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Analysis of Extreme Sea Surface Temperature along the Western Coastal area of Chungnam: Current Status and Future Projections

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Abstract: Western coastal area of Chungnam, including Cheonsu Bay and Garorim Bay, has suffered from hot and cold extremes. In this study, the extreme sea surface temperature on the western coast of Chungnam was analyzed using the quantile regression method, which extracts the linear regression values in all quantiles. The regional MOHID (MOdelo HIDrodinâmico) model, with a high resolution on a 1/60° grid, was constructed to reproduce the extreme sea surface temperature. For future prediction, the SSP5-8.5 scenario data of the CMIP6 model were used to simulate sea surface temperature variability. Results showed that the extreme sea surface temperature of Cheonsu Bay in August 2017 was successfully simulated, and this extreme sea surface temperature had a significant negative correlation with the Pacific decadal variability index. As a result of future climate prediction, it was found that an average of 2.9°C increased during the simulation period of 86 years in the Chungnam west coast and there was a seasonal difference (3.2°C in summer, 2.4°C in winter). These seasonal differences indicate an increase in the annual temperature range, suggesting that extreme events may occur more frequently in the future.

Keywords: Extreme temperature, Quantile regression, Future climate projection

Introduction

Climate change can cause multiple types of climate-related events in terms of occurrence and intensity. It increases the likelihood of compound hazards that comprise simultaneously or sequentially occurring events to cause extreme impacts in natural and human systems (Collins et al., 2019). IPCC (Intergovernmental Panel on Climate Change) recently reported that extreme events have become more frequent and intense in all land regions. Some recent extremes observed over the past decade appear to have been caused by humans on the climate system. Marine heatwaves have approximately doubled in frequency since the 1980s, and human influence has very likely contributed to most of them since at least 2006. They also denote that changes in extremes continue to become larger. For example, as global warming increases by 0.5°C, the intensity and frequency of the hot extreme increases markedly. The occurrence rate of some extreme events unprecedented in the observational record will increase with 1.5°C of global warming. Projected percentage changes in frequency are larger for rarer events (IPCC, 2021). As extreme events are increasing due to climate change, there are many interests in these events, such as a hot extreme, a cold extreme and an extreme rainfall.

These extreme events, such as the hot extreme, due to climate change is also important for regional aspect. As the frequency of anomalously high sea surface temperatures has increased along 38% of the world's coastlines, there is much research for investigating the damaged area (Lima and Wethey, 2012; Smale and Wernberg, 2012; Wernberg et al., 2013; Mills et al., 2013; Lee et al., 2018). Mills et al. (2013) denote that a marine heatwave, a hot extreme event, affects the distribution of the longfin squid. Smale and Wernberg (2012) report that the extreme temperature has exceeded the physiological limits of seaweeds, leading to the extirpation of marginal populations, which are unlikely to recover owing to life-history traits and

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oceanographic processes. Lee et al. (2018) analyzed the mass mortality cases in fish farms on the South coast of Korea from 1998 to 2016. They found that the extreme temperature caused 57.5% of the damage to fish farms. Because the regional impact of these extreme events directly affects human's lives, it is important to know the current status and future projections of these extreme events.

The west coast area, Chungnam, has inland bays such as Cheonsu Bay and Garorim Bay, which are deeply connected inland. The total length of the coastline is about 1242 km long, and many low-altitude cities are distributed. Cheonsu Bay is vulnerable to extreme sea surface temperatures because advisories are issued most days when the hot extreme occurs in Korea (Kim and Yang, 2019). Because more than 90% of fish farms are concentrated in Cheonsu and Garorim Bays, these extremely hot events not only direct damage to fish farms but also cause the low-oxygen water mass in the bottom layer aggravating the damage. So, systematic research is needed.

Therefore, in this study, we analyzed the extreme SST status and future projection in the western coastal area of Chungnam. Analysis of in situ observation data and correlation study with climate indices were performed, and future prediction experiments were also conducted. The following section describes the data and methods used in this study. Section 3 presents the quantile regression analysis results and the model simulation results to confirm the extreme SST status and future projection in the west coast area, Chungnam. Section 4 provides a summary and a discussion of the results.

Data and Methods

Quantile regression analysis

To confirm the extreme SST status in the west coast area, Chungnam, analysis of in situ observation data and correlation study with climate indices were performed. Extreme SST has been defined in many ways. In Hobday et al. (2016), A marine heatwave is defined as when seawater temperatures exceed a seasonally-varying threshold (usually the 90th percentile) for at least five consecutive days. To use these definitions, rather than using regular observation data provided bimonthly, one-hour or at least one-day interval data should be used. However, there is a lack of data observed at the corresponding time interval for the entire Yellow Sea. NIFS/KODC data, which exist as bimonthly data, have existed steadily for a long time. Therefore, in this study, we used serial oceanographic observations provided by the National Institute of Fisheries Science/Korea Oceanographic Data Center (NIFS/KODC) as in situ data. Observations have been carried out bimonthly frequency since 1961. Historical data with many missing values were removed, and the data only for the last 35 years from 1983 to 2017 were used. Two climate indices were used to identify major factors influencing the extreme sea surface temperature change of the west coast area, Chungnam. The Arctic Oscillation Index (AO) and Pacific Decadal Oscillation (PDO) were investigated. The AO is defined as the time series of the first EOF mode from the monthly sea level pressure anomaly north of 20^{o}N (Thompson and Wallace, 1998; Mo, 2000). The historical AO index can be obtained from NOAA's Climate Prediction Center (CPC). The PDO is defined by the EOF first mode time series of the monthly Pacific surface temperature anomaly north of 20^{o}N and provided by NOAA's Joint Institute for the Study of the Atmosphere and Ocean (JISAO) (Mantua et al., 1997). All climate indices were extracted from 1983 to 2017 to identify the analysis period with in situ observation datasets used in this study.

A quantile regression method was applied to analyze extreme surface temperature fluctuations. Quantile regression has the ability to estimate slopes of changes not only in the mean but in all parts of the distribution of a time series. Therefore, this method can provide a more complete picture of long-term temporal trends in those series (Barbosa, 2011). Quantile regression can be viewed as an extension of ordinary least squares regression. While ordinary least squares regression is based on the minimization of the residuals between real data and regression slope, quantile regression is based on the minimization of the sum of asymmetrically weighted absolute residuals (Koenker and Hallock, 1994). Under the method proposed by Koenker and Hallock (2001), an estimate of the quantile regression value (β_τ) of each quantile can be calculated by minimizing the function,

$$\mathrm{Min}\left[\sum_{y_i>\beta X_i}\tau|y_i-\beta X_i|+\sum_{y_i<\beta X_i}(1-\tau)|y_i-\beta X_i|\right]$$

where y_i is a dependent variable; X_i is an independent variable; β_τ is a quantile regression value of the τ quantile. The τ has a value between 0 and 1, and the higher the τ value, the higher the quantile regression result can be calculated (Lee et al., 2012; Lim and Chang, 2018).

Extreme SST event simulation and future projection

Two models were used to reproduce the extreme sea surface temperature event, MOHID (MOdelo HIDrodinâmico) and ROMS (Regional Ocean Modeling System). The MOHID model was developed in 1985 at the Marine and Environmental Technology Research Center (MARETEC) of Instituto Superior Ténico (IST) at the University of Lisbon, Portugal. It provides a vertical hybrid coordinate system that can combine the vertical σ coordinate and z coordinate systems as designed. The code is freely distributed on the MOHID website (http://www.mohid.com/). The ROMS model was constructed using the Coupled Ocean, Atmosphere, Wave, Sediment, Transport (COAWST) System. The COAWST modelling system not only can easily set the ROMS model as a single model but also uses the coupler program Model Coupling Toolkit (MCT) to perform the atmospheric model Weather Research and Forecasting Model (WRF) or the wave model Simulating Waves Nearshore (SWAN). It has the advantage of being able to easily connect WAVEWATCH III (WW3) to couple modelling.

Using MOHID and ROMS model, we simulated the extreme sea surface temperature event. The model domain covers the area from 117°E to 144°E and from 28°N to 48°N with a horizontal resolution of 1/12°

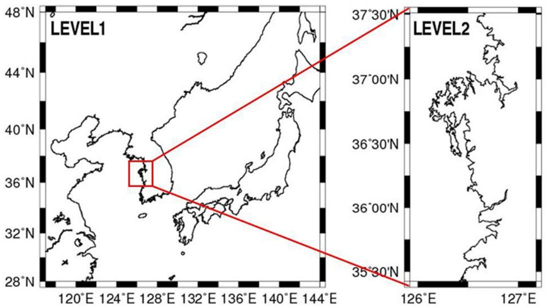

Fig. 1. Model area (Level 1) with the nested subdomain (Level 2).

(hereafter LEVEL1). In order to focus on the extreme sea surface temperature event, a nested grid system was additionally used with a horizontal resolution of 1/60° for the west coast area, Chungnam (125.9°E-127.2°E, 35.4°N-37.5°N, hereafter LEVEL2) (Fig. 1). The simulation was conducted in August 2017, when the extreme sea surface temperature event lasted for 11 days in Chang-ri, Seosan, in the Cheonsu Bay of the west coast of the Chungcheong Province. The model results were compared and verified with the objective analysis and other reanalysis data and data from the real-time observation system. For verification, we used Global Observed Ocean Physics Temperature Salinity Heights and Current Reprocessing (ARMOR3D) datasets for verification. They provide monthly temperature, salinity, heights, geostrophic currents and mixed layer depth on a 1/4 degree regular grid and 50 depth levels from the surface down to the bottom. The monthly mean sea surface temperature of MOHID and ROMS and various reanalysis datasets (GLOSEA5, GLOSRYS2V4, ORAS5) are compared based on ARMOR3D.

For simulation for future projection, future prediction experiments were also conducted using CMIP6 (Coupled Model Intercomparison Project Phase 6) data. CMIP6 provides an SSP scenario similar to the RCP scenario provided by the existing CMIP5. The SSP1-2.6 scenario is a low-carbon scenario of a sustainable socioeconomic structure with good adaptability and climate change due to the reduction of social inequality and the rapid development of eco-friendly technologies. The SSP2-4.5 scenario is a moderategrowth socio-economic scenario, assuming an intermediate stage in the mitigation of climate change and socio-economic development. The SSP3-7.0 scenario is a scenario of a socio-economic structure that is vulnerable to climate change due to imbalances in socio-economic development and institutional restrictions. The SSP5-8.5 scenario is a high-emission scenario of a socio-economic structure with a good ability to adapt to climate change but low mitigation capacity due to the absence of climate policy, fossil fuel-based growth and high human investment. The scenario most similar to the 1.5°C temperature rise suppression under the Paris Climate Agreement is the SSP1-2.6 scenario, and the scenario similar to the future where the current trend continues is SSP3-7.0 (Lee et al., 2020). In this study, we simulated and analyzed the future extreme sea surface temperature in the west coast area. The model used only the MOHID model based on the performance verification results of extreme sea surface temperature event. Simulations were performed using the MIROC6 (Model for Interdisciplinary Research on Climate, version 6) data provided by WCRP (World Climate Research Program) as initial and boundary data (https://esgf-node.llnl.gov/projects/cmip6/). In order to confirm the effect of the high emission scenario, the difference between the results of the first 15 years (2015-2030) and the latter 15 years (2085-2100) of the simulation was analyzed.

Results

Quantile regression analysis

In general, sea surface temperature data has a distribution similar to the Gaussian normal distribution, in which the frequency of the mean is highest, and the frequency of the extreme values is gradually decreased. However, the Yellow Sea has a high sensitivity to atmospheric factors, and the tidal current is strong because its average depth is too shallow (44 m). Considering these characteristics, it is necessary to analyze the surface temperature distribution of the Yellow Sea.

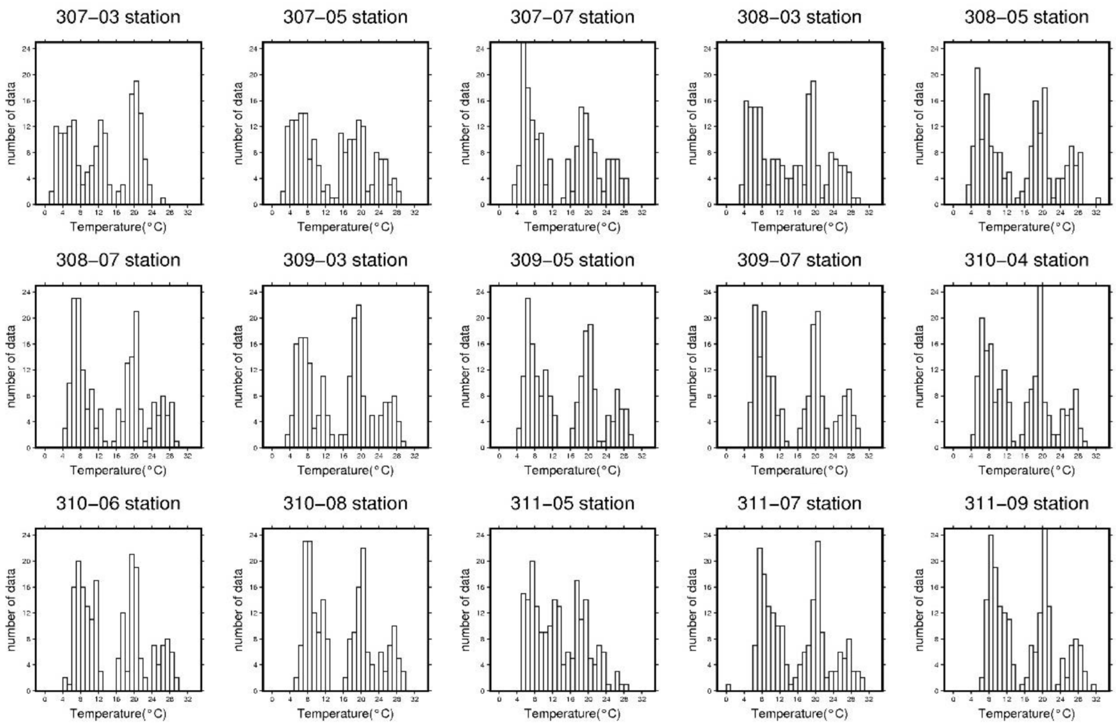

Fig. 2. Histogram of the sea surface temperature at various serial observation stations located in the Yellow Sea.

Fig. 2 shows the histogram of sea surface temperature of the in situ observation data of the Yellow Sea. The number above each histogram represents the serial observation point in NIFS/KODC. The histogram shows a multimodal distribution with three modes: 4-8°C, 18-20°C, and 22-28°C. As a result of analyzing the histogram in the same way for other areas, such as the East/Japan Sea or South Sea of Korea, multimodal distribution did not appear in other areas. This multimode emerged by combining the characteristics of the NIFS/KODC data and the characteristics of the Yellow Sea. Because NIFS/KODC provides the in-situ data bimonthly, the observation data also has a multimodal distribution rather than a Gaussian distribution. Also, because the seasonal (winter, summer, spring/autumn) changes in the sea surface temperature of the Yellow Sea are distinct, this multimodal distribution appears well separated by mode. Therefore, it suggests that in order to obtain the extreme sea surface temperature trend having such a distribution, a threshold value considering the distribution should be selected. To find the extreme sea surface temperature, we analyzed the third mode (22-28°C) of in situ observation data using a quantile regression method. In most stations, we found that more than 80% of the quantiles contained values of the third mode. To analyze the extreme value of this third mode, we analyzed the data based on the upper quartiles. As a result, we set the 90% quantile regression line as a threshold and the sea surface temperature above the 90% quantile regression line as an extreme value. Therefore, in this study, correlation analysis was performed using values above 90% quantile at each station to analyze the extreme sea surface temperature.

Fig. 3 depicts the correlation coefficients between the climate index and the extreme sea surface temperature of each station in the Yellow Sea. The correlation study was performed by matching up the time of the climate index and the extreme sea surface temperature of each station. Because we take the data more than 90% quantile to obtain the extreme sea surface temperature, the number of data is very small at 10 percent (616/6160) compared to the actual data for 35 years. So, we have to consider the increased confidence interval because the number of data is decreased when calculating the correlation between the climate index and the extreme sea surface temperature. Considering the changed threshold value, there are significant negative correlations at the 90% confidence interval with the PDO at -3 months (PDO lead) and positive but insignificant correlations with the AO. This result implied that large-scale climate variability affects the extreme sea surface temperature.

Extreme SST event simulation and future projection

Fig. 4 shows the monthly mean sea surface temperature distribution of ARMOR3D, objective analysis data,

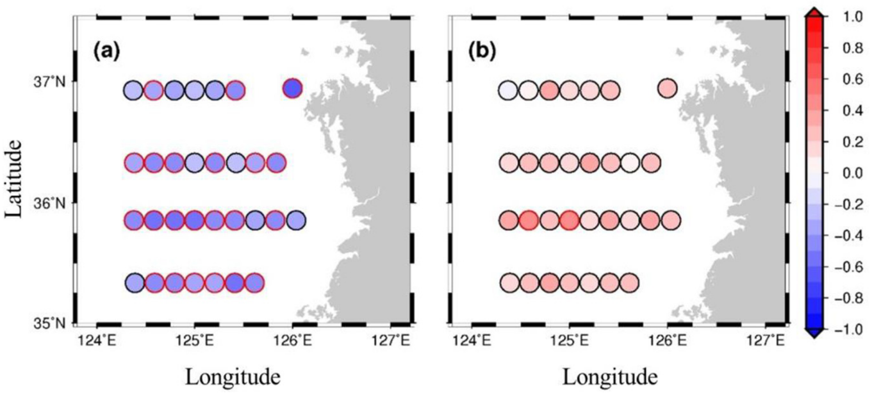

Fig. 3. Correlation map between the extreme sea surface temperature and (a) PDO index, (b) AO index. Stations exceed the 90% confidence interval are marked with red circle

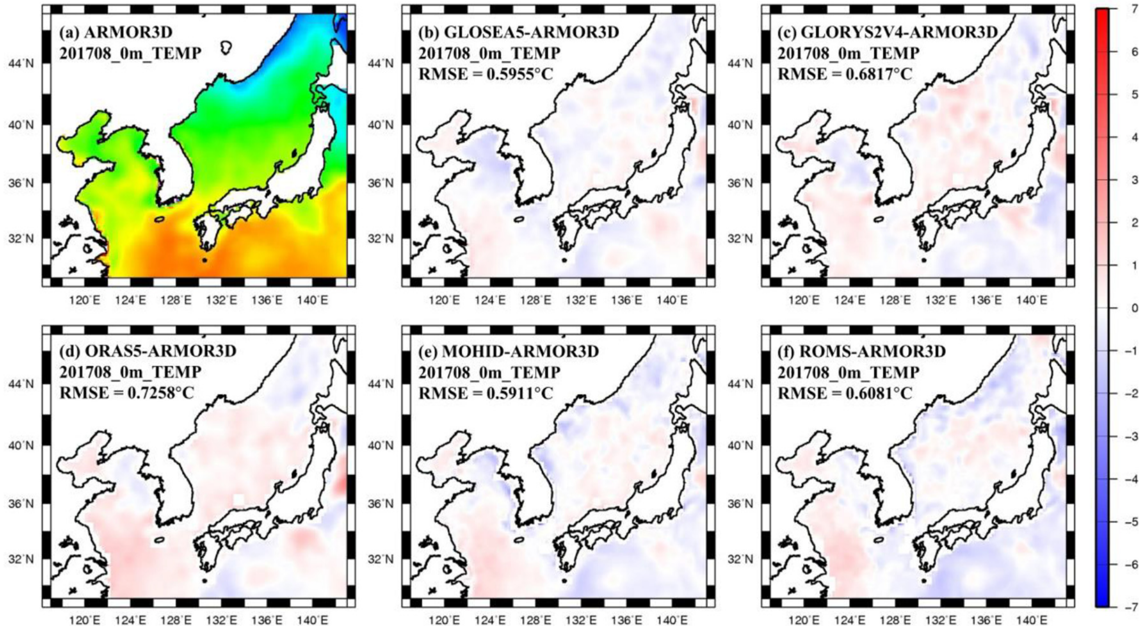

Fig. 4. (a) Spatial distribution of monthly mean SST of ARMOR3D and (b)-(f) SST difference distribution between ARMOR3D and (b) GLOSEA5, (c) GLORYS2V4, (d) ORAS5, (e) MOHID, (f) ROMS in August 2017.

and the sea surface temperature difference distribution between ARMOR3D and various reanalysis data (GLOSEA5, GLOSRYS2V4, ORAS5) and simulated results (MOHID, ROMS) in August 2017. Various reanalysis and objective analysis data were obtained from CMEMS (Copernicus Marine Environment Monitoring Service, https://marine.copernicus.eu/) with a horizontal resolution of 1/4°. The RMSE of the MOHID model was 0.5911, and the ROMS model was 0.6081. It means that the simulation performance of the MOHID model and the ROMS model, compared to other reanalysis data, has no problem in simulating the ocean in the East Asia Sea and has the advantage of obtaining high-resolution data compared to other models.

To confirm the simulation performance of the extreme sea surface temperature event in the Cheonsu Bay, a comparison was performed with the coastal oceanographic observation data provided by the NIFS/KODC. For this purpose, data were collected from August 1 to August 16, 2017 for the Seosan Chang-ri station and Boryeong Hyoja Island station in Cheonsu Bay (Table 1). The model data were calculated as mean values for the areas of 126.2°E to 126.6°E and 36.35°N to 36.8°N in the Cheonsu Bay area. During this period, Chang-ri, Seosan, experienced the extreme sea surface temperature exceeding 28°C from August 3 to August 13, and extreme temperature

Table 1. Daily sea surface temperature of real time marine environment fishery information observation data (Seosan and Boryeong) and simulation results (MOHID, ROMS) from Aug. 1st to Aug. 16th 2017

Date / Area	8/1	8/2	8/3	8/4	8/5	8/6	8/7	8/8	8/9	8/10	8/11	8/12	8/13	8/14	8/15	8/16
Seosan	27.8	27.6	28	28.7	28.3	28.2	28.2	28.9	28.6	28.6	28.6	28	28.6	27.4	27.6	27.7
Boryeong	26.8	27.0	27.3	27.8	27.6	27.4	27.3	27.1	26.6	26.8	27.2	27.8	27.4	26.6	26.4	26.4
MOHID result	27.7	28.1	28.1	28.4	28.6	28.7	28.6	28.6	28.4	28.2	28.1	28.0	27.5	27.2	26.9	27.0
ROMS result	26.0	26.4	26.8	27.1	27.4	27.7	27.7	27.7	27.4	27.2	27.0	27.0	26.8	26.5	26.3	26.0

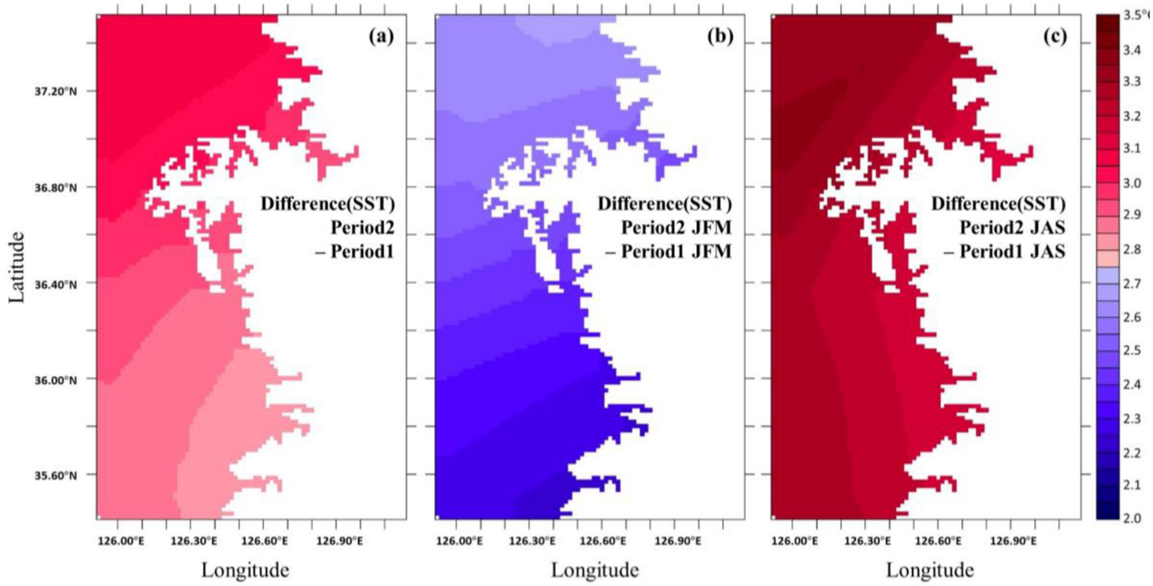

Fig. 5. Sea surface temperature difference distribution between Period 2 (2085-2100) and Period 1 (2015-2030) in (a) whole season, (b) winter and (c) summer.

warnings were issued for other periods. In Hyojado, Boryeong, no extreme sea surface temperature exceeding 28°C occurred, but from August 2 to August 13, the sea surface temperature value exceeding 27°C was continued, so an extreme temperature warning was continuously issued. Similar to the high-temperature period in Chang-ri, Seosan, the results of the MOHID model showed the extreme sea surface temperatures exceeding 28°C for 11 days from August 2 to August 12, and the sea surface temperature value exceeding 27°C continued for other periods. It implied that the extreme sea surface temperature event in Cheonsu Bay was simulated well in the MOHID model. In the case of the ROMS model, the extreme sea surface temperature exceeding 28°C did not appear, but the sea surface temperature exceeding 27°C continued from August 4 to August 12. It means that the extreme sea surface temperature event appearing in the observation data is sufficiently simulated, in particular, in the MOHID model. Therefore, future projection simulation of extreme sea surface temperature in the west coast of Chungnam was performed using the MOHID model.

From the Sixth Assessment Report of CMIP6, the frequency, duration and spatial extent of marine heatwaves will further increase under the future global warming in the 21st century. They project marine heatwaves will become four times more frequent in 2081-2100 under the SSP1-2.6 scenario, or eight times more frequent under the SSP5-8.5 scenario (IPCC, 2021). So, we performed the analysis focusing on the difference between the first 15 years of integration (2015-2030, hereafter Period 1) and the last 15 years of integration (2085-2100, hereafter Period 2).

Fig. 5 shows the difference between the time-averaged sea surface temperature of Period 1 and Period 2. The difference in sea surface temperature between the two periods is 3.0°C, suggesting that the sea surface temperature of Cheonsu Bay will increase by about 3°C over 85 years (Fig. 5(a)).

However, Fig. 5(b) and Fig. 5(c) implied that these changes in sea surface temperature show different patterns depending on the season. The difference between two periods in winter has a lower increase than that of all seasons and the difference between two periods in summer has a higher increase than that of all seasons. This trend is evident in the annual cycle. Fig. 6 depicts the difference in annual cycle between the two periods for 126.2°E to 126.6°E and

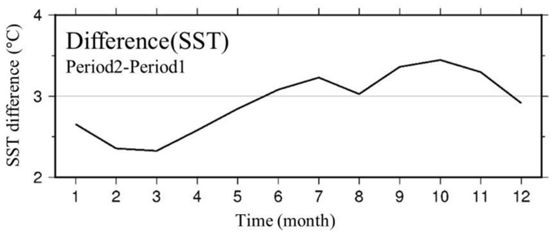

Fig. 6. The difference in the annual cycle of sea surface temperature between Period 2 (2085-2100) and Period 1 (2015-2030) at Cheonsu Bay (126.2°E-126.6°E, 36.35°N-36.8°N).

36.35°N to 36.8°N. There are two peaks in July and October and the seasonal difference is clearly shown. Compared to winter, the sea surface temperature will rise about 0.8°C in summer. This means that in the future climate, the seasonal sea surface temperature difference will be larger than in the past, and it implies that more frequent extreme events will occur.

Summary and Discussion

This study analyzed the current status and the future projection of the extreme sea surface temperature along the west coast area, Chungnam. Using the serial observation data provided by NIFS/KODC, we defined the current status of the extreme sea surface temperature and showed the relationship between the climate index and the extreme sea surface temperature. We also simulated the extreme sea surface temperature event using two ocean models (MOHID and ROMS) and verified them using objective analysis data and various reanalysis data. At last, we simulated the future projection around the Korean marginal Sea using the MOHID ocean model and found the seasonal difference in future projection.

By analyzing the histogram of sea surface temperature provided by NIFS/KODC, there is a multimodal distribution with three modes: 4-8°C, 18-20°C, and 22-28°C, which means that the seasonal (winter, summer, spring/autumn) changes in the sea surface temperature of the Yellow Sea are distinct. From this distribution, we found that the extreme sea surface temperature appeared above 90% quantile and calculated the correlation between the two climate indices (AO and PDO) and the extreme sea surface temperature data. The PDO has a significant negative correlation coefficient. This relationship implied that the large-scale climate variability affects the extreme sea surface temperature along the west coast area, Chungnam.

From the extreme sea surface temperature event simulation in August 2017 using two ocean models, the MOHID and ROMS models have a better performance than other reanalysis data around the Korean marginal Seas, in particular, the MOHID model has a good performance in reproducing the extreme sea surface temperature event in August 2017. Therefore, a future projection simulation of extreme sea surface temperature in the west coast area of Chungnam was performed using the MOHID model. In a future projection, there are large seasonal differences between the two periods in sea surface temperature. The amount of sea surface temperature rise in summer is 0.8°C larger than the amount of sea surface temperature rise in winter. This seasonal difference denotes more frequent extreme events will occur in future summer and future winter.

This study focused on the current status and the future projection of the extreme sea surface temperature along the west coast area, Chungnam. However, explaining how the climate index affects the extreme sea surface temperature around the Korean marginal seas remains unresolved. Also, how the seasonal difference becomes large in the future and why the two peaks appear in the seasonal cycle remains unresolved. So, an in-depth analysis of the physical mechanism of atmospheric variables and ocean-atmosphere interactions is required rather than analyzing only oceanic variables.

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References

Barbosa, S. M., M. G. Scotto, and A. M. Alonso, 2011, Summarising changes in air temperature over Central Europe by quantile regression and clustering. Nat. Hazards Earth Syst. Sci., 11(12), 3227-3233.

Collins, M., Sutherland, M., Bouwer, L., Cheong, S. M., Frolicher, T., DesCombes, H. J. and Timmermans, M. L. 2019, Extremes, abrupt changes and managing risk. Available online: http://ecite.utas.edu.au/148967/ (accessed on 10 December 2019).

Hobday, A.J., Alexander, L.V., Perkins, S.E., Smale, D.A., Straub, S.C., Oliver, E.C., Benthuysen, J.A., Burrows, M.T., Donat, M.G., Feng, M. and Holbrook, N.J., 2016, A hierarchical approach to defining marine heatwaves. Prog. Oceanogr., 141: 227-238.

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi: 10.1017/9781009157896.

Kim, T. H. and Yang, C. S., 2019, Preliminary Study on Detection of Marine Heat Waves using Satellite-based Sea Surface Temperature Anomaly in 2017-2018. J. Korean Soc. Mar, 25(6), 678-686.

Koenker, R. and F. Schorfheide, 1994, Quantile spline models for global temperature change. Clim. Change, 28(4): 395-404.

Koenker, R. and K.F. Hallock, 2001, Quantile regression, J. Econ. Perspect., 15(4): 143-156.

Lee, K., H.J. Baek, C.H. Cho, 2012, Analysis of changes in extreme precipitation in Seoul using quantile regression, J. Clim. Res., 7(3): 199-209.

Lee, D. C., Won, K. M., Park, M. A., Choi, H. S. and Jung, S. H., 2018, An Analysis of Mass Mortalities in Aquaculture Fish Farms on the Southern Coast in Korea; Korea Maritime Institute: Busan. Korea, 67, 1-16.

Lee, J.H., Sung, H.M., Shim, S.B. and Boo, K.O., 2020, International Data Node System for CMIP6 Climate Change Projections, J. Clim. Res., 11(4): 247-257

Lim, B. J. and Chang, Y. S., 2018, Analysis of Long-term Linear Trends of the Sea Surface Height Along the Korean Coast based on Quantile Regression, The Sea, 23(2): 63-75.

Lima, F. P. and Wethey, D. S., 2012, Three decades of high-resolution coastal sea surface temperatures reveal more than warming. Nat. Commun., 3(1), 1-13.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M. and Francis, R.C., 1997, A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. Amer. Meteor. Soc., 78, 1069-1079.

Mills, K. E., Pershing, A. J., Brown, C. J., Chen, Y., Chiang, F. S., Holland, D. S. and Wahle, R. A., 2013, Fisheries management in a changing climate: lessons from the 2012 ocean heat wave in the Northwest Atlantic. Oceanogr., 26(2), 191-195.

Smale, D. A. and Wernberg, T., 2013, Extreme climatic event drives range contraction of a habitat-forming species. Proc. Royal Soc. B P ROY SOC B-BIOL SCI, 280(1754), 20122829.

Thompson, D.W.J. and Wallace, J.M., 1998, The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. Geophys. Res. Lett., 25, 1297-1300.

Wernberg, T., Smale, D. A., Tuya, F., Thomsen, M. S., Langlois, T. J., De Bettignies, T. and Rousseaux, C. S., 2013, An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. Nat. Clim. Change, 3(1), 78-82.

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