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이학석사학위논문

Asymmetry of seasonal sea
surface temperature variation in
the sea around Korean Peninsula

한반도 주변해 계절수온변화의 비대칭성

2014년 2월

서울대학교 대학원

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곽 현 영

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이 논문을 이학석사학위논문으로 제출함

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곽현영

곽현영의 석사학위논문을 인준함

2014년 2월

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Abstract

Asymmetry of seasonal sea surface temperature variation in the sea around Korean Peninsula

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Sea Surface Temperature (SST) is an important component of climate and weather systems at various time scales. In this study, asymmetric seasonal variation of SST in the seas around Korean Peninsula is investigated using reanalysis and observation data. Specifically, the asymmetry of the SST seasonal variation is estimated quantitatively, and is compared with heat advection and surface net heat flux using SST data and atmospheric variables from ECMWF.

Two definitions were used to quantify the asymmetry of the seasonal variation;. 'day ratio' defined as a ratio of number of days in increasing temperature trend to total days. 'Amplitude ratio' means ratio of semi-annual amplitude to annual amplitude of temperature variation implies that the seasonal variation of temperature is asymmetric if day ratio is far from 0.5 or amplitude ratio is large.

Day ratio of SST shows an opposite feature to air temperature. Air temperature increases slowly, whereas SST decreases slowly in the study area. Spatial distribution of SST amplitude ratio is more complex than that of air temperature. There are substantial disagreement between the day ratio and the amplitude ratio over the highly asymmetric regions, such as northern East/Japan Sea and Kuroshio path. Phase difference between annual and semi-annual components causes this disagreement.

Heat advection and surface heat flux were estimated using model SST and current data. Incoming heat advection shows negative correlation with the asymmetry index of the SST seasonal variation, whereas surface net heat flux has positive correlation with the SST asymmetry index. Model sensitivity test, which performs no current along the boundary, shows prominent cause of asymmetry in seasonal variation different feature. Asymmetry decreases significantly when there is no current.

Keywords : sea surface temperature, seasonal variation,
asymmetry, surface heat flux, heat advection

Student Number : 2012-20332

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1. Introduction

Sea Surface Temperature (SST) plays a key role in changing climate and weather systems at various time scales, specifically via air-sea momentum and heat exchange processes. Therefore, the research of SST variation is fundamental and crucial in the ocean, atmosphere, fisheries and ecology. The seasonal variation of water temperature has a large impact on primary production and marine habitats (Wang et al., 2003, Belkin, 2009).

While the seasonal variation of SST is qualitatively diagnosed in many regional seas, relatively little attention has been given to understand the asymmetric seasonal variation of SST. The asymmetry is of interest because it reflects a complexities of ocean dynamics which includes nonlinear processes (Bartos and Janosi, 2005, 2006).

The asymmetric seasonal variation of air temperature, rapid cooling and gradual warming in mid-latitudes has been studied (Ashkenazy et al., 2008). However, relatively little research has been done to understand the asymmetric seasonal variation of SST that is able to influence the air temperature at various time scales. SST might influence on the surface wind (Wallace et al, 1989), and both air

temperature and SST had a great impact on each other by air-sea interaction. Therefore, it is important to understand the air-sea interaction and surface heat flux to explain the SST variation (Cayan 1992, Hirose et al., 1999, Subrahamayam et al., 2008).

The SST is influenced by not only air-sea interaction but by ocean heat advection by currents. The Kuroshio and the Tsushima Currents are the most important pathways for heat transport, causing SST variations in the seas around Korean Peninsula (Figure 1). The seasonal variation of SST and its asymmetry might be strongly influenced by air-sea interaction and heat advection in the sea around Korean Peninsula (Kang, 1984, Dong, 2007, Cho, 2009, Seo et al., 2013).

The main objective of this study is to quantitatively assess the asymmetry of SST seasonal variation around Korean Peninsula and to ascertain spatial distribution of asymmetry. Also, the role of horizontal ocean heat advection on the SST asymmetry will be diagnosed.

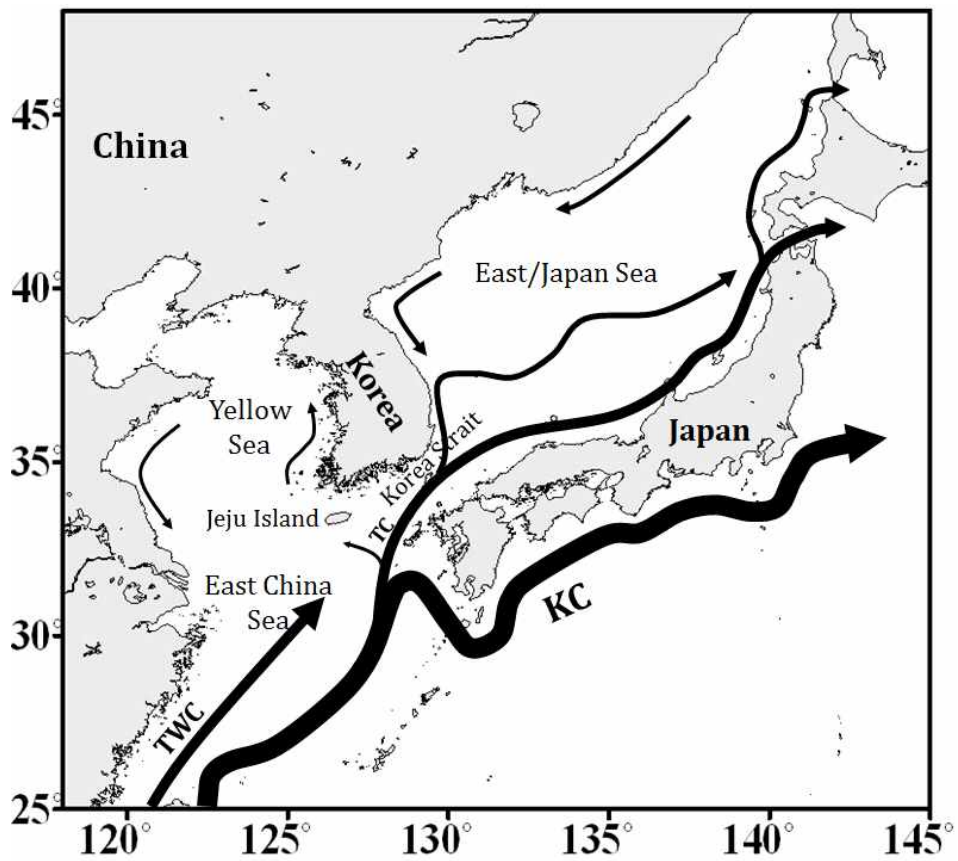


Figure 1. Major currents in the study area

2. Data and Methodology

2.1 Data

Both satellite-observed and model-simulated SST data are used; The satellite SST is Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) provided by UK Met Office (Donlon et al., 2012). This system combines in situ data with infrared and microwave satellite data. It is daily, and covers global with $1/20^\circ$ of spatial resolution.

Model-simulated SST data is from Regional Ocean Modeling System (ROMS), simulated from 1993 to 2011. The model domain is 115°E – 142.5°E and 24°N – 52°N , including East China Sea, Yellow Sea, East Sea and Northwestern Pacific. The Ocean model has 0.1° of horizontal resolution and 40 vertical levels. Simple Ocean Data Assimilation (SODA) from 1993 to 2010 and Hybrid Coordinate Ocean Model (HYCOM) data in 2011 were used as an open boundary data. Surface forcing is from European Centre for Medium-Range Weather Forecast (ECMWF) interim daily data. 10 major tidal forcing were applied (Egbert and Erofeeva, 2002), 12 rivers were included. Vertical mixing scheme was K-Profile Parameterization (Large et al., 1994).

The model-simulated SSTs from the year 2006 to 2010 are used to calculate the seasonal variation of SSTs.

Atmospheric variables such as air temperature and wind stress from ECMWF (European Centre for Medium-Range Wether Forecast) interim daily data with 0.75° of horizontal resolution are used to calculate surface heat fluxes.

2.2 Calculation of heat advection and heat flux

Heat advection is given by

$$Q = \iint \rho c_p T(z) U(z) dz dx$$

where ρ is density of sea water, c_p is heat capacity of sea water, and $T(z)$ and $U(z)$ are temperature and current velocity at the depth of z .

The surface net heat flux Q_{net} is given by

$$Q_{\text{net}} = Q_s - (Q_b + Q_h + Q_e)$$

where Q_s is solar radiation, Q_b is long-wave radiation, Q_h is sensible heat flux, and Q_e is latent heat flux. If Q_{net} is positive, ocean gains heat from atmosphere. four components, Q_s , Q_b , Q_h , and Q_e , are estimated by empirical formulas as follows (Kim and Kimura, 1995, Seckel and Beaudry, 1973, Efimova, 1961).

$$Q_s = (0.865 - 0.5C^2)(1 - \alpha)Q_0$$

$$Q_0 = A_0 + A_1 \cos \phi + B_1 \sin \phi + A_2 \cos 2\phi + B_2 \sin 2\phi, \quad \phi = (t - 21)(360/365)$$

where C is amount of cloud, α is albedo, t is Julian day, and coefficients of Q_0 follow Table 1.

$$Q_b = \epsilon \sigma T_a^4 (0.254 - 0.00495 e_a) (1 - \delta C) + 4 \epsilon \sigma T_a^3 (T_s - T_a)$$

$$Q_h = \rho_a c_{pa} c_h (T_s - T_a) W$$

$$Q_e = \rho_a L c_e (q_s - q_a) W$$

where emissivity of the sea surface ϵ is 0.97, Stefan-Boltzmann constant σ is $5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$, cloud coefficient $\delta = 0.60$, air density $\rho_a = 1.125 \text{ kg m}^{-3}$, $c_{pa} = 1.048 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$, bulk transfer coefficient $c_h = 1.1 \times 10^{-3}$, $c_e = 1.2 \times 10^{-3}$, T_s , T_a are sea surface temperature and air temperature, respectively, e_a is vapor pressure, W is wind speed, L is latent heat of evaporation, q_s is saturated specific humidity at T_s , and q_e is specific humidity.

Table 1. The coefficients used to calculate Q_0 (Seckel and Beaudry, 1973)

	Latitude 20°S-40°N	Latitude 40°N-60°N
A_0	$-15.82 + 326.87 \cos L$	$342.61 - 1.97L - 0.018L^2$
A_1	$9.63 + 192.44 \cos(L + 90)$	$52.08 - 5.86L + 0.043L^2$
B_1	$-3.27 + 108.7 \sin L$	$-4.80 + 2.46L - 0.017L^2$
A_2	$-0.64 + 7.80 \sin 2(L - 45)$	$1.08 - 0.47L + 0.011L^2$
B_2	$-0.50 + 14.42 \cos 2(L - 5)$	$-38.79 + 2.43L - 0.034L^2$
L = latitude		

3. Result

3.1 Asymmetry of seasonal air temperature and sea surface temperature variation

‘Day ratio’ was defined to quantify the asymmetry in the seasonal variation of temperature. In this studied, it is defined as the ratio of the number of increasing days of temperature to total period from 2006 to 2010.

$$DR = \frac{\text{number of days of temperature increasing trend}}{\text{total period}(2006 \sim 2010)}$$

Therefore, it implies that the seasonal variation of temperature is symmetric if DR is 0.5. DR larger (smaller) than 0.5 implies that temperature warms (cools) gradually and cools (warms) rapidly.

Figure 2 shows the spatial DR distribution of air temperature and sea surface temperature. DR of air temperature is over 0.5 in the whole area, whereas DR of SST is less than 0.5 except some coastal regions. It means that the seasonal air temperature increases gradually, whereas SSTs increase rapidly. It is noticeable that the DR of SST is less than 0.3 in the Kuroshio path.

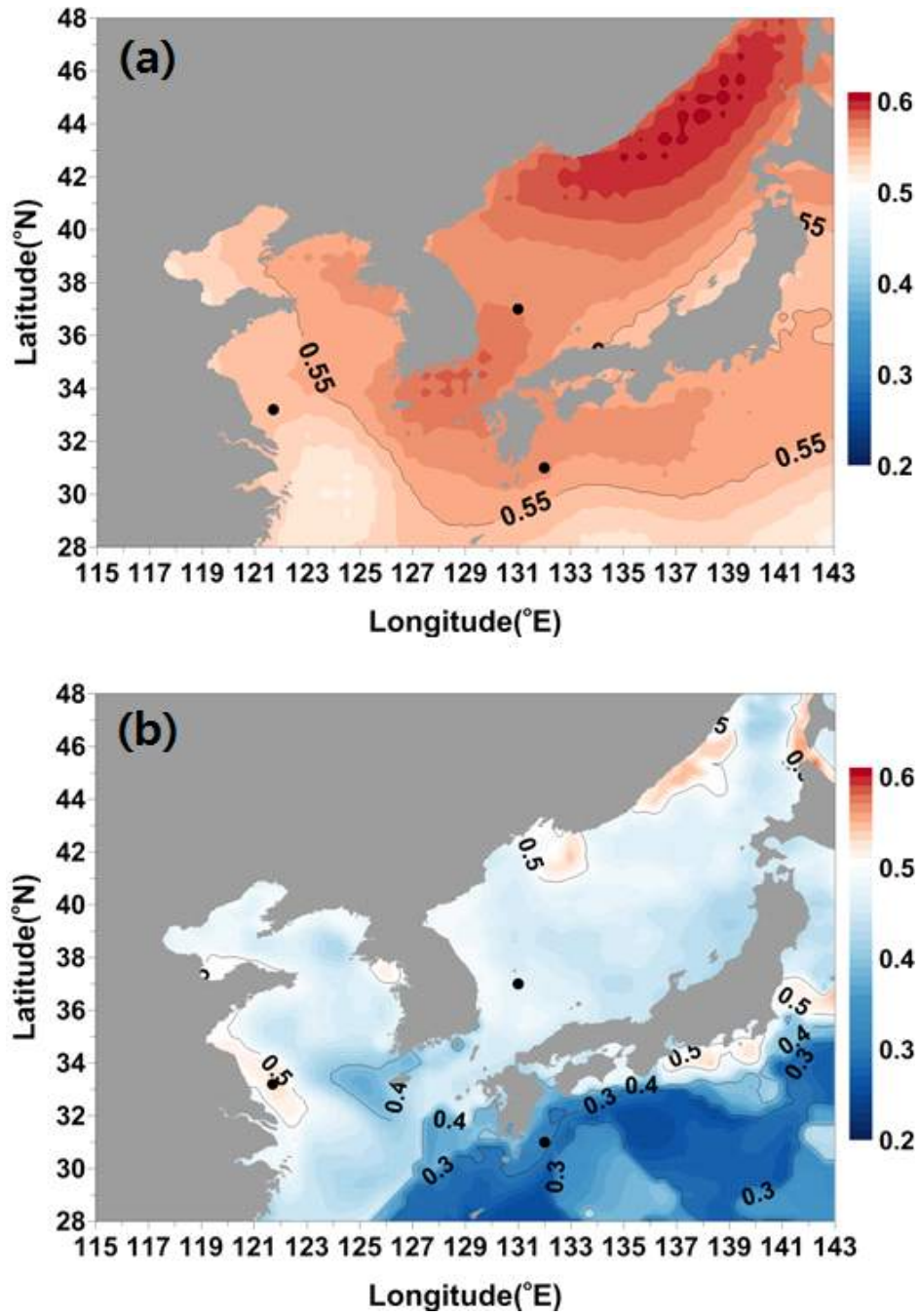


Figure 2. Day ratio of (a) air temperature and (b) SST.

3.2 Harmonic analysis of air temperature and sea surface temperature

If the seasonal temperature variation is symmetric, only the annual variation exists. However, seasonal variations of both air temperature and SST are asymmetric, as shown in Figure 2. Spectral analysis of SST shows that annual and semi-annual variation are dominant in the study area.

Harmonic analysis is used to resolve the annual and the semi-annual temperature variations.

$$T_i = \bar{T} + A_1 \cos(w_1 t_i - \phi_1) + A_2 \cos(w_2 t_i - \phi_2)$$

where $\bar{T}$ is mean temperature, and A_1 and A_2 denote the annual and the semi-annual amplitude respectively. w_1 and w_2 are angular velocities, ϕ_1 and ϕ_2 denote the annual and the semi-annual phases respectively at each grid, at time step i .

The amplitudes of annual air temperature and SSTs range from 6 to 15°C and from 4 to 12°C respectively (Figure 3a and b). The annual amplitudes are larger in the north than in the south. The

semi-annual amplitude of air temperature is $0.5\text{--}2.5^{\circ}\text{C}$, which is smaller than the annual amplitude (Figure 3c). Consistent with the annual amplitude, the semi-annual amplitude is relatively larger in the north. In the northern East/Japan Sea, the amplitude of semi-annual temperature is larger than 2.0°C (Figure 3d). While the annual amplitude of SST is smaller than that of air temperature, the amplitude of semi-annual SST is comparable to that of air temperature. The semi-annual amplitude of SST is small along coastal areas of China, Korean Peninsula and Japan, but it peaks in the coast of Russia, especially in northern East/Japan Sea.

The annual phase of air temperature is $210\text{--}230^{\circ}$, less than 210° in the coastal region (Figure 4a). In contrast, the semi-annual phase of air temperature is $120\text{--}150^{\circ}$ and is large in the coastal areas (Figure 4c). The annual phase of SST is faster than that of air temperature by $10\text{--}20^{\circ}$ and it is relatively fast along the coast (Figure 4b). The semi-annual phase of SST is less than 120° and is generally faster than that of air temperature (Figure 4d).

Temperature variation is symmetric when the amplitude of semi-annual variation is negligible than that of annual variation, that is, if the ratio of the semi-annual amplitude to the annual amplitude (amplitude ratio) is remarkable, seasonal temperature variation might be asymmetric. Therefore, spatial distributions of day ratio and of amplitude ratio show similar features except northern East/Japan Sea.

It may affect to the annual and semi-annual phase difference. Amplitude ratio of air temperature is less than 0.20 in the whole area, less than 0.10 along the coastal region of the Yellow Sea, and large in northern East/Japan Sea where semi-annual amplitude is significantly large. Though the amplitude ratio of air temperature is small in whole area, that of SST is shows large value over 0.20 in the west of Jeju island, Pacific, and northern East/Japan Sea (Figure 5). It means that semi-annual variation of SST is affected by not only air-sea interaction, but also other factors including heat advection.

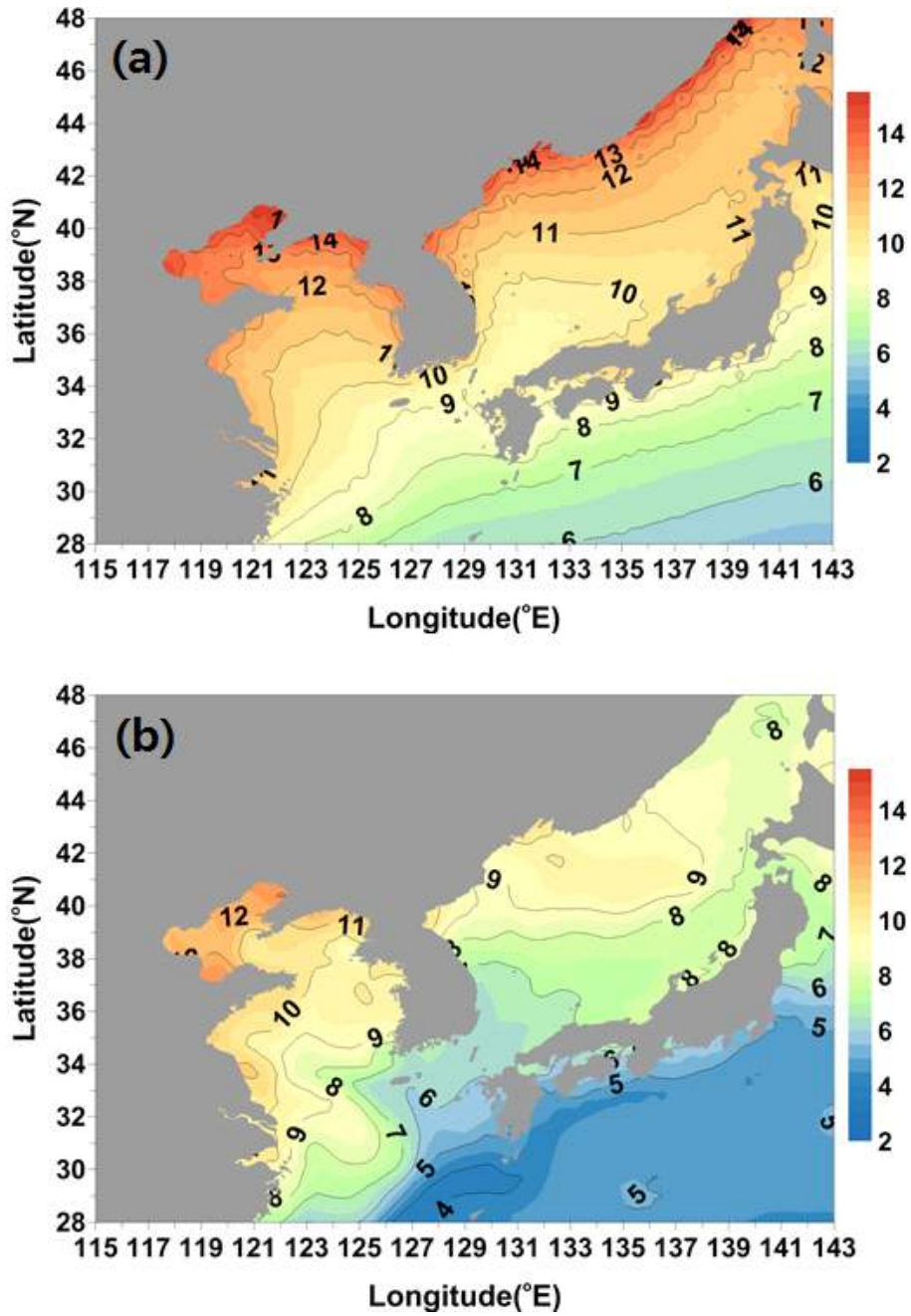


Figure 3. Annual amplitude (°C) of (a) air temperature and (b) SST and semi-annual amplitude (°C) of (c) air temperature and (d) SST.

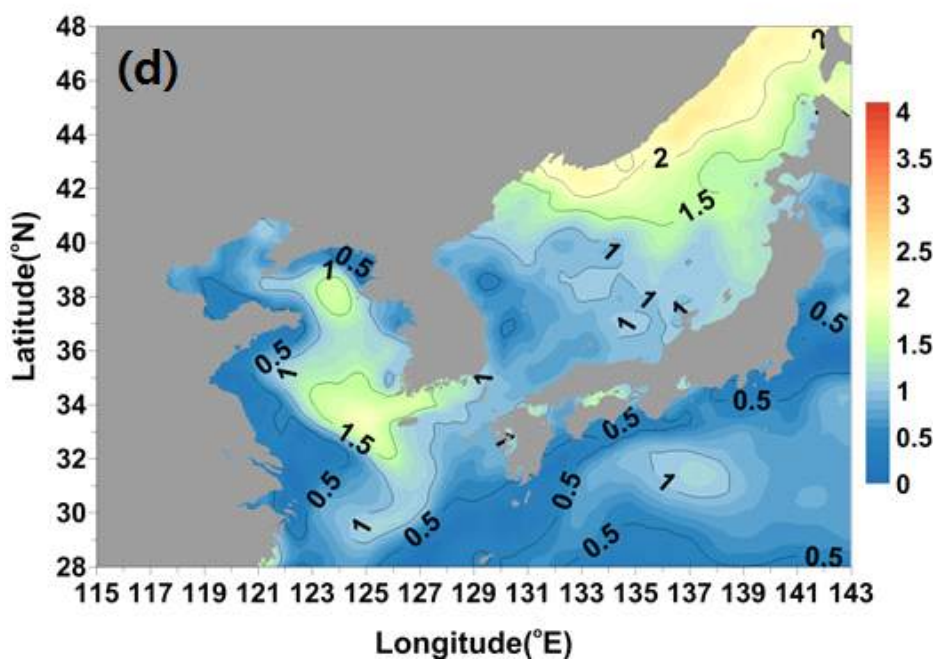
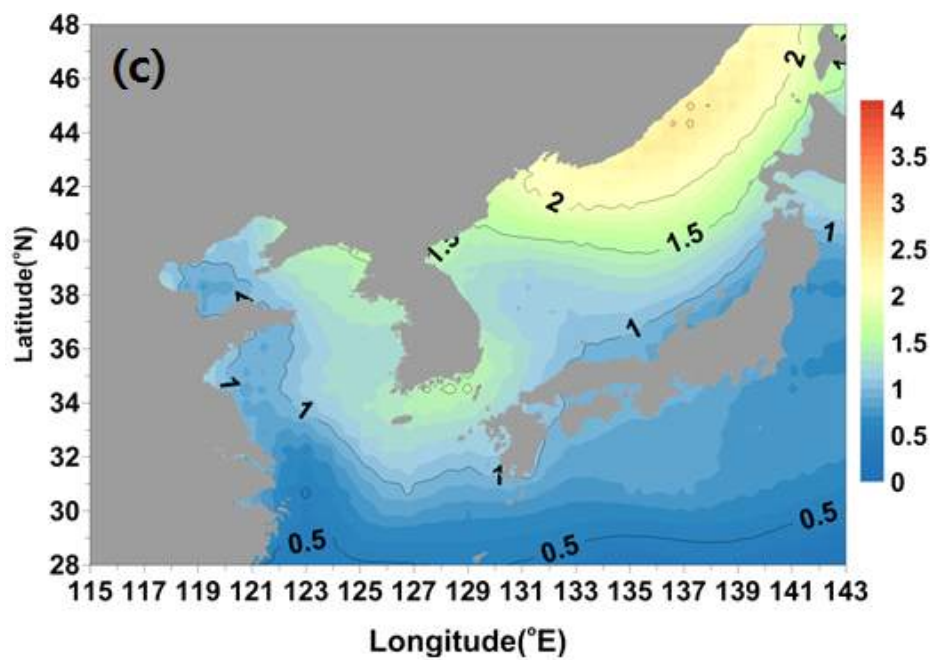


Figure 3. (continues)

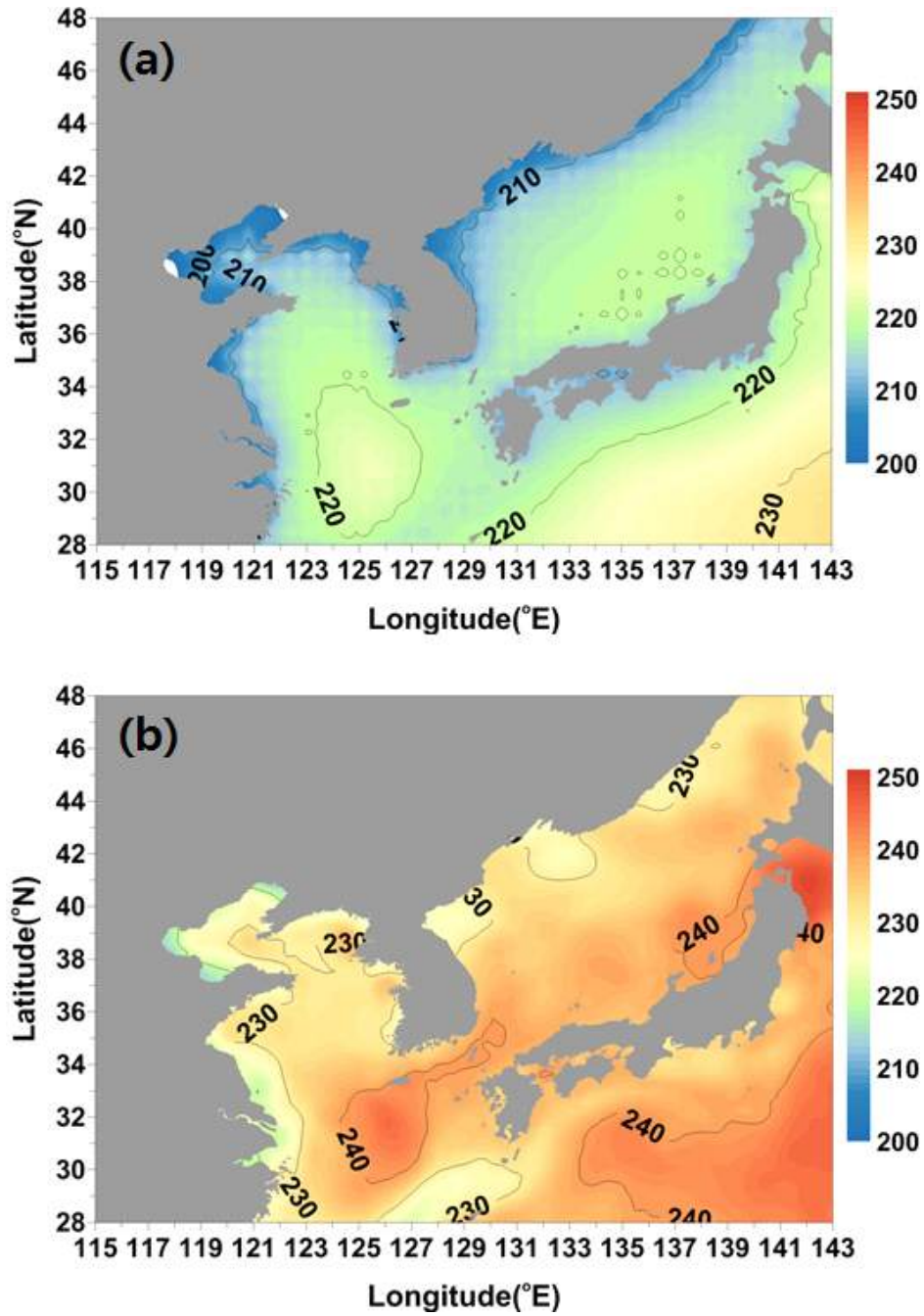


Figure 4. Annual phase ($^{\circ}$) of (a) air temperature and (b) SST and semi-annual phase ($^{\circ}$) of (c) air temperature and (d) SST.

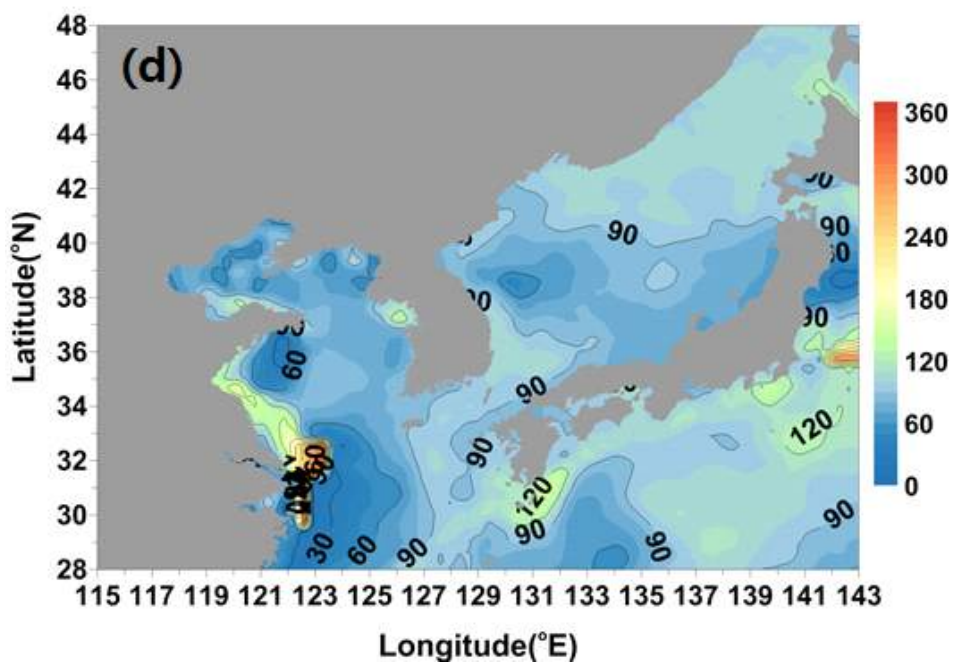
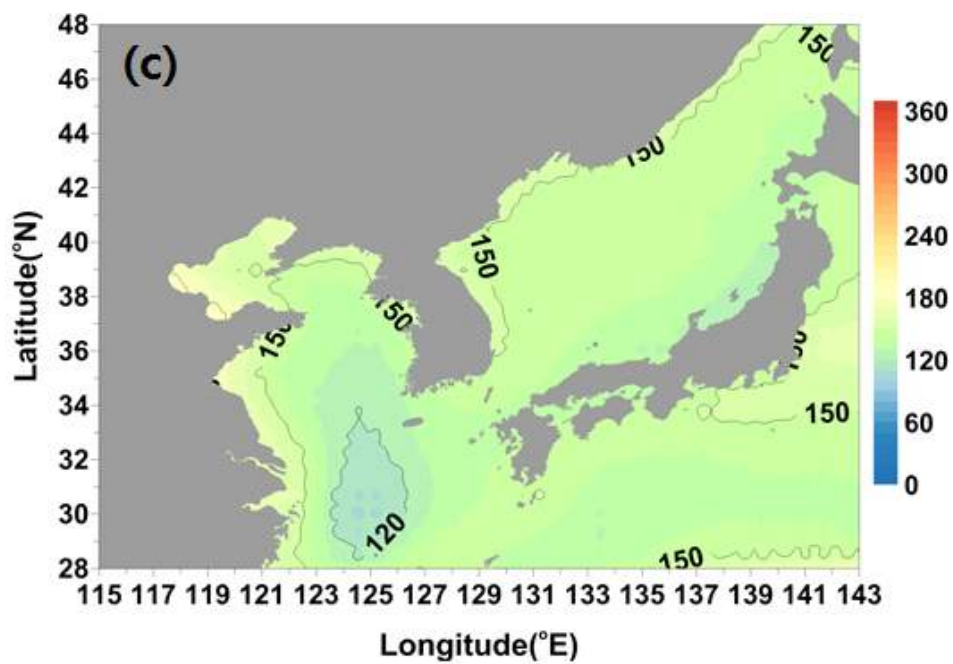


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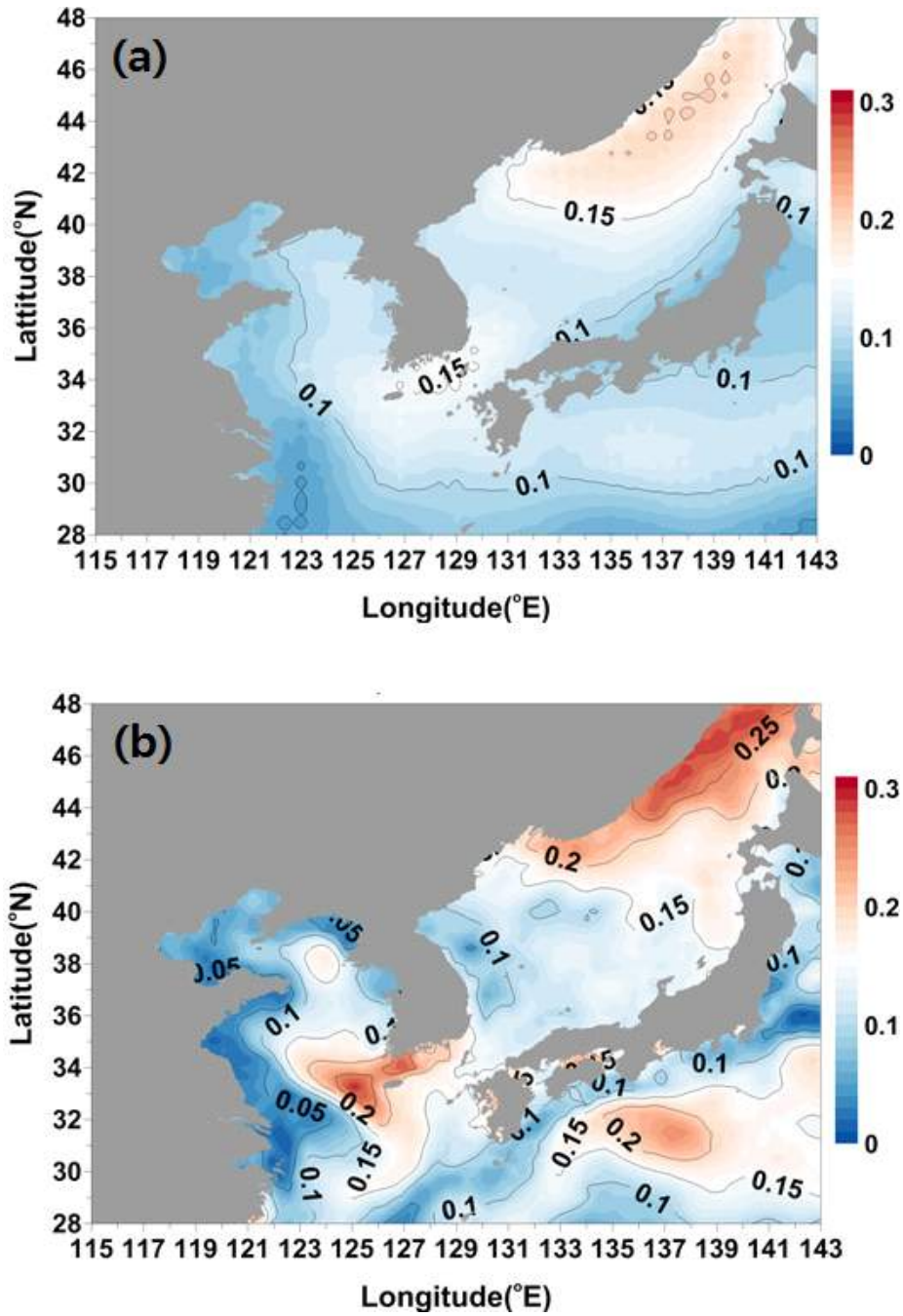


Figure 5. Amplitude ratio of (a) air temperature and (b) SST.

3.3 Surface heat flux and heat advection

In this section, model-simulated SSTs and current velocity are used to elucidate the relationship between incoming heat advection and the asymmetry in the seasonal variation of SSTs. Here, incoming heat advection means heat advection only incoming to each grid, not considering outward advection. Before estimating the heat advection, the model-simulated SSTs and the day ratio are compared with those of satellite observed SSTs to validate model result (Figure 6), respectively. Model SST and satellite observed SST are highly correlated with 0.99 of square of correlation coefficient (R-squared).

Spatial features of day ratio and amplitude ratio are similar to those of satellite observed SST (Figure 7). However, the area of gradual SST warming is slightly wider than that of observation, especially in coastal areas and northern East/Japan Sea. On the other hand, SSTs cool more slowly in many areas in the model. The amplitude ratio of the model-simulated SST is lower than that of the satellite-observed data except the Western Pacific. It means that the annual variation of model SST more dominantly drive the seasonal variation than satellite observed SST.

Surface net heat fluxes are estimated from the model-simulated

SSTs and atmospheric variables from ECMWF. Five-year-averaged surface net heat fluxes are mostly positive in the coastal region (Figure 8b). The air-sea interaction is turned out to be the most important factor taking the heat out of the surface Ocean. The Kuroshio and the Tsushima Current flowing region shows large negative surface fluxes. More than 10 GW of heat is emitted to air in those area.

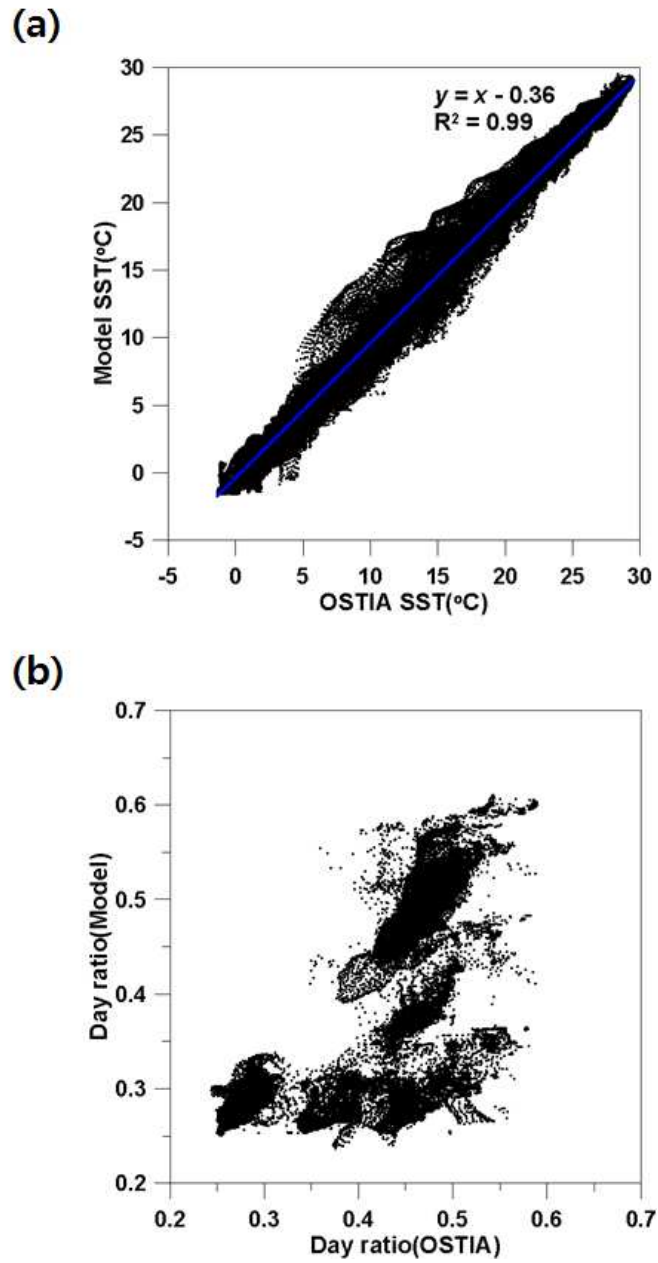


Figure 6. Correlations between (a) satellite observed SST and model result and between (b) Day ratio of satellite observed SST and that of model result.

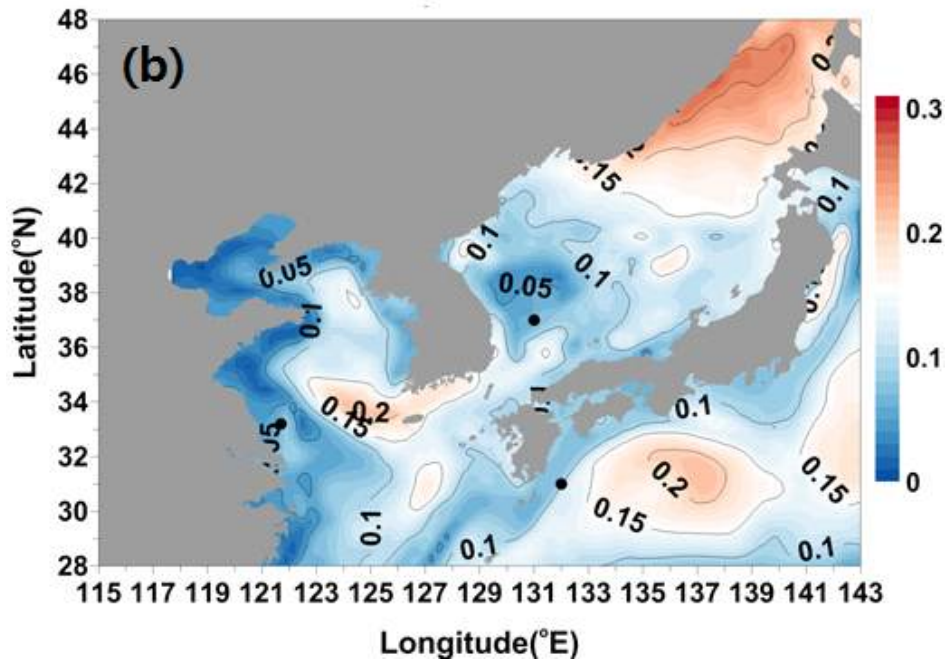
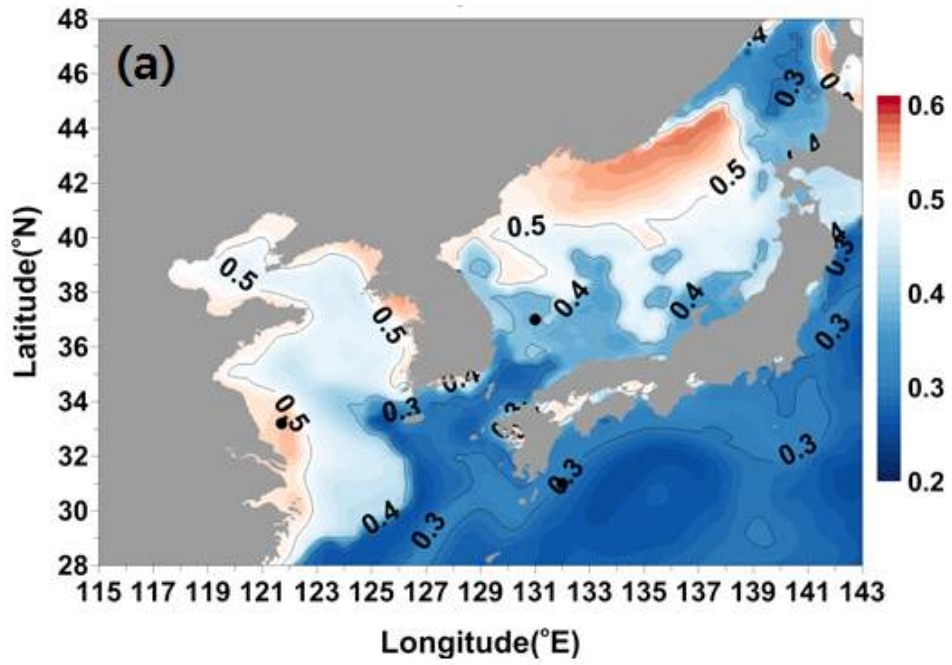


Figure 7. (a) Day ratio and (b) amplitude ratio of model SST result.

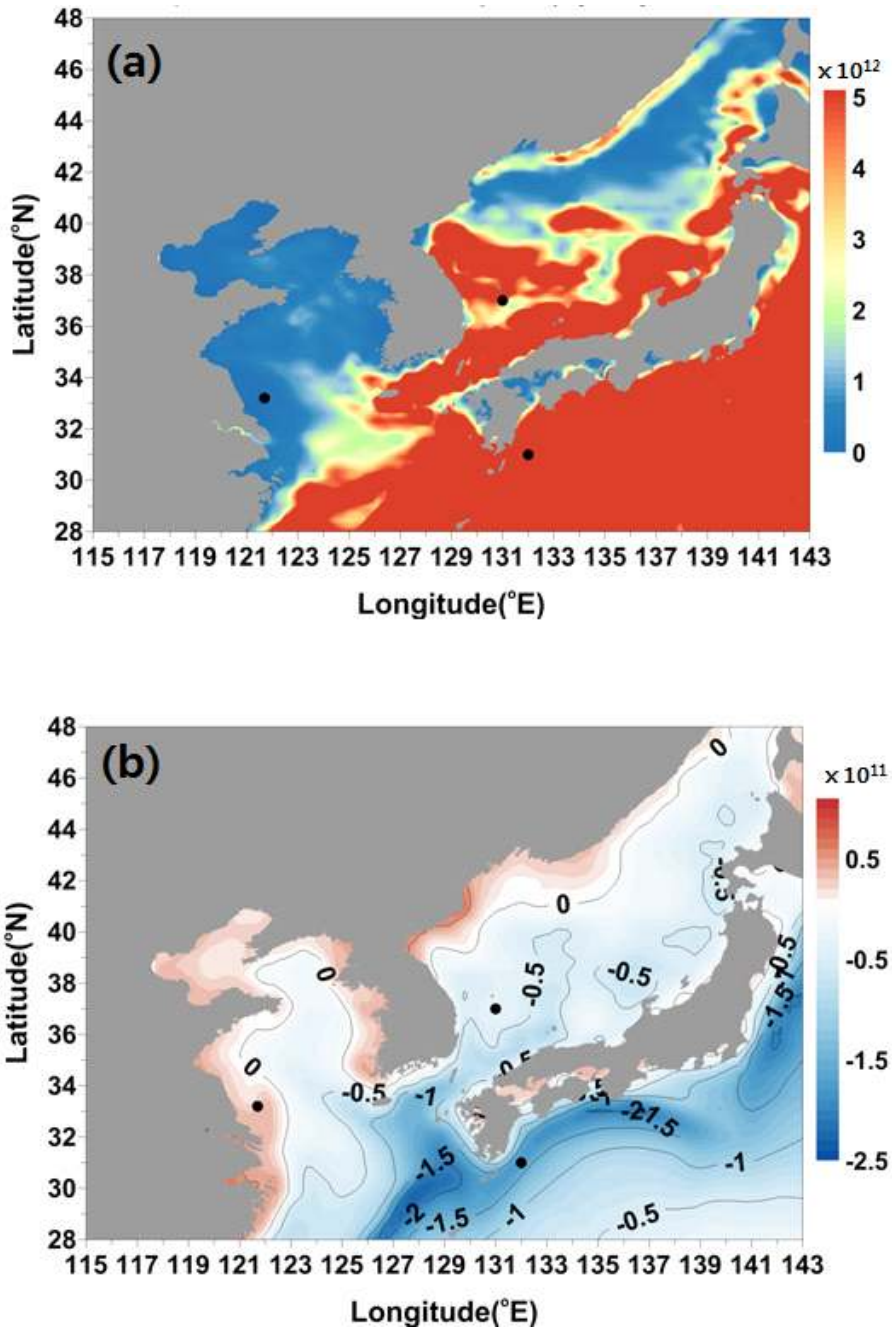


Figure 8. (a) Mean heat advection in the surface 100m layer and (b) mean surface net heat flux from 2006 to 2010. Both units are Watt.

4. Discussion

4.1 The relation of the SST variation with heat advection and surface heat flux

Correlations are calculated between the day ratio and the incoming heat advection in the surface 100m layer, and also between the day ratio and the mean surface net heat flux from 2006 to 2010 (Figure 9). The day ratio and the incoming heat advection are negatively correlated, whereas the day ratio and the surface net heat flux are positively correlated. Where incoming heat advection is large, ocean loses heat by air-sea interaction. On the other hand, where heat advection is small, air-sea interaction is weak, thus surface net heat flux is small.

Three different spatial groups are defined based on the day ratio; (1) $DR \leq 0.33$, (2) $0.33 < DR < 0.5$, and (3) $DR \geq 0.5$. Where $DR \leq 0.33$, SST decreases very slowly and these areas include the Western Pacific, Korean Strait, eastern East China Sea, and the northern East Sea, where warm current flows. In coastal areas and northern East/Japan Sea, $DR \geq 0.5$, heat advection is less than 1.0 TW, except coast of northern East/Japan Sea. In those areas, surface net heat

fluxes are mostly positive (Figure 10 and 11).

Three different regions, Chinese coast in the Yellow Sea, East/Japan Sea, and Kuroshio path, are chosen to examine the seasonal variation of SSTs, surface net heat fluxes, and ocean heat advection in the 100 m layer (Figure 12). At point 1, where ocean heat advection is dominant, SST decreases very slowly and the mean ocean heat advection is remarkably large as 269.89 TW (Table 2). Coastal areas, at point 3, SST warms slowly, the mean ocean heat advection is small, mean surface net heat fluxes are mostly positive, and DR is close to DR of air temperature. At point 2, in transit area, both the ocean heat advection and surface net heat fluxes are approximately in the middle, between the values at point 1 and 3.

Since the incoming heat advection was calculated in the surface 100 m layer, it is not easy to quantify the relationship among the SST, ocean heat advection, and surface heat fluxes. It might be possible to compare the SST, heat advection, and surface heat flux quantitatively if surface heat advection is calculated.

When SST increase, heat advection accelerates the temperature warming speed and decelerate cooling speed when SST decreases. Therefore, gradual cooling occurs in the ocean, though air temperature increases more slowly than decreasing.

Table 2. Each value of DR, mean heat advection, and mean surface net heat flux at the point 1 to 3.

	Point 1	Point 2	Point 3
DR	0.29	0.39	0.54
DR of air temperature	0.57	0.57	0.54
Mean heat advection(10^{12} W)	269.89	10.41	0.65
Mean surface net heat flux(10^{10} W)	-15.60	-0.43	2.82

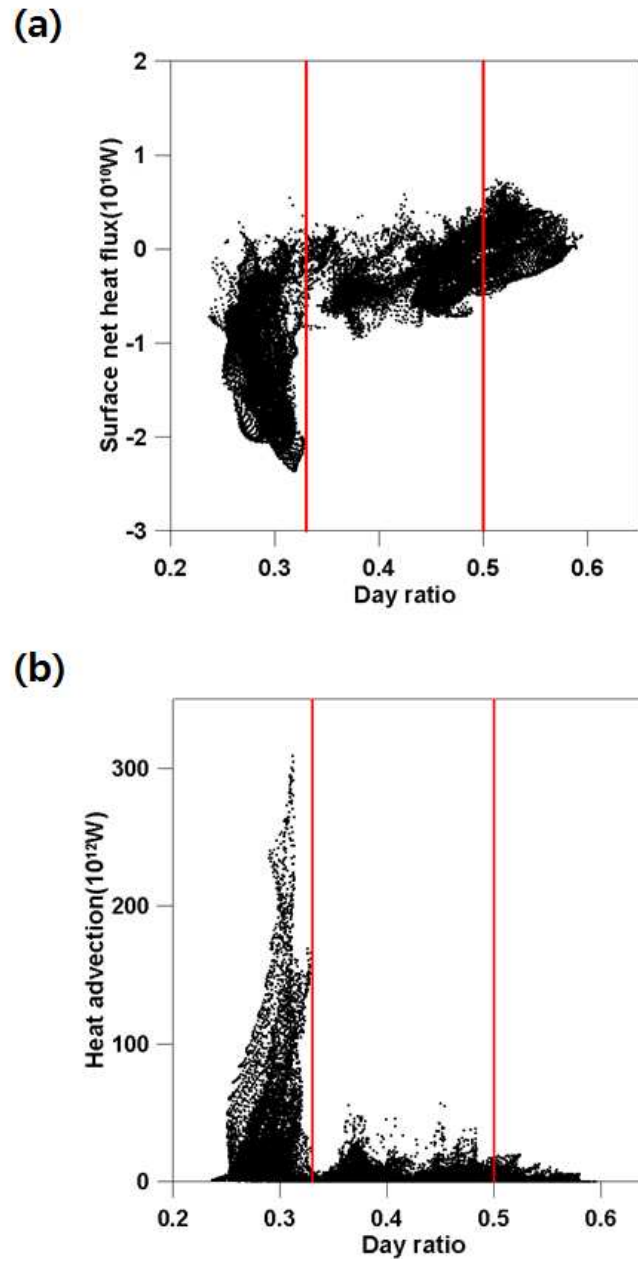


Figure 9. Correlations (a) between day ratio and incoming advection in the surface 100m layer and (b) between day ratio and surface net heat flux.

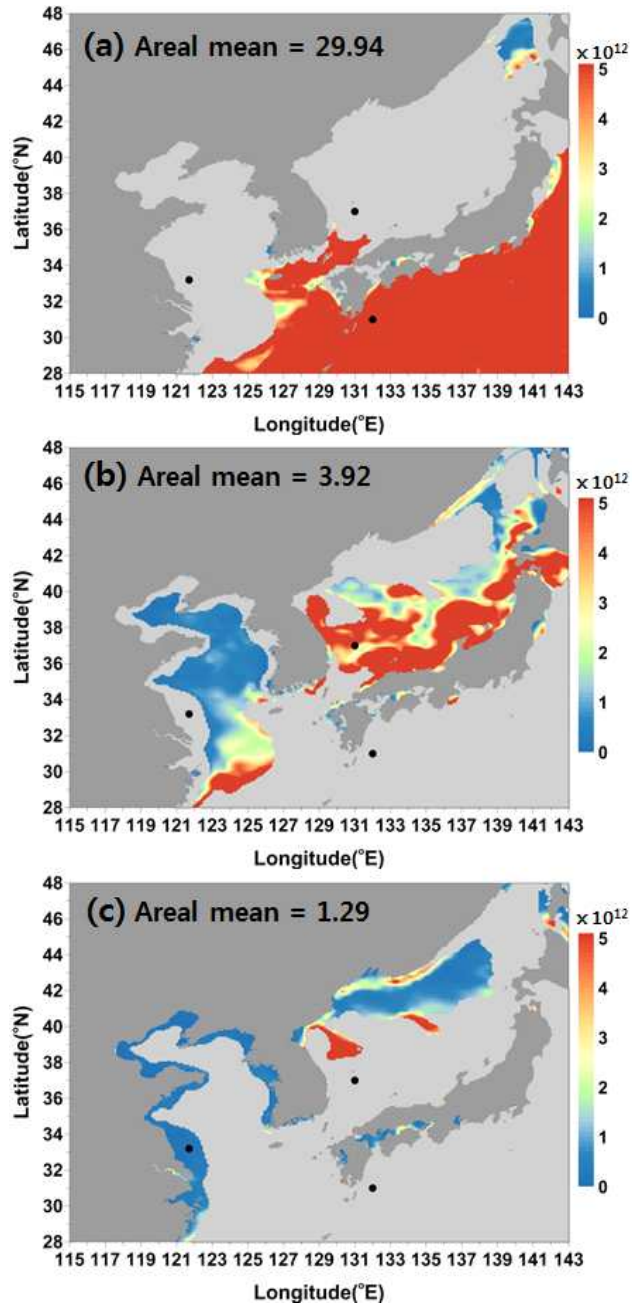


Figure 10. Spatial distribution of mean incoming heat advection(Watt) from 2006 to 2010 in each area (a) $DR \leq 0.33$, (b) $0.33 < DR < 0.5$, and (c) $DR \geq 0.5$.

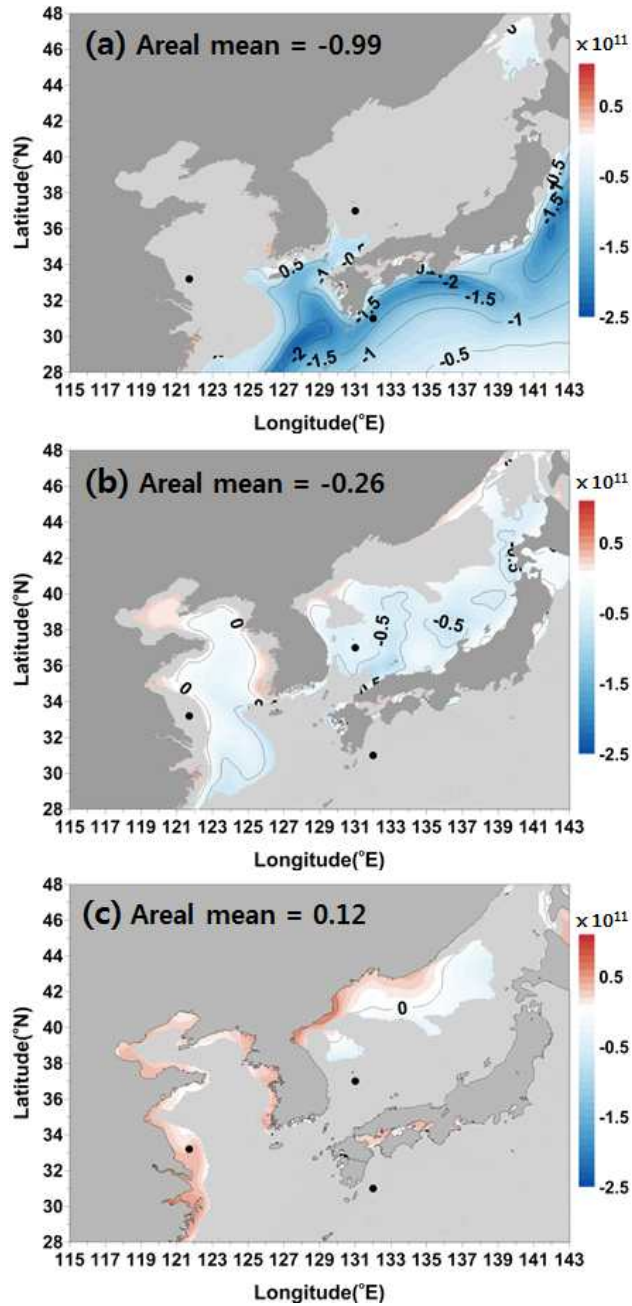


Figure 11. Spatial distribution of mean surface net heat flux(Watt) from 2006 to 2010 in each area (a) $DR \leq 0.33$, (b) $0.33 < DR < 0.5$, and (c) $DR \geq 0.5$.

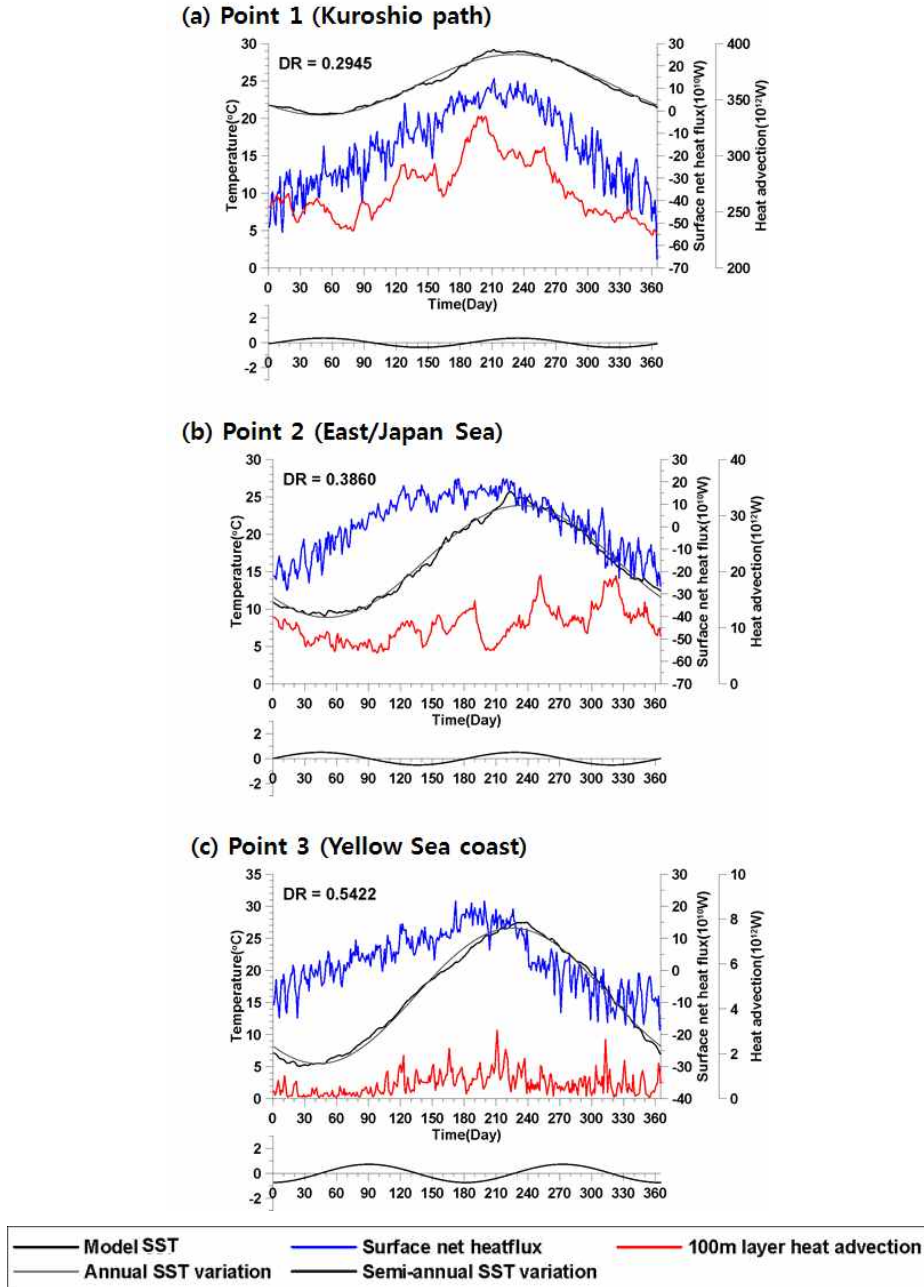


Figure 12. Five-year-mean SST, 100m layer heat advection, and surface net heat flux at the point 1 to 3 from 2006 to 2010. Semi-annual amplitudes are plotted on the different axis, under the model SST plot.

4.2 Model sensitivity test

Model sensitivity test was performed to evaluate the effect of the heat advection on the asymmetric seasonal variation of sea surface temperature. Currents along the open boundary and surface height anomaly were set to zero for whole period. Surface elevation by tide was imposed.

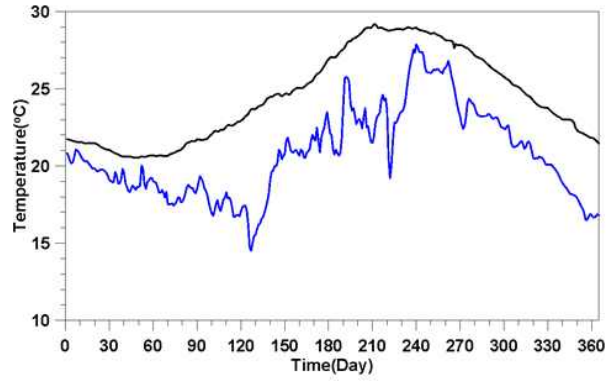
Day ratio without current is remarkably changed. It shows more symmetric seasonal variation than that with current in the Northwestern Pacific, Korea Strait, and the East/Japan Sea (Figure 14). In contrast, in the coastal region of the Yellow Sea, seasonal SST variation becomes more asymmetric, warming is more slow.

Seasonal SST at the selected three points, Kuroshio path, the East/Japan Sea, coastal region, are remarkably different from the SST variation with current (Figure 13). Mean temperature of the study area decreases due to no supply of heat by current from the southern boundary. Temperature increases more slowly and increasing period become longer. Day ratios also closed to 0.5, which means seasonal variation of SST is more symmetric (Table 3).

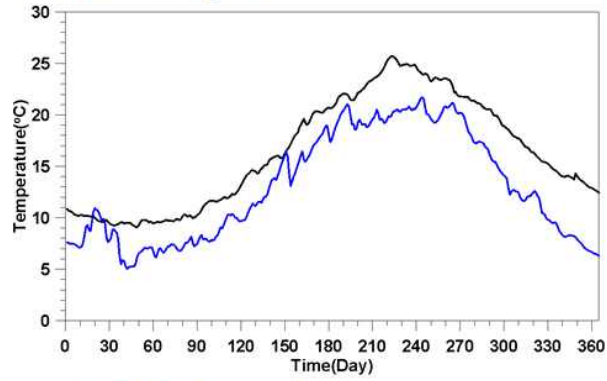
When there are no heat advection by current, seasonal variation of

SST becomes more symmetrically. This model sensitivity test supports that heat advection is a major cause of asymmetric seasonal SST variation.

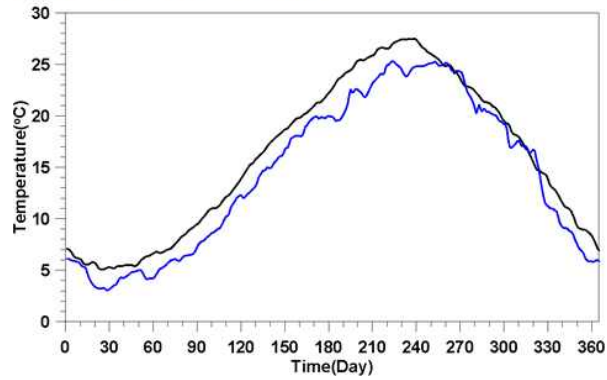
(a) Point 1 (Kuroshio path)



(b) Point 2 (East/Japan Sea)



(c) Point 3 (Yellow Sea coast)



— With current — Without current

Figure 13. Seasonal SST variations of model with current and model without current.

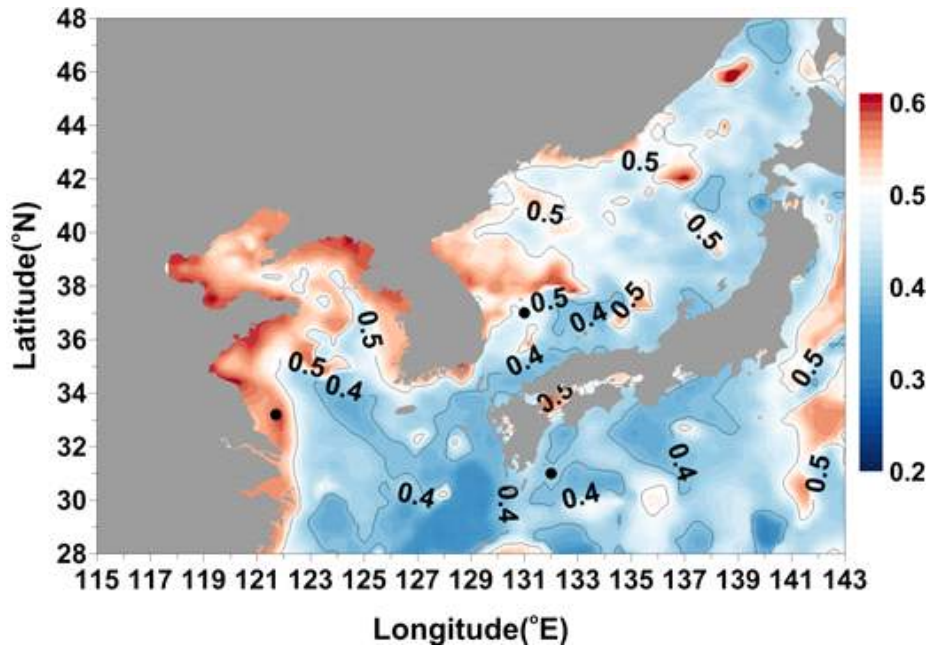


Figure 14. Spatial DR distribution of model without current.

Table 3. Day ratios of air temperature, SST with current, SST without current at selected three points.

	Point 1	Point 2	Point 3
DR of air temperature	0.57	0.57	0.54
DR of model result with current	0.30	0.39	0.54
DR of model result without current	0.40	0.49	0.53

5. Conclusion

The seasonal variation of the sea surface temperature (SST) is remarkably different from that of air temperature in the sea around the Korean Peninsula. SST decrease slowly and increase rapidly, except some coastal region, whereas air temperature in most region, increases slowly and decreases rapidly.

Day ratio is an index of quantify asymmetric seasonal temperature variation. Day ratio of air temperature is over 0.5 in the study area, whereas that of SST is over 0.5 only in some coastal region. Day ratio of Kuroshio path is under 0.3, SST decreasing is much slower than increasing.

It is thought asymmetric seasonal temperature variation is due to significantly large semi-annual amplitude. However, amplitude ratio distribution is different from the day ratio distribution though semi-annual fluctuation would affect the asymmetric temperature variation. Semi-annual amplitude does not mean asymmetric level, because the difference between annual and semi-annual phases contributes to temperature variation.

Study area could be divided into three according to day ratio.

where the seasonal SST warming is more gradual than cooling, heat advection is large, over 29 TW, and lose heat by air-sea interaction. On the other hand, where the seasonal SST increasing is slower than decreasing, both incoming heat advection and surface net heat flux are small.

From the model sensitivity test, heat advection seems reasonable possibility as a factor of asymmetric seasonal SST variation. when the currents along the open boundary were absent, seasonal variation of SST is more symmetric, except coastal region of the Yellow Sea. It implies that heat advection is main cause of the asymmetric seasonal SST variation. It is thought that when SST increases, heat advection accelerate the temperature warming speed and decelerate cooling speed when SST decreases. As a result, gradual cooling occurs in the ocean, though air temperature increasing is more slowly than decreasing.

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요약

표층 수온은 기후와 날씨의 중요한 변수이다. 2006년부터 2010년까지 OSTIA에서 제공하는 수온 자료, ECMWF에서 제공하는 대기변수들을 이용하여 표층수온 계절 변화의 비대칭성을 확인하고 수온 변화의 비대칭성을 이루는 열과 표면에서 대기-해양 간의 총 열수지와 각각 비교하였다.

온도 계절 변화의 비대칭의 정도를 정량화하기 위하여 증가일률(day ratio)과 진폭비(amplitude ratio)를 정의하였다. 증가일률은 전체 기간에 대하여 온도가 증가하는 추세에 있는 날 수의 비이며, 진폭비는 일년주기 진폭에 대한 반년주기 진폭의 비이다. 따라서 증가일률이 0.5에서 멀어질수록, 진폭비가 클수록 온도 계절변화가 비대칭적이라고 할 수 있다.

수온의 증가일률은 기온과 반대 모습이 나타난다. 기온은 증가가, 수온은 감소가 완만하다. 수온 진폭비의 공간분포는 기온보다 복잡한 모습이 나타난다. 동해 북부와 쿠로시오 경로와 같이 증가일률과 진폭비의 공간 분포에서 계절 수온 변화가 비대칭적으로 나타나는 지역이 다른데, 이는 일년주기와 반년주기의 위상차가 영향을 주는 것으로 생각된다.

모델의 수온과 유속 자료를 이용하여 이루는 열과 표층에서 대기-해양의 총 열수지를 계산하였다. 계절 표층 수온 변화의 비대칭성은 유입되는 열류량과 음의 상관관계가, 표면의 총 열수지와는 양의 상관관계가 나타난다. 초기조건의 열린 경계에서 유속을 없애고 모델 민감도 실험을 수행한 결과 해류가 없을 때, 수온의 계절변화는 더 대칭적으로 나타났다.

주요어 : 표층 수온, 계절변화, 비대칭, 표층 열수지, 열류량

학 번 : 2012-20332