 7.0~8.0°C lower than the water temperature. As water temperature decreased, the difference between water temperature and air temperature increased. The difference between surface water temperature and air temperature throughout the year was larger in the south and center of the bay than in the north and the coast of Seosan A sea dike. The

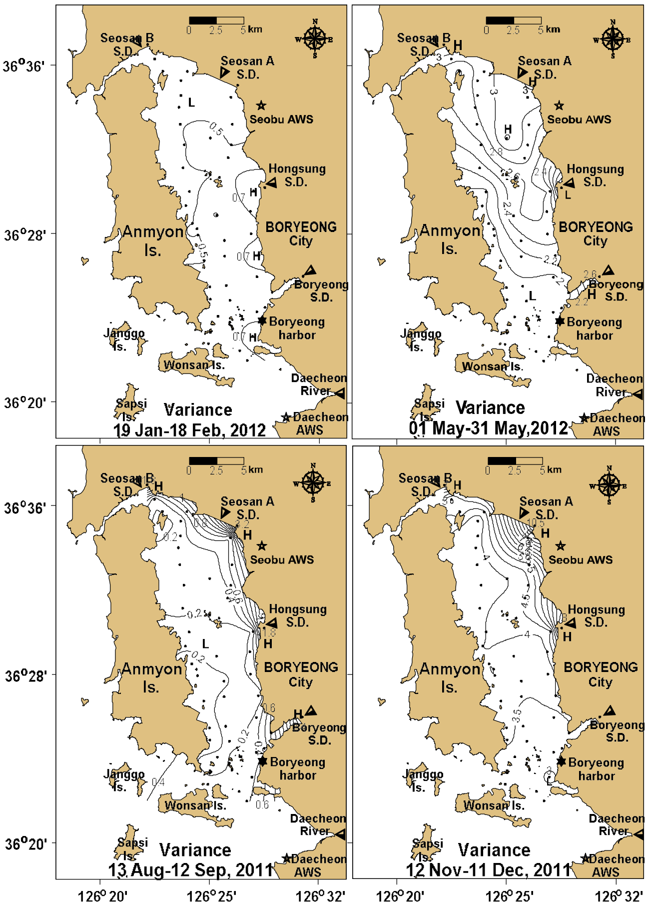

Fig. 4. Same as Fig. 3 except for variances of surface water temperature.

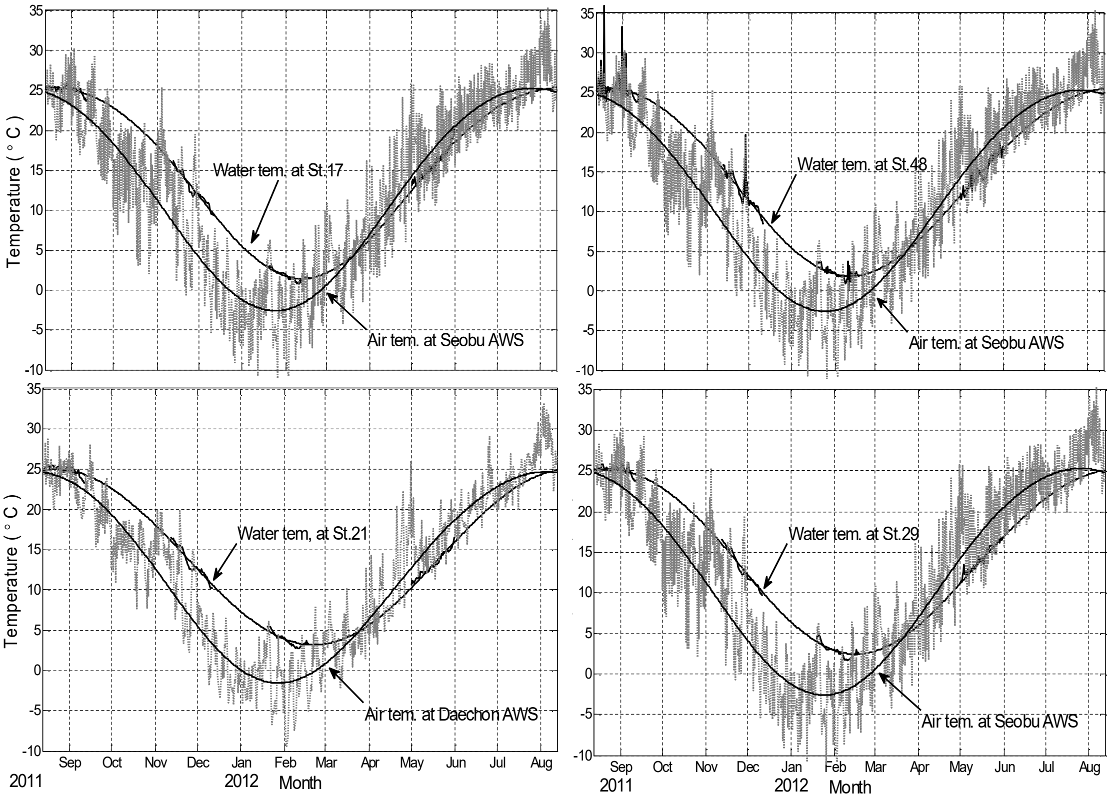

Fig. 5. Annual variations of water temperature at stations 17, 48, 21, and 29 and air temperature at AWS stations in Daecheon and Seobu from August 13, 2011 to August 12, 2012. Dotted lines show annual fluctuations of observed air temperature. Yearly harmonic solid lines were computed by harmonic analysis with observed sea water and air temperature data, respectively.

difference between water temperature and air temperature by sea area did not show much difference during the drop of water temperature (mid-August to mid-March). During water temperature increase period (late March to early August), differences in air temperature and water temperature for shallow waters of the northern bay were smaller than those of other seas where influence of atmosphere on surface water temperature was large.

Analysis of annual and semi-annual periods of surface water temperature and air temperature fluctuations was conducted for stations of the north-south line of Cheonsu Bay (if missing, surrounding stations were analyzed). Each harmonic constant is shown in Table 1. Average annual and semi-annual fluctuation amplitudes of air temperature were 13.6°C and 0.8°C, whereas water temperature averages were 11.3°C (83% of air temperature) and 0.5°C (63%), respectively, lower than air temperature. Phases in which the air temperature and water temperature were at their maximum were August 3 (5.9°) and August 19 (345°), respectively. Air temperature increase was about 16 days earlier than the water temperature. Stations with large annual fluctuation amplitudes of water temperature were around St. 17~18, 32 in the north of the bay, while stations with small fluctuation amplitudes were around St. 22~23. They tended to increase gradually toward the center and north of the bay. Like the amplitude, the annual fluctuation phase also slowed to 10.3 to 11.5° in the south of the bay, but increased to 1.1° in the north through the center of the bay.

Figure 6 shows differences in annual water temperature fluctuations at the four stations in the bay (St. 21, 29, 17, 48) shown in Table 1 and Figure 5. In the figure, from late October to mid-March, the water temperature in the south of the bay (St. 21) was higher than that in the middle of the bay (St. 29), around the Seosan A sea dike (St. 48), and the north of the bay (St. 17). However, from the end of March, a spatial reversal occurred in the distribution of water temperature, and the water temperature gradually decreased in the order of the north of the bay, followed by the Seosan A sea dike, the middle of the bay, and the south of the bay. The period when the water temperature difference between sea areas was not large between September and October in autumn and March in spring.

Table 1. Annual and semi-annual harmonic constants of surface water temperatures from station 34 to station 19 and air temperatures at Seobu (SB), Daechon (DC) AWS station.

St.	Annual		Semi-ann.		St.	Annual		Semi-ann.	
	Amp. (°C)	Pha. (°)	Amp. (°C)	Pha. (°)		Amp. (°C)	Pha. (°)	Amp. (°C)	Pha. (°)
34	10.9	8.8	0.1	323.4	31	11.7	4.7	0.7	150.0
21	10.9	9.2	0.1	216.1	46	11.5	5.4	1.1	193.2
22	10.1	10.3	0.6	160.2	32	12.0	1.9	0.6	182.0
23	10.2	11.5	0.4	122.4	48	11.8	2.3	0.7	156.0
24	11.0	8.6	0.3	186.1	13	11.5	3.9	0.8	168.0
36	11.1	5.7	0.6	240.9	17	12.0	1.8	1.0	176.4
40	10.9	7.0	0.2	187.1	18	12.0	1.2	1.0	153.7
04	10.8	8.3	0.1	100.7	19	11.8	1.1	1.0	166.5
05	10.9	9.2	0.2	61.9	Mean	11.3	5.9	0.5	175.3
06	11.2	5.2	0.5	146.3					
28	11.4	8.9	0.2	254.3	SB AWS	13.1	347.9	0.8	121.6
30	11.4	3.6	0.5	160.2	DC AWS	14.0	342.1	0.8	141.6

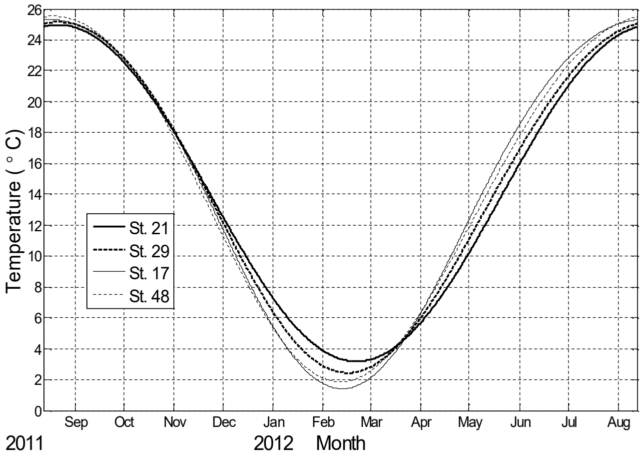

Fig. 6. Annual variations of water temperature computed by harmonic analysis at stations 21, 29, 17, and 49 from August 13, 2011 to August 12, 2012.

3.2 Water temperature fluctuation due to freshwater runoff

To understand the effect of freshwater runoff or discharge on water temperature fluctuations in waters of Cheonsu Bay (locations of rivers and sea dikes), time series data of discharge flow rates at major freshwater runoff and discharge points are presented on the left side of Figure 7. The largest discharged flow point during the year was the Seosan A sea dike, which showed a volume transport of $571\times 10^6 m^3$. However, this amount was almost concentrated in the summer July~August. Other points are largely similar. The release volume transport in the summer season (August 13 to September 12, 2011) is $43\times 10^6 m^3$ in Seosan A sea dike, $18\times 10^6 m^3$ in Seosan B sea dike, $14\times 10^6 m^3$ in Boryeong sea dike, $8\times 10^6 m^3$ in Hongsung sea dike and $4\times 10^6 m^3$ in Daecheon river. Discharge was concentrated in the summer season in Seosan A and B sea dikes. In Boryeong and Hongsung sea dikes, it was distributed relatively evenly at $114\times 10^6 m^3$~$220\times 10^6 m^3$ throughout the four seasons. In Daecheon river, a small amount of volume transport was released (average: $0.05\times 10^6 m^3$ per day and $19\times 10^6 m^3$ per year). The right side of Figure 7 shows change of water temperature in the sea dike and surrounding sea areas due to discharge of fresh water from Seosan A sea dike, which released about $1.37\times 10^6 m^3$~$9.89\times 10^6 m^3$ in one discharge in about 2 hours of release time from August 13 to 20, 2011 during the rainy season. Data used for water temperature time series analysis in Figure 7 were obtained after removing tide and seasonal fluctuations.

After freshwater discharge, the surface water temperature in the bay showed a fluctuation of water temperature in the form of falling and then rising or rising and then falling during the discharge period. These fluctuations were somewhat different in shape. However, the amplitude and period tended to gradually decrease from the sea dike (St. 50) to the southern center of the bay (St. 28).

3.3 EOF analysis of surface water temperature

Table 2 shows EOF fractions and cumulative percentages from the 1st mode to the 5th mode obtained through the analysis of surface water temperature time series for four seasons. Excluding the summer season, the first and second modes accounted for 87~96% and 2~5% of water temperature variance, respectively.

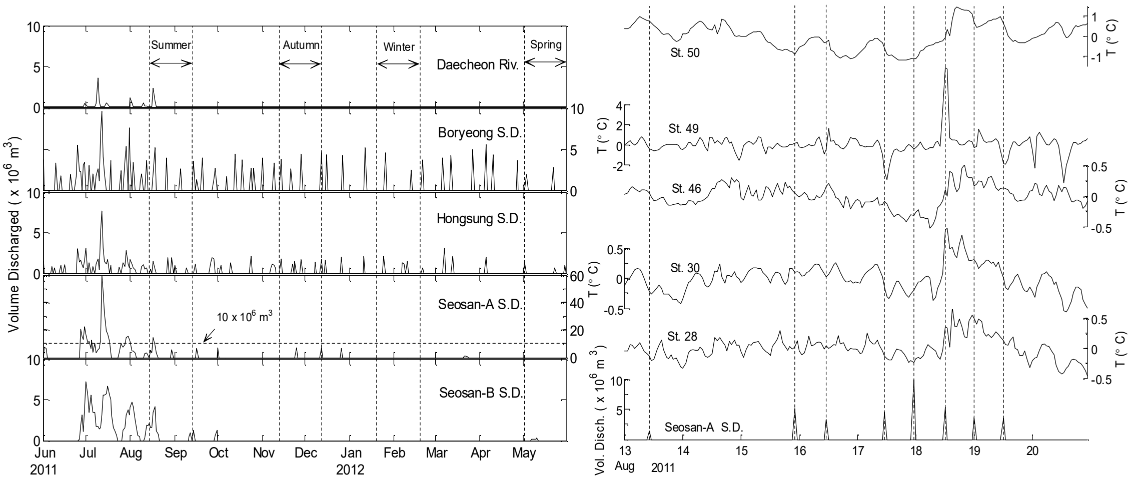

Fig. 7. Time series of river water discharges at Daecheon River, Boryeong, Hongsung, Seosan-A and Seosan-B Sea Dike in Cheonsu Bay from June 2011 to May 2012 (left). Seasons expressed as Summer, Autumn, Winter, and Spring in the figure show the period when the surface temperatures are monitored for Cheonsu Bay. Time series of water temperatures from which tidal and seasonal components are removed at stations 28, 30, 46, 49, and 50, and river discharge at Seosan-A Sea Dike during August 13 to 20, 2011 (right).

Table 2. Percentage and cumulative percentages of total variance explained by the lowest five modes of empirical orthogonal functions

Period	MODE	1st	2nd	3rd	4th	5th
Winter (1.19~2.18)	Percent	87.0	5.3	3.8	1.4	0.9
	Cumulative Percent	87.0	92.3	96.1	97.5	98.4
Spring (5.1~5.31)	Percent	89.4	3.5	1.8	1.4	0.9
	Cumulative Percent	89.4	92.9	94.7	96.1	97.0
Summer (8.13~9.12)	Percent	70.4	13.0	6.6	4.3	1.8
	Cumulative Percent	70.4	83.4	90.0	94.3	96.1
Autumn (11.12~12.11)	Percent	95.7	2.1	0.7	0.6	0.2
	Cumulative Percent	95.7	97.8	98.5	99.1	99.3

These two modes accounted for 92~98% of the total variance. In summer, the first mode accounted for 70% of the variance, which was the lowest percentage among all seasons. The autumn accounted for 96% of the variance, the largest among the four seasons. Winter and spring accounted for 87~89% of the variance. In the second mode, summer and autumn accounted for 13% and 2.1% of variance, respectively, while winter and spring accounted for 4~5% of the variance. Thereafter, in the third, fourth, and fifth modes, results were similar to those in the second mode.

Figures 8 and 9 show distributions of the first and second modes of seasonal EOF in Cheonsu Bay. Distribution of only the same sign (+) functions within the sea area indicated that their change was in phase. Both positive (+) and negative (-) functions at the same time indicated opposite correlations. In the first mode, all EOF signs were the same. Thus, water temperature fluctuations occurred simultaneously in all sea areas. However, in the second mode, opposite fluctuations occurred in sea areas having positive and negative signs. Spatial distribution of the first mode, which accounted for 70~96% of the total variance, agreed well with the spatial distribution of water temperature variance shown in Figure 4. The first mode of summer and autumn had large values for shallow waters off the coast of Seosan-Boryeong near Seosan A sea dike. In particular, as the first mode appeared large in Seosan A, B, Hongsung, and Boryeong sea dikes, water temperature fluctuations in summer, autumn, and spring were the greatest in coastal waters around the sea dike. They gradually decreased toward the center and west of the bay. The place where the first mode had the lowest fluctuation was around the southern entrance

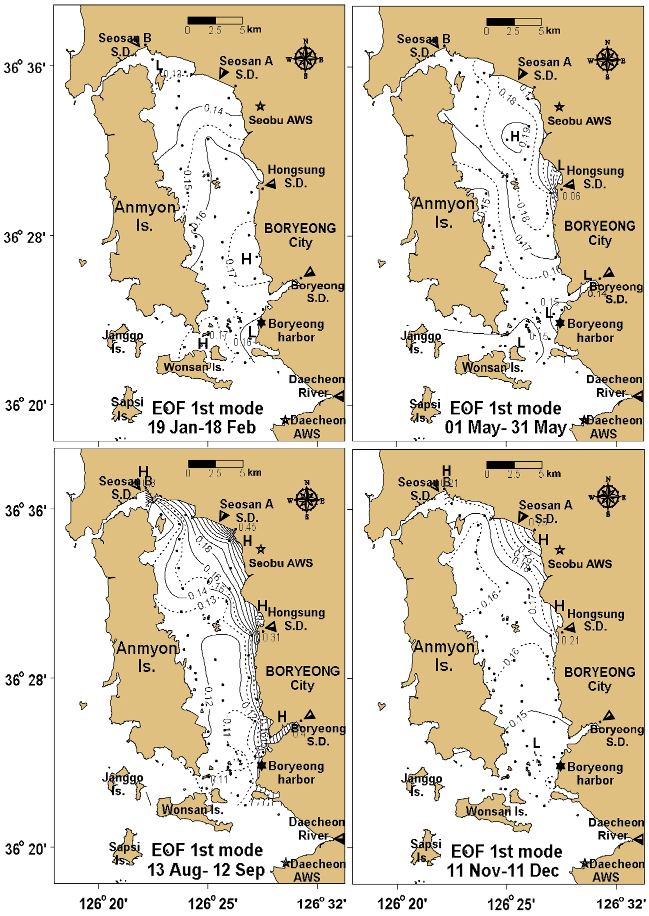

Fig. 8. Spatial distributions of the first EOF mode explaining 70~96% of total variance of sea surface temperature in January, May, August, and November, 2011~2012.

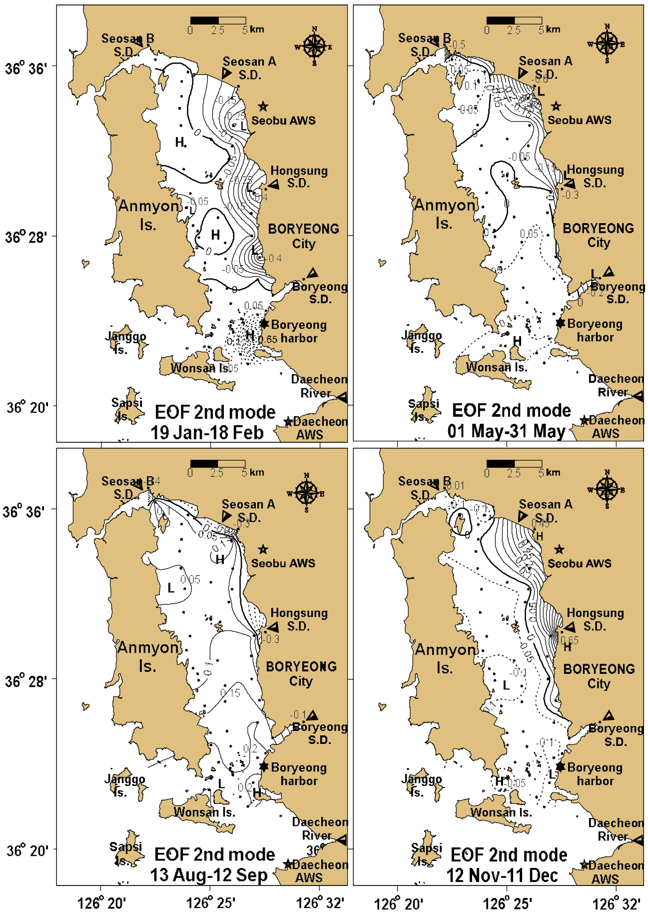

Fig. 9. Same as Fig. 8, except that this is for the second EOF mode explaining 2~13% of total variance.

of the bay. However, the first mode of winter increased from 0.13 to 0.17 from north to south of the bay.

The second mode of EOF in Figure 9, which explained 2 to 13% of the total water temperature variance, had opposite signs throughout the season, bordering the shallow coast of Seosan~Boryeong and the deep bay. The spatial distribution of the function in the eastern sea area of Anmyeon Island was not very different, although the change was large in the shallow coast of Seosan~Boryeong. Winter seasons (January-February) ranged from 0 to +0.1 in southern and western areas of the bay and from 0 to −0.4 in the eastern coastal area of the bay. In spring (May), the negative sign area that appeared on the east coast is reduced, and the positive sign area in the south of the bay expanded. In the summer season (August~September), the negative sign area in the east was reduced the most while the positive sign area in the south and west was expanded to the maximum. However, in autumn (November~December), negative areas in the east of the bay gradually expanded again.

Figure 10 shows temporal variation of time coefficients of the first and second EOF modes for each season. The first mode showed a tendency to rise or fall during the measurement period (one month). In the figure, seasonal (monthly) fluctuation trends were first removed and then shown. Equations for these trend lines were: $y = -0.18x + 2.79$ (August~September), $y = -1.39x + 20.81$ (November~December), $y = -0.44x + 6.75$ (January~February), $y = 1.01x - 15.59$ (May), where x was the number of days in each period. The surface water temperature decreased the most from November to December, but increased in May. One-day and half-day cycles appearing in the tidal phenomenon were excellent throughout the four seasons in the fluctuation of the time coefficient in the first mode shown in Figure 10. However, unlike tidal fluctuations in which semi-diurnal component predominated, daily cycle was excellent. The amplitude of the daily fluctuation

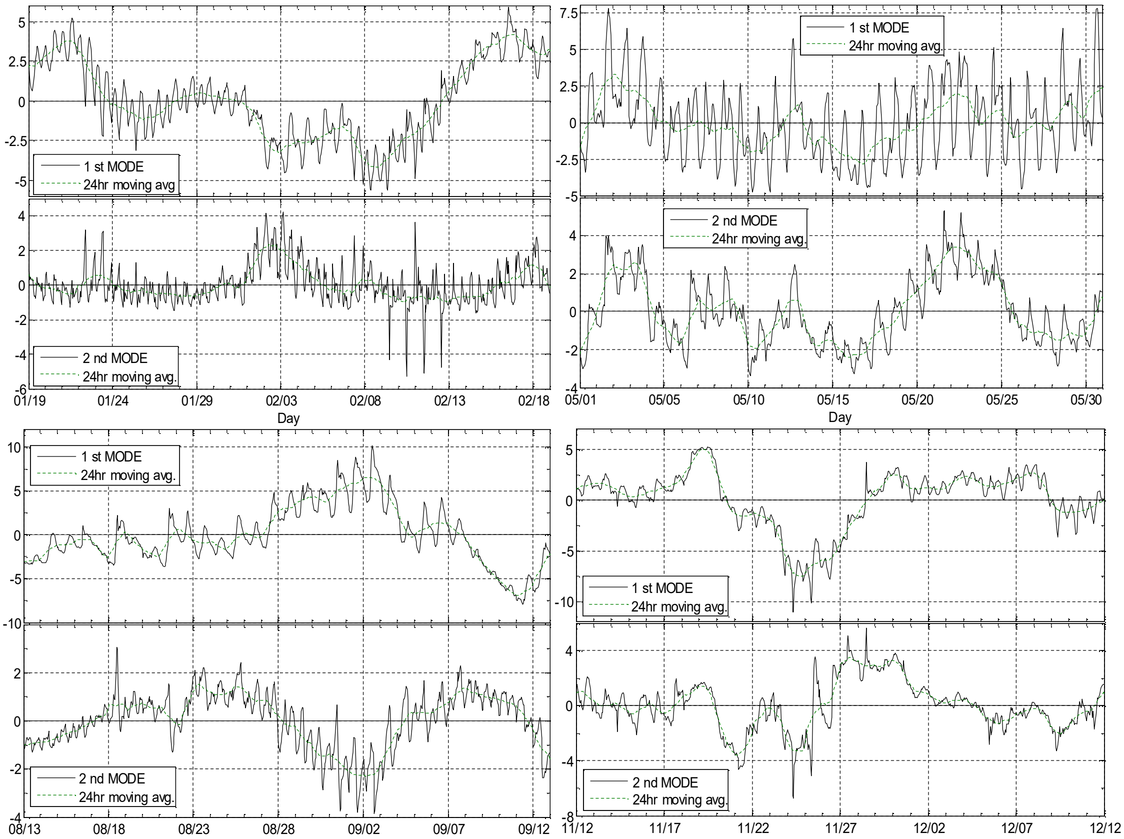

Fig. 10. Time series of time coefficients corresponding to the first and the second EOF modes in January, May, August, and November, 2011~2012. Dotted lines in the figure show 24-hour running means of time coefficients of the first and the second modes for sea surface temperature.

was large in spring (May) and small in autumn (November to December). The 24-hour moving average of the first mode time coefficient for each season was very similar to the fluctuation pattern of the daily air temperature. Thus, the fluctuation of the first mode time coefficient indicated seasonal change in surface water temperature due to atmospheric effects.

The second mode time coefficients had smaller period and amplitude than the one-day fluctuation component of the first mode. The 24-hour moving average exhibited a fluctuation pattern in phase or opposite to the first mode depending on the season. In particular, in winter, the amplitude of periodic fluctuations for more than one day was very small. Thus, the correlation with the periodic fluctuations of more than one day in the first mode was very small. The moving average of the second mode time coefficient in spring was generally in phase with the first mode moving average. Variation patterns of the first and second mode time coefficients were the most consistent during different seasons. However, in the summer, opposite phase from late August to mid-September was found. Autumn showed the same phase as spring. Their correlation decreased after December.

4. Discussion

The coast of Seosan A, B sea dikes in the north of the bay is a place where the influence of the intertidal zone is large due to sedimentation of suspended matter and shallow water depth (2~5 m) by freshwater discharge. The surface water temperature (Fig. 3) was 24.4~25.4°C in summer. It increased from south to north in the bay (Lee et al., 2012a; 2014). The water temperature in autumn was higher in the south of the bay. It decreased toward the north. The winter water temperature was 1.8 to 4.6°C. It decreased from the south to the middle and north. It was less than 2.0°C in northern shallow waters. In spring, water temperature increased from the south to the middle and northern coasts of the bay. Kim et al. (2005) have found that the water temperature in spring is in the range of 10~14°C from seasonal surface and bottom water quality surveys, showing an increase of about 2°C from the bay inlet to the inner bay. However, it ranged from 8 to 11°C in winter season ranged. It was high at the entrance to the bay, showing a decrease of about 2°C toward the inner bay. Thus, water temperature in spring and summer increased more in the north of the bay than that in the middle-south of the bay, while water temperature in autumn and winter decreased (Figs. 3 and 6). The depth of the Cheonsu Bay became shallower from about 20 m to 10 m from the center to the north sea area (Fig. 1). As a result, the inflow of offshore water from the open sea through the Baeksajang port (Baeksasudo) at the northern entrance was smaller than that at the southern entrance of the bay. Tidal exchange of seawater through the northern entrance is weak (Jung et al., 2013). Therefore, surface water temperature in central and northern parts of the bay was more affected by land coastal and air temperature than that in the south part. Water temperature fluctuations due to atmospheric effects were outstanding. The largest variation in surface water temperature throughout the year coincided with that of sea areas (Fig. 4). The main reason for the increase in the spatial water temperature variation is that the water depth in the central to northern waters of Cheonsu Bay is about 10 m, and becomes shallower toward the north. In addition, the inflow of open seawater from the Yellow Sea through Baeksajang Port (Baeksa Sudo) at the northern entrance of the bay is smaller than that at the southern entrance of the bay, so the tidal currents through the northern entrance are weaker than those at the southern entrance. Therefore, the surface water temperature in the central and northern part of the bay is more influenced by the land coast and atmospheric temperature than in the southern part, and the variation due to the atmospheric influence is excellent. For this reason, in spring and autumn, when seasonal temperature fluctuations are large, there is a large spatial temperature variation between the shallow north and northeastern coasts of the bay and the southern part of the bay. The maximum year-round water temperature gradient between the southern and northern areas of Cheonsu Bay was 4°C in May.

In the comparison of air temperature and water temperature (Fig. 5), the surface water temperature gradually increased as the air temperature was higher than the water temperature from mid-March to mid-August. However, from the end of August to early March, water temperature decreased. Park et al. (2013) found that in the distribution of water temperature conducted bimonthly at 16 stations in the bay from 2010 to 2011, the water temperature was 3.3 to 7.7°C higher than the air temperature in December and February, but 0.3 to 2.8°C lower in June and August. The fact that the water temperature in Cheonsu Bay was significantly different from the air temperature in winter than in summer suggested that Cheonsu Bay supplied heat and water vapor to the surrounding atmosphere with a great influence on the weather in winter. The cause of the difference in water temperature between winter and summer could be due to convection effectively generated in all layers of seawater caused by vertical mixing from strong cooling of the sea surface and bottom friction of the tide in the winter season (Park and Kim, 2012). However, solar heat was unable to flow deeper from the surface in the summer season due to the influence of suspended solids caused by stratification of the surface layer and tidal current. In other words, the seawater in Cheonsu Bay formed a strong stratification on the surface layer due to sea surface heating from the atmosphere. Since frictional mixing of the seafloor caused by the tidal current had difficulty to reach the surface layer, temperature difference between the air temperature and the surface water temperature occurred depending on the sea area (depth). However, when the water temperature decreased, the tidal mixing from the sea floor and sea surface cooling occurred efficiently below and above the water layer so that the entire water layer was easily mixed, leading to a small temperature difference between the air temperature and the surface water temperature. The difference in air temperature and water temperature throughout the year was greater in the south-central bay than in the north and coasts of the sea dikes. This shows that coasts of the sea dikes in the north and northeast of the bay have less tidal communication and shallow water depth. Thus, surface water temperature in these seas reacted with the atmosphere better. The annual fluctuation of water temperature (Table 1) was 83% smaller in amplitude and 16 days slower in phase compared to air temperature. This phase difference appears as various influencing factor characteristics depending on the sea area, but it is generally due to the physical property that water has a higher specific heat than air (Crisp and Howson, 1982; Webb and Nobilis, 1997). In order to more quantitatively grasp the relationship between air temperature and water temperature, it is necessary to consider the seasonal phenomenon according to the temperature rise period (time from early spring to summer) and the temperature decrease period (time from late summer to winter). This phenomenon occurs because the specific heat of air is smaller than the specific heat of water, so the water temperature lags behind the air temperature. The water temperature amplitude increased toward the north of the bay, with phase faster than that of the south.

In the comparative analysis of the annual fluctuation curves of air temperature and water temperature in Fig.5, the air temperature and surface water temperature showed a difference of about 15 days (average difference between the time of maximum and minimum temperature throughout the year). As mentioned above, the annual phase difference between air temperature and water temperature fluctuations is determined to be due to the difference in specific heat of air and sea water. In order to identify more specific causes, it is necessary to identify the long-term average phase difference and ocean meteorological factors involved in the phase difference from the heat balance relationship of the sea area based on long-term monitoring data for more than one year. In general, extracting annual components can be more accurately extracted if there are more than several years of data, but extracting annual components from a one-year time series may result in lower accuracy. In particular, there is a concern that the size of the annual component may be reduced if it is extracted while considering various components due to the characteristics of harmonic analysis. It is difficult to obtain water temperature monitoring data for several consecutive years in the entire Cheonsu Bay area. As a priority, this study focused on simultaneous and continuous water temperature monitoring at 50 stations covering the entire sea area, albeit only for one month per season for one year. Therefore, in terms of the observation period and interval, there is a possibility that the accuracy is somewhat lower than that of long-term observation. In the future, it is thought that the characteristics of time fluctuations can be identified more accurately if a few representative water temperature monitoring stations in Cheonsu Bay are selected and long-term monitoring analysis is conducted at these stations.

In estuary of rivers or sea dikes, changes in surface water temperature may occur due to density flow from river discharge or runoff, salinity slope caused by an increase in river flow, and spatiotemporal variation of the estuary front (Mcclimans, 1988). The discharge flow to the bay from the sea dike or river was the highest in the summer (Fig. 7 left). Lee et al. (2012a) found that during the survey of freshwater discharge in the bay from November 2009 to August 2011, discharges were concentrated in July~August, a heavy rainy season in the summer (76~83% of the annual discharge occurred during June~September). After the discharge of river water from the Seosan A sea dike, the water temperature in the bay generally showed fluctuations in the form of falling and then rising, or rising and then falling (Fig. 7 right). When a large amount of river water, which has a different temperature from the ocean surface layer, is discharged into the bay at once, a dynamic mixing process occurs between the river water and surface sea water, and during this process, the surface water temperature of the surrounding sea area is thought to show very diverse variations. In the future, in-depth research on the water temperature fluctuation pattern during discharge of river water in the bay is needed.

In the EOF analysis of water temperature, the sign of the first mode value at all stations in Cheonsu Bay was positive (+), meaning seasonal variation in surface water temperature. In the first mode, the maximum appeared in autumn while the minimum appears in summer, with winter and spring being in the middle (Table 2). The winter season also showed relatively low values as in the summer season. Surface water temperature in Cheonsu Bay fluctuated greatly in the fall, while summer and winter seasons showed constant surface water temperatures without much fluctuations. This first mode fluctuation was in good agreement with results shown for seasonal distribution of surface water temperature variance (Fig. 4). As such, spatial distribution of the first mode component (Fig. 8) was consistent with that of water temperature variance (Lie et al., 1986; Min and Kim, 2006). Spatial distributions of the first mode in Cheonsu Bay were the largest around sea dikes in summer, autumn, and spring, but decrease toward the center of the bay. In winter, the value of the first mode increased from the north of the shallow area to the south where the depth was relatively large. The entrance to the south of the bay, which had fast tidal current and deep water, showed the smallest first mode value in all seasons. These results, indicated that the deeper the water depth and the stronger the tidal currents, the less the surface water temperature fluctuated. The water depth was shallow and areas around the sea dike and the estuary directly affected by river water or fresh water from the land were sea areas with great variability in salinity and other water components as well as water temperature. In addition, air temperature (Fig. 5), tidal mixing, heating, and cooling at the sea level had a synergistic effect on fluctuations of sea conditions in the bay due to freshwater discharge. Compared to other closed bays, Cheonsu Bay has many sea dikes and estuaries that are likely to discharge a large amount of fresh water from the land along the north-eastern coasts of the bay. Therefore, spatially, these sea areas have different temperature fluctuation patterns from the south and west of the bay.

Meanwhile, in the second mode, after the influence of the first mode of seasonal fluctuations due to air temperature or the like was removed, sea areas having positive (+) values and sea areas having negative (-) values existed. The second mode had opposite phases (signs) throughout the year in shallow waters of Seosan~Boryeong and Anmyeon island-the central waters of the Bay. Due to different water depth distribution in the east-west direction and bottom layer mixing caused by tidal currents in Cheonsu Bay, a vertical mixed layer developed in the east coastal areas of Seosan~Boryeong along the tidal front. During autumn and winter seasons, the fluctuation of surface water temperature decreased as it went toward the land coast due to the effect of low temperature freshwater from the sea dike located on the eastern coast of the bay (negative (-) change in surface water temperature gradient). However, from spring to summer, the negative value of the second mode areas in the east coast of the bay was reduced due to the influence of freshwater that had increased in water temperature contrary to autumn and winter. In the south and west of the bay, the extent of the rise in surface water temperature due to stratification strengthening and inflow of external offshore water increased (positive (+) change in surface water temperature gradient) and the positive value of the second mode areas gradually expanded. Therefore, the distribution of the second mode represented the change of the surface water temperature gradient in the east~west and north~south directions of Cheonsu Bay. In the vicinity of shallow waters of Seosan~Boryeong, the second mode component also showed a large difference by season, indicating that the surface water temperature in this sea area fluctuated significantly throughout the year.

From the fluctuation of the first mode time coefficient (Fig. 10), the surface water temperature decreased significantly in November and December but increased in May. The short-term fluctuation was excellent in the one-day and half-day cycles according to the tide. The one-day cycle was more dominant because daily change in air temperature acted more on water temperature. The fluctuation amplitude of the daily cycle was the greatest in spring. Daily air temperature had the greatest effect on the Cheonsu Bay during the period of water temperature rise. The 24-hour moving average of the first mode time coefficient was very similar to the air temperature fluctuation pattern. Daily fluctuation of surface water temperature in the first mode had a very high correlation with air temperature (Min and Kim, 2006). The fluctuation of the time coefficient in the second mode from December to February had a low correlation with the first mode, showing a correlation of in-phase in May and inversely from August to September. The fall period in November had the same phase correlation as the spring season (May). Therefore, the fluctuation of the second mode time coefficient was affected by the air temperature to some extent during water temperature increase (spring) and fall (autumn). However, in winter and summer, sea conditions or topographic characteristics that are opposite or irrelevant to air temperature fluctuations can act as a temporal fluctuation factor of the surface water temperature gradient at each station.

5. Summary and conclusion

Temporal and spatial fluctuations in surface water temperature in Cheonsu Bay and the relationship between air temperature and river runoff fluctuations were analyzed using seasonal surface water temperature time series data. The surface water temperature increased from the south to the north of the bay during the spring~summer season, but decreased toward the north during the autumn~winter season when water temperature decreased. Due to the shallow depth and weak currents, central and northern regions of the bay were greatly influenced by the shoreline and air temperature, and surface water temperature fluctuation was dominant. Sea areas around the north-eastern sea dikes of the bay showed the maximum water temperature during water temperature increase, but showed the lowest water temperature during water temperature decrease. The water temperature variance was large in the north~east coast, but small in the south~west coast of the bay. The difference between surface water temperature and air temperature was the greatest in the winter season, being larger in the southern and central parts of the bay than in surrounding coasts of the north-eastern sea dikes. In the northern part of the bay, the temperature difference between the water temperature and the air temperature was small during water temperature increased. Thus, the northern part of the bay was is greatly affected by the atmosphere. The annual fluctuation range of surface water temperature increased and the phase increased from the south to the north of the bay. On the other hand, it is thought that data analysis based on monitoring survey data for one year across the bay could have identified the more detailed seasonal fluctuations of water temperature across the bay and its causes. However, the major achievement of this study is that it was able to identify the seasonal changes in water temperature in the closed Cheonsu Bay area and its characteristics for the entire bay area. When fresh water was discharged from the sea dike, the surrounding surface water temperature decreased and then increased, or increased and then decreased. The farther away from the sea dike, the smaller the fluctuation range. If the water temperature monitoring survey is carried out for more than 365 days a year in the future and the detailed water temperature fluctuation patterns and causes of the entire bay are identified, it is thought that it can play a significant role as the basis for relocation and restructuring of the aquaculture industry in each area of Cheonsu Bay.

In the EOF analysis of water temperature, the first mode represented seasonal variation of the surface water temperature and the second mode represented variability of surface water temperature gradient in the east~west and north~south directions of the bay. The maximum in the first mode appeared in autumn and the minimum in summer, consistent with seasonal distribution of surface water temperature variance. In the second mode, the coast of Seosan~Boryeong and the east coast of Anmyeon Island showed opposite phases with the boundary of the center of the bay. From autumn to winter, the range of fluctuations in water temperature drop increased from the center of the bay to the north and east due to the effect of cold fresh water. However, from spring to summer, the range of fluctuations in water temperature rise increased toward the south and west of the bay. The periodic fluctuation of the first mode time coefficient dominated in the one-day and half-day period. The pattern of the one-day fluctuation was similar to the air temperature fluctuation. The second mode time coefficient was in a phase with the first mode in spring and autumn. However, there wais no correlation or inverse phase in winter and summer due to sea conditions or topographic characteristics. Temporal and spatial fluctuations in surface water temperature in Cheonsu Bay were mainly affected by air temperature fluctuations and sea condition fluctuations caused by freshwater runoff. As a result of the EOF analysis, it was found that fluctuations due to tide and tidal current were dominant. In addition to these factors, further analysis and research on monsoon, internal tide, and coastal tidal front fluctuations that might affect fluctuations of surface water temperature in Cheonsu Bay are needed in the future.

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