Journal of the Korean Society of Marine Environment & Safety
Research Paper
Vol. 26, No. 3, pp. 233-241, May 31, 2020, ISSN 1229-3431(Print) / ISSN 2287-3341(Online) https://doi.org/10.7837/kosomes.2020.26.3.233

Change the Annual Amplitude of Sea Surface Temperature due to Climate Change in a Recent Decade around the Korean Peninsula

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Abstract : *We examined long-term variations in sea surface temperature (SST) and annual amplitudes of SST around the Korean Peninsula. Two SST data sets with data periods of approximately 51 years and longer than 100 years, respectively, were obtained from the National Institute of Fisheries Science and Japan Meteorological Agency. SST of Korean waters clearly increased during last 51 years (1968-2018), which was 2.5 times higher than the global trend. This significant increasing trend was caused by the dominant increasing SST trend during winter. However, a negative and positive SST anomaly frequently appeared during winter and summer, respectively, in a recent decade. These features of seasonal SST variation have changed the annual amplitude of SST, and resulted in a drastically increasing trend after 2009. Using the longer SST data set, it was revealed that the decreasing SST trend in winter began in the 2000s and the increasing SST trend in summer bagan in the 1990s. During a recent decade, there was a distinctive SST increase in summer, whereas a clear decrease in winter. In summary, the annual amplitude of SST around the Korean Peninsula significantly changed from a decreasing trend to an increasing trend during a recent decade.*

Key words : *Sea surface temperature, Annual amplitude, Climate change, Long-term trend, Korean waters*

1. Introduction

The Intergovernmental Panels on Climate Change (IPCC) approved the Summary for Policymakers (SPM) of the Special Report on Ocean and Cryosphere in a Changing Climate (SROCC) in September 2019. The report stated that global warming has occurred unabated since 1970 and that rate of ocean warming has more than doubled since 1993. Furthermore, IPCC reported that sea surface temperature (SST) has risen on a global scale, at a rate of 0.09 ℃/decade over the satellite era (1980-2017) and at an average rate of 0.05 ℃/decade for the period 1900-2017 (IPCC, 2019). Ocean warming has various associated effects, such as sea level rises and changes in the biomass of marine organisms, habitats of marine animals, fisheries and coastal ecosystems. Moreover, IPCC projected that under low and high emission scenarios, the ocean will warm two to four times and five to seven times, respectively, compared with the observed changes since 1970 (IPCC, 2019).

It is well known that the increasing SST trend in the East Asian Marginal Seas (EAMSs) is one of the highest in the world. For example, Belkin (2009) reported that the East Asian Seas were warming at 2-4 times the global mean rate, and the most rapid warming could be observed in the land-locked and semi-closed East Asian Seas such as the East Sea and East China Sea. Bao and Ren (2014) used the monthly mean Hadley Centre Global Sea Ice and Sea Surface Temperature (HadlSST) data set to show that all the sea areas around China had undergone significant rising trends in annual mean SST during the last 140 years (from 1870 to 2011) and over the last 50 years (from 1962 to 2011), with greater and more significant warming generally occurring in autumn and winter. Tang et al. (2009) reported that significant warming trends are found in both summer and winter around the Northern East China Sea. Wang et al. (2013) examined both historical and satellite data sets from 1957 to 2001 also described decade to decade variations in the warming and cooling trends in the seas east of China, with steady and rapid warming trends occurring after the 1980s, and significant warming trends appearing after 1985. In addition, Hwang et al. (2012) examined satellite data over a 19 year period (1990-2008) and described increasing annual SST amplitudes in the North East China Sea, the Korea Strait and the southwestern part of East Sea, but decreased amplitude in the other waters of EAMSs. Furthermore, Imada et al. (2017) reported increasing land surface temperatures over Japan during the summer and autumn, but decreasing winter and spring temperatures since the late 1990s.

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Studies focusing solely on Korean waters have also reported increasing SST trend. Kim et al. (2001) insisted that the East Sea might serve as a natural laboratory for analyzing global changes in the future because of the rapid turn-over time of the ocean conveyor-belt relating to the rapid warming trend in the upper layer. Kim et al. (2018) showed that the warming in the Yellow Sea and the East China Sea reached a peak in the last 1990s, and this was then followed by a significant cooling trend related with the role of the Pacific Decadal Oscillation (PDO) and the Siberian High. Kwak et al. (2015) conducted in-situ and satellite SST analyses to determine warming trends of 0.024 ℃/year and 0.011 ℃/year, respectively, for the period 1984 to 2013 in the seas around the Korean Peninsula. The differences between the long-term trends of the two data sources mainly relate to differences in the Yellow Sea.

Several studies have focused specifically on reporting seasonal features associated with increasing SST trends in Korean waters. For example, Kang (2000) analyzed the decreasing trends in the annual range of SST variations over a 60 years period (1936-1995) at 18 coastal observation stations along Korean coastal areas. The results showed that winter SSTs are increasing, whereas summer SSTs show a decreasing tendency. Lee and Kim (2013) determined that SSTs in the ECS had increased at a rate of about 0.03 ℃/year in recent years, and that the increase in winter was dominant. However, Min and Kim (2006) used 26 coastal SST time series from 1964 to 2004 to show that the decreasing tendency in the annual amplitude was mainly due to the significant increasing tendency of SST in winter. Kim et al. (2011) reported that the SST around the Korean Peninsula has warmed since 1880 by about 1 ℃, which was about twice that of global-mean ocean surface warming. They also showed that ocean surface warming is larger during the boreal winter than during summer.

As the special report of IPCC, Marine heatwaves (MHWs) usually occurred around the Korea Peninsula since 2010s during summertime (Kim and Han, 2017). MHWs in the Korean waters have a serious impact on fisheries and cause mass mortalities in aquaculture (KMA, 2017; KMA, 2018; KMA, 2019). In addition, since 2010, extreme low water temperature due to cold waves during wintertime has frequently occurred around the coastal areas and the inner bays along the southern and western coast of Korea during wintertime, due to cold waves closely related to the Arctic Oscillation (Han et al., 2019).

Previous studies have shown that the increasing SST trend of in Korean waters is dominant during winter. However, it is highly probable that the increasing SST trend relates the occurrence of abnormal water temperatures occurring during both summer and winter after 2010. In this study, we examine the long-term SST trend during summer and winter in Korean waters based on long-term SST observation data, and focus particularly on recent fluctuating trends. Through these results, we also examine changes in the annual SST amplitude in relation to climate change during the recent decade around the Korean Peninsula.

2. Data and Methods

To examine the long-term trend in sea water temperature changes within Korean waters, we used SST data obtained from NIFS Serial oceanographic Observations (NSO) of the by Korea Oceanographic Data Center (KODC) of National Institute of Fisheries Science (NIFS). SInce 1968, the NSO has measured physical and biogeochemical factors six times annually at 207 stations in Korean waters (Fig. 1). This study analyzed SST data obtained by NSO from 1968 to 2018 to understand the long-term changes in the annual SST amplitudes around the Korean Peninsula.

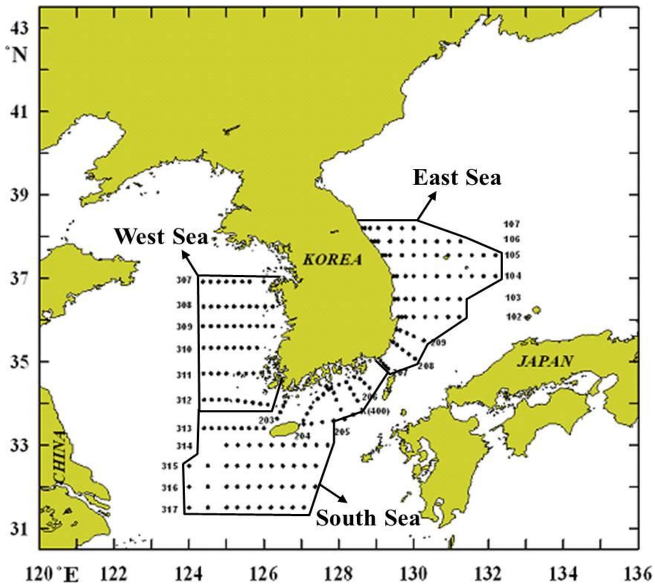

Fig. 1. Location of NIFS Serial oceanographic Observation conducted by NIFS and oceanic areas within Korean waters.

We determined variations in annual SST and the annual amplitudes of SST, which were calculated by the difference in SST between summer (August) and winter (February) over 51 years. Moreover, we analyzed the long-term SST trend and the annual SST amplitude in three different areas; the East Sea, South Sea, and West Sea, as shown in Fig. 1. The terms “South Sea” and “West Sea” were respectively used in this study to divide the inner Exclusive Economic Zone (EEZ) ocean areas of the Republic of Korea in the northern East China Sea and the Yellow Sea.

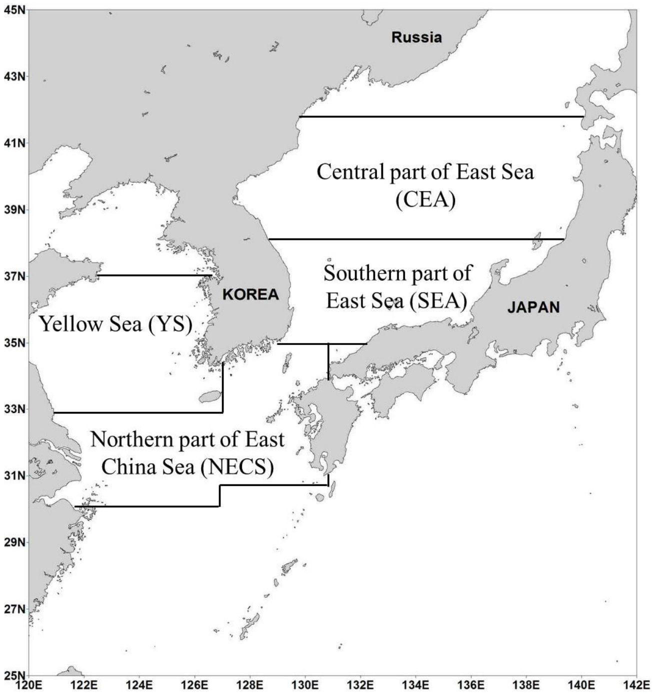

Fig. 2. Separation of oceanic areas by COBE-SST.

We also used Centennial in situ Observation-Based Estimates of the variability of Sea Surface Temperature and marine meteorological variables (COBE-SST) obtained by the Japan Meteorological Agency (JMA) to understand longer variations in SST changes around the Korean Peninsula. The grid for SST has been improved to one degree by JMA conducting objective analysis through quality control of maritime weather observation data including SST reported from the ship (Ishii et al., 2005). These SST grid point data are analyzed on a large spatial scale and are intended for use as boundary values to monitor global climate change and as input data for numerical models. It is not appropriate to analyze the differences in the long-term change trend in SST per sea areas, due to the fine spatial scales provided and the sea area characteristics in EAMSs. Therefore, the EAMSs were divided according to the sea characteristics, and the average SST of each sea was calculated using field observation data from each sea area to determine the rate of increase (Takatsuki et al., 2007). In this dataset, the oceanic areas were divided four areas; the central part of the East Sea, the southern part of the East Sea, the Yellow Sea, and the northern part of the East China Sea (Fig. 2).

We, then, examined the long-term changes in annual and seasonal SSTs and the annual SST amplitude around the Korean Peninsula using these two long-term data sets.

3. Results

3.1 Long-term changes in SST and annual SST amplitude in the Korean waters using NSO

Using SST data obtained by NSO, we examined the long-term changes in annual mean SST within Korean waters during last 51 years (1968-2018) (Fig. 3). The annual mean SST in Korean waters showed an increasing trend of 0.0241 ℃/year from 1968 to 2018, although there was large interannual variation. This implies that annual SSTs in Korean waters increased by approximately 1.23 ℃ over the 51 year periods. However, the annual global mean SST increased by only about 0.49 ℃ during the same period, according to COBE-SST obtained from the JMA (JMA, 2019).

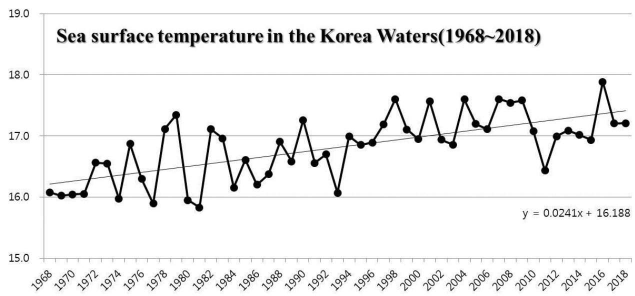

Fig. 3. Temporal variations in annual mean SSTs in Korean waters from 1968 to 2018 according to NSO data.

We also analyzed the long-term changes in annual SSTs for each area over the 51 years (Fig. 4). The highest increasing annual SST trend was 1.43 ℃ in the East Sea, followed by 1.23 ℃ in the West Sea, whereas the South Sea showed a relatively low increasing trend of approximately 1.03 ℃. The reasons for the high increasing SST trend in the East Sea are considered to be related to the following: the intensity of the Tsushima Warm Current in relation to recent global warming (Choi et al., 2009), where heat from the intensified Tsushima Warm Current is transported via advection to the East Sea, and the change in the location the polar front in the East Sea, where the polar front in the East Sea has moved due to the intensification of the Tsushima Warm Current and global warming (Lee et al., 2003).

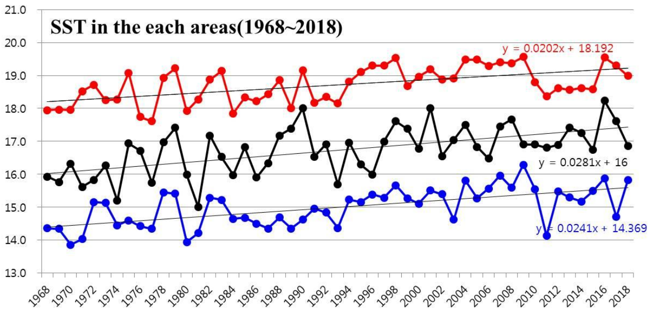

Fig. 4. Temporal variations in annual mean SST in each oceanic areas from 1968 to 2018 by NSO (black, red, and blue circles represent the East Sea, West Sea, and South Sea, respectively).

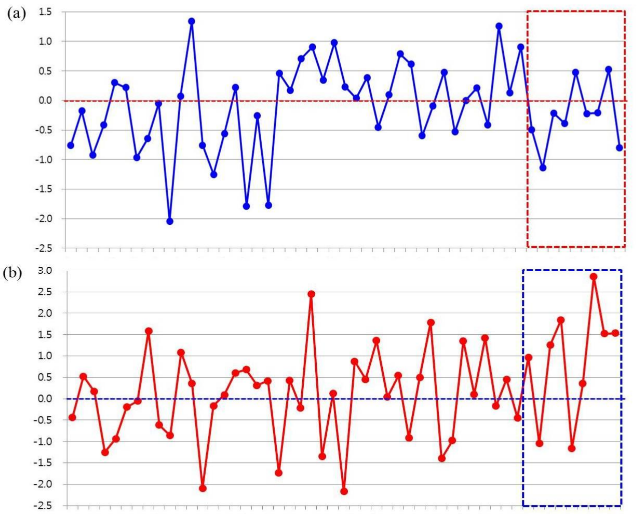

Fig. 5. Temporal variations in SSTA in Korean waters during winter (a) and summer (b) from 1968 to 2018 by NSO. Blue dot lines indicate the period of 2010s.

To understand long-term SST change in Korean waters, we examined NSO SST Anomaly (SSTA) data, in February and August from 1968 to 2018, which were calculated from 1981-2010 mean SSTs. The temporal variation in the SSTA in February is shown in Fig. 5(a). A positive SSTA dominated from 1990 to 2009 during 15 of the 20 years. However, a negative SSTA dominated during the last 10 years (from 2009 to 2018), and this occurred during 7 of the 10 years. Temporal variations in the SSTA in August are also shown in Fig. 5(b), where it is evident that a significant positive SSTA dominated in Korean waters during summertime between 2009 and 2018, and occurring during 7 of the 10 years. In addition, the SSTA exceeded 1.5 ℃ during 4 of the 7 years (2013, 2016, 2017 and 2018), highest SSTA occurred in August 2016 and was approximately 2.85 ℃ higher than the mean SST. The variations in the SSTA during both seasons obtained from the two time series imply that there would have been a warming trend in SSTs during summer and a cooling trend during winter around the Korean Peninsula during the decade 2009 to 2018.

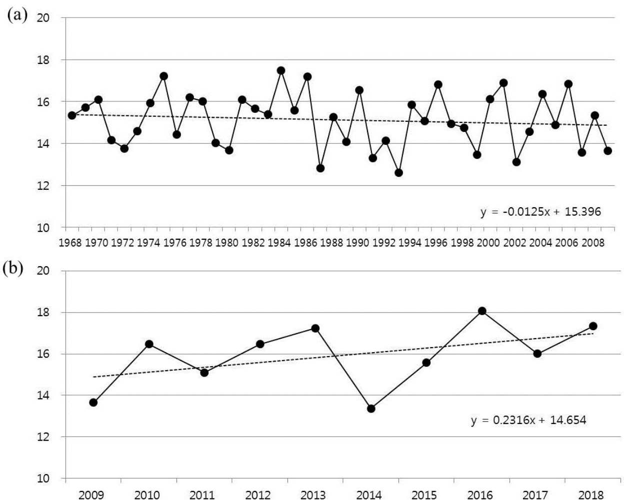

Fig. 6. Temporal variations in annual SST amplitude in Korean waters (a) from 1968 to 2009 and (b) from 2009 to 2018.

We thus used NSO annual SST data to analyzed the temporal variation in SST both before and after 2009 to better understand changes in the long-term SST trend in Korean waters. The temporal variation in the annual SST amplitude in Korean waters prior to 2009 is shown in Fig. 6(a) and that after 2009 is shown in Fig. 6(b), where the annual SST amplitude was calculated as the difference between SSTs in August and February. During the 40 years from 1968 to 2009, the annual SST amplitude decreased slightly by about －0.0125 ℃/year in Korean waters, although interannual variations existed. However, in the more recent decade from 2009 to 2018, the annual SST amplitude distinctively increased by approximately 0.2316 ℃/year, although the investigation period was not long enough. These results show distinctive inverse SST trends, and it thus appears that oceanographic and climate conditions dramatically changed around the Korean Peninsula between 2009 and 2018.

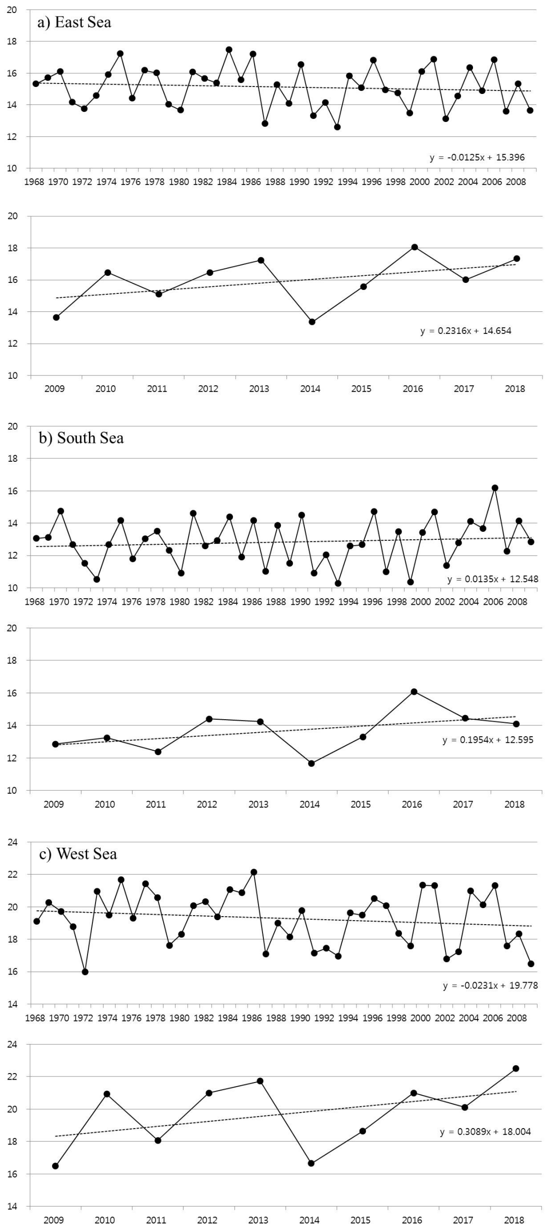

Fig. 7. Temporal variations in annual SST amplitude in (a) the East Sea, (b) South Sea, and (c) West Sea from 1968 to 2009 (upper panels) and from 2009 to 2018 (lower panels).

We also examined variations in the annual SST amplitude for each area of the Korean waters both before and after 2009, and the results are shown in Fig. 7. The temporal variations in annual SST amplitude in the East Sea are similar to those in the Korean waters. The annual SST amplitude showed a decreasing trend of about －0.0125 ℃/year from 1968 to 2009, but significant increasing trend of about 0.2316 ℃/year for the decade 2009 to 2018. However, the case in the South Sea differs slightly. The annual SST amplitude showed an increasing trend both before and after 2009, but the annual SST amplitude after 2009 was 15 times higher than that prior to 2009. In the case of the West Sea, the trends in annual SST amplitude were clearly different before and after 2009. The annual SST amplitude showed a decreasing trend of about －0.0231 ℃/year prior to 2009, but this changed to a clearly increasing trend of about 0.3089 ℃/year in the decade 2009-2018. These results showed that a dramatic change occurred in the trends of annual SST amplitudes in both the West Sea and East Sea around 2009.

The KMA (2017) reported that abnormally high SSTs during summertime in the Korean Peninsula between 2009 and 2018 in relation to abnormal heat waves related to a heat dome phenomena, the no passing of typhoon, and the abnormal strength of the Tsushima Warm current. They also reported the appearance of abnormally low SSTs during wintertime around the Korean Peninsula in the same period in relation to the negative Arctic Oscillation caused by abnormal Arctic warming, the strong Siberian High, and the occurrence of La Nina (KMA, 2019). Therefore, it is considered that climate change impacts, such as heat waves/cold waves, the passing of typhoons, and advected heat from the warm current have strongly influenced SSTs in the Korean waters.

3.2 Long-term changes in SST and annual SST amplitude in Korean waters according to COBE-SST data

The COBE-SST data set is provided in the form of SSTAs, calculated from 1981-2010 mean SST, on a global scale from 1891 to the present day and the data are shown as annual and seasonal values. In this study, we used annual and seasonal SSTA data for the four areas (the central part of the East Sea, the southwestern part of the East Sea, the Yellow Sea, and the northern East China Sea). SSTA data periods for the central and southwestern parts of the East Sea covered the period 1908 to 2018 and those in the Yellow Sea and the northern East China Sea covered the period 1901 to 2018. Using these data, we examined long-term SST variations around the Korea Peninsula from the early 1900s to the near present day.

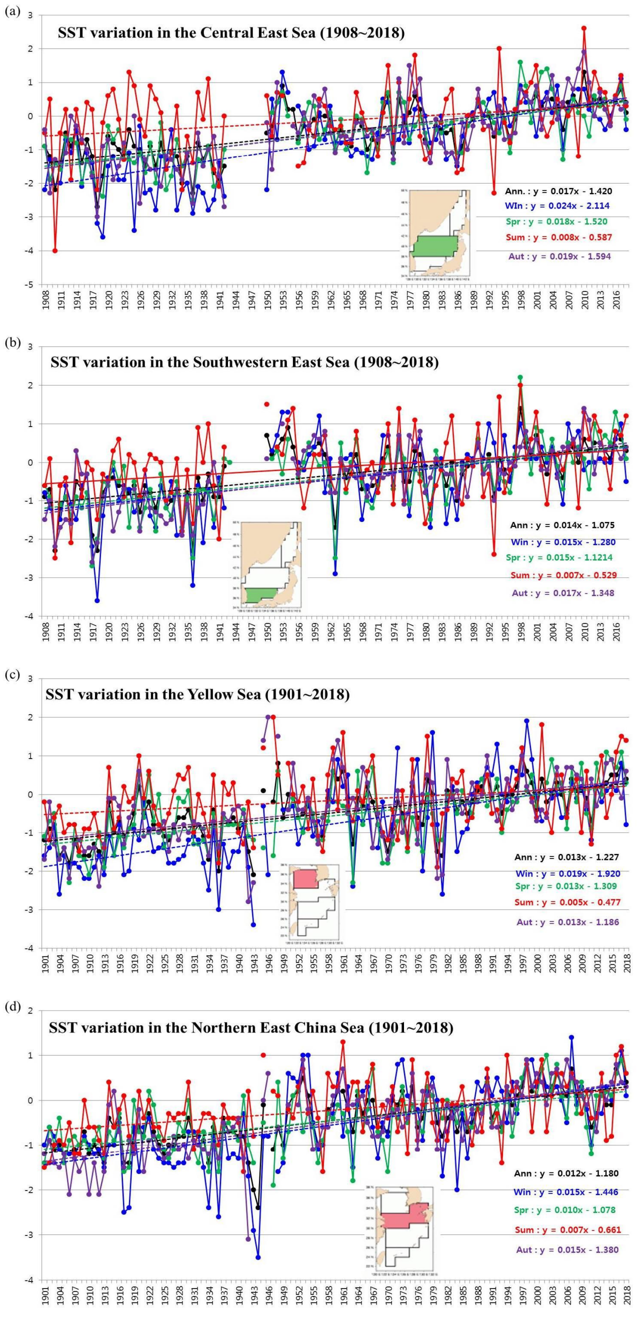

Fig. 8. Temporal variations in annual and seasonal mean SSTAs in (a) the central part of the East Sea, (b) the southern part of the East Sea, (c) the Yellow Sea, and (d) the northern part of the East China Sea ((a) and (b) are from 1908 tp 1918 and from 1908 to 2018 ((a) and (b)) and from 1901 to 2018 and (c) and (d) are from 1901 to 2018).

SSTA variations from 1908 to 2018 in the central part of the East Sea are shown in Fig. 8(a). In this area, the annual mean SST increased by about 0.017 ℃/year over the 101year period, which equals a rise of approximately 1.68 ℃ over 100 years. Seasonally, the highest trend related to the increasing trend in winter SST of about 0.024 ℃/year, whereas those in autumn and spring were approximately 0.019 ℃/year and 0.018 ℃/year. The increasing SST trend in summer was the lowest at about 0.008 ℃/year and equaled approximately one-third of the increasing winter trend. An increasing SST trend in winter is evidently dominant in this area. In the southwestern part of the East Sea, increasing annual mean SST trend was approximately 0.014 ℃/year from 1908 to 2018, which equals 1.39 ℃/year for the past 100 years (Fig. 8(b)). In this area, the increasing SST trend was highest in autumn at about 0.017 ℃/year, whereas increasing SST trends in winter and spring were similar at about 0.015 ℃/year. The lowest increasing SST trend in this area related to the increasing SST trend in summer. During the 108 years from 1901 to 2018, there was an increasing annual SST trend in the Yellow Sea of about 0.013 ℃/year, which equals 1.20 ℃ over 100 years. The highest increasing SST trend was about 0.019 ℃/year in winter, whereas the trends in autumn and spring were similar at about 0.013 ℃/year, and the lowest increasing SST trend occurred in summer at about 0.005 ℃/year. Finally, the increasing annual SST trend in the northern East China Sea was approximately 0.012 ℃/year over the 108 years from 1901 to 2018, which equals approximately 1.11 ℃over 100 years. The higher increasing SST trends were about 0.015 ℃/year and occurred in autumn and winter, whereas that in summer was only about 0.007 ℃/year.

The analysis of longer-term variations in SST around the Korean Peninsula shown certain features about long-term SST trends in this region. The increasing trend in annual SSTs occurred from the lower to higher latitudes. Moreover, the increasing SST trends in the all areas were clearly dominant in winter and almost 2-4 times higher than those in summer. It is evident that the increasing SST trend around the Korean Peninsula over the period of more than 100 years was caused by the significant increasing SST trend during winter.

We then examined the changes in SST during summer and winter around the Korean Peninsula on a decadal time scale from the 1950s to 2010s. We also examined the long-term trend in SST changes around the Korean Peninsula since 1950s, as many ocean survey data prior to this were missing in relation to the war in

1940s. The variations in SSTAs in winter on decadal intervals from the 1950s to the 2010s at four areas around the Korean Peninsula are shown in Fig. 9(a). It is evident from this figure that the highest SSTA peaks occurred in winter in all areas during the 1990s. After the 2000s, SSTA around the Korean Peninsula showed a decreasing trend, although SSTA in the Yellow Sea was slightly increased in the 2010s. However, there were dramatic changes in the SSTA variations during summer around the Korean Peninsula after the 1990s (Fig. 9(b)).

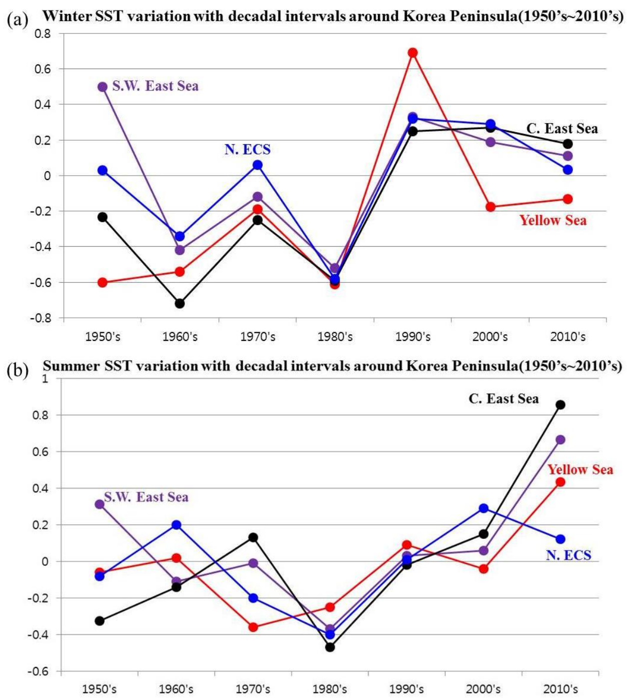

Fig. 9. Temporal variations in decadal mean SSTAs in the central part of the East Sea (black circles), the southwestern part of the East Sea (purple circles), the Yellow Sea (red circles), and the northern part of the East China Sea (blue circles) from the 1950s to the 2010s during (a) winter and (b) summer.

Decreasing SSTA trends around the Korean Peninsula dominated from the 1950s to the 1980s, but there were clear changes in the SSTA trend during summer in all areas around the Korean Peninsula after the 1990s. In particular, SSTAs in summer were significantly increased in the 2010s around the Korean Peninsula, although the SSTA trend in summer was slightly decreased in the northern East China Sea. From these two time-series, it is evident that SSTAs in summer (winter) were distinctively increased (decreased) during 2009-2019 around the Korean Peninsula, which means that the annual SST amplitude was also increased during this same period. This result differs considerably from those of the previous studies, which reported a decrease in the annual SST amplitude but a dominant increasing SST trend during winter in this area.

4. Summary and Discussion

The Korean waters undoubtedly have one of the highest increasing SST rates in the world, previous studies have implied that this high increasing SST trend could be caused by the dominant increasing SST trend during winter.

In this study, we examined long-term changes in SSTs and the annual amplitudes of SSTs using two ocean data sets: NSO SST data obtained from NIFS and COBE-SST obtained from JMA, which contained periods of approximately 51 years and longer than 100 years, respectively. The NSO SST data showed that annual mean SSTs in the Korean waters increased about 1.23 ℃ over 51 years from 1968 to 2018, which was 2.5 times higher than the increasing global mean SST trend. During the most recent decade (2009-2018), negative SSTAs were dominant in winter and positive SSTAs were dominant in summer. These results imply that the annual SST amplitude may have increased during this recent decade. The results also showed that the annual amplitude of SST in the Korean waters underwent a decreasing trend from 1968 to 2009 and subsequent increasing trend from 2009 to 2018. The annual SST amplitudes in the East Sea and Yellow Sea were decreased from 1968 to 2009 but clearly increased from 2009 to 2018, whereas the annual SST amplitude in the South Sea slightly increased from 1968 to 2009 but only minimally increased than from 2009 to 2018.

The results of COBE-SST analysis showed increasing SST trends in winter over more than 100 years in four sea area around the Korean Peninsula; these values were approximately two to four times higher than those in summer. In addition, there were changes in decadal mean SSTs between the 1950s to the 2010s. SSTs in winter showed a decreasing trend after the 1990s, but SSTs in summer showed an increasing trend after the 1980s. In particular, these decreasing and increasing trends were clearly evident during the most recent decade investigated (2009-2018). This means that the annual SST amplitude around the Korean Peninsula increased during this recent decade. It is considered that higher SSTs in summer and the lower SSTs in winter are related to climate change in association with abnormal Arctic warming and the heat-dome phenomena in East Asia, which has occurred in recent years.

In this study, we utilized long-term SST data to examine long-term SST variations and changes in annual SST amplitude in Korean waters and around the Korean Peninsula. Water temperature is altered by surface heat fluxes and advection heat. Our future studies will examine the reasons for long-term changes in the annual amplitude of SST using atmosphere and ocean current variation data. Moreover, we aim to analyze the impacts of climate change on the change in SST trends in Korean waters.

Utilizing the time series data, we delineated certain unusual trends like winter SSTA in the Yellow Sea from the 1990s to the 2010s and summer SSTA in the northern part of the East China Sea in the 2010s. These unusual trends are believed to be related to global and regional climatic impacts and inner oceanic impacts, and it is thus necessary to investigate the reasons for such unusual trends in seasonal SSTs around the Korean Peninsula.

Acknowledgement

We would like to thank to JMA for providing the COBE-SST data set. This study was funded by a grant from the National Institute of Fisheries Science (R2020044).

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Received : 2020. 04. 02.
Revised : 2020. 04. 27.
Accepted : 2020. 05. 28.