ENVIRONMENTAL RESEARCH
LETTERS

LETTER • **OPEN ACCESS**

Two major modes of East Asian marine heatwaves

To cite this article: Seonju Lee *et al* 2020 *Environ. Res. Lett.* **15** 074008

IOP Publishing Environ. Res. Lett. 15 (2020) 074008 https://doi.org/10.1088/1748-9326/ab8527

Environmental Research Letters

OPEN ACCESS

RECEIVED
16 January 2020

REVISED
19 March 2020

ACCEPTED FOR PUBLICATION
31 March 2020

PUBLISHED
22 June 2020

LETTER

Two major modes of East Asian marine heatwaves

Seonju Lee[1,2], Myung-Sook Park[1], Minho Kwon[3], Young Ho Kim[3,4] and Young-Gyu Park[3]

[1] Korea Ocean Satellite Center, Korea Institute of Ocean Science & Technology (KIOST), Busan, Republic of Korea
[2] Ocean Science, University of Science and Technology, Daejeon, Republic of Korea
[3] Ocean Circulation and Climate Research Center, KIOST, Busan, Republic of Korea
[4] Department of Oceanography, Pukyong National University, Busan, Republic of Korea

E-mail: mspark@kiost.ac.kr

Keywords: marine heatwave, East Asian marginal seas, basin-wide warming mode, dipole mode

Supplementary material for this article is available online

Q What means basin-wide?

Abstract

We show two major modes of East Asian marine heatwaves (MHWs) associated with two contrasting sea surface temperature patterns over the subtropical western North Pacific (WNP). In the first MHW mode, ocean warming over East Asia occurs along with the subtropical WNP from the earlier winter by an El Niño-Southern Oscillation. The basin-wide ocean warming is finally intensified to an extreme warming state around East Asia, where a high-pressure region in zonal waves across the Eurasian continent passes. In contrast, at the early stage, the second MHW mode is unfavorable with ocean cooling. However, MHWs over East Asia occur due to a significant intensification of a zonally elongated high-pressure zone in response to anomalous subtropical convection in addition to mid-latitude zonal waves. Due to the importance of persistent ocean warming as well as immediate atmospheric forcing, MHW inducible oceanic and atmospheric interactions are clearly distinguishable from those of atmospheric heatwaves.

CGT

winter?

겨울~여름 warming?

1st mode 와의 차이가?

1. Introduction

According to a recent Intergovernmental Panel on Climate Change (IPCC) special report (IPCC 2018), the current global temperature has increased by more than 1.0 °C in comparison to the pre-industrial period. Accordingly, significant increases in the frequency and intensity of extreme climates have also been reported, such as heatwaves, cold surges (Meehl *et al* 2000), heavy rainfall (Stott 2016), and tropical cyclones (Knutson *et al* 2010). Such extreme events can have a devastating impact on humans and ecosystems. In particular, extreme high sea surface temperatures (SSTs) exceeding a seasonally varying threshold (usually the 90th percentile) are called a marine heatwave (MHW) (Hobday *et al* 2016); these events have been gaining increasing public and scientific interest. MHWs are currently causing coral bleaching, mass deaths of marine animals, and changes in species found in marine communities in oceans worldwide (Mcwilliams *et al* 2005, Wernberg *et al* 2013, Frölicher and Laufkötter 2018).

추후 Refer.

Recent studies on global trends and case analyses over the Mediterranean Sea (Olita *et al* 2007) and ocean waters near Australia (Oliver *et al* 2017) have expanded their research area of extreme climate events to include MHWs, which considerably differ from an atmospheric heatwave. Regarding the induction of an MHW, some researchers have emphasized anomalous ocean dynamics and physical conditions (Feng *et al* 2013, Pearce and Feng 2013, Oliver *et al* 2017), whereas others have emphasized the atmospheric effect (Sparnocchia *et al* 2006, Olita *et al* 2007). First, MHWs can occur primarily through favorable ocean conditions such as positive SST anomalies or a strengthening of warm ocean currents. Pearce and Feng (2013) focused on the seas off Western Australia during the summer from 2010 to 2011, which peaked at 3 °C above normal conditions by the strong Leeuwin current, which brings in warm tropical waters. Similarly, Oliver *et al* (2017) showed that the longest and strongest MHW occurred in the Tasman Sea off Southeast Australia in 2015–2016, with an anomalously strong East Australian Current. Second, the atmospheric contribution of MHW is mostly explained through the accumulation of heat flux in the ocean because of the anomalous high-pressure and/or weakened wind speed. In particular, Sparnocchia *et al* (2006) showed that an abnormally high SST in the Ligurian Sea occurred due to calm weather conditions. Olita *et al* (2007) found that Central Mediterranean Sea warming in 2003 occurred with a European atmospheric heatwave under conditions including hot air temperatures, a calm surface wind, and a reduction of the upward heat flux.

In addition, whereas multiyear variations in atmospheric heatwaves have been widely investigated based on regional and physical differences (Perkins *et al* 2012, Dian-Xiu *et al* 2014, Lee and Lee 2016, Yeo *et al* 2019), the long-term variation in MHWs has been identified only at the global scale (Oliver *et al* 2018). Using satellite observations and *in situ* data from 1925 to 2016, Oliver *et al* (2018) revealed up to a 54% increase in the number of annual MHW days, which highlights the impact of global warming. However, the changes in mean SST cannot account for the majority of these changes. The authors documented that climate variability, such as the El Nino-Southern Oscillation (ENSO) and Pacific Decadal Oscillation, both contribute to large variations in MHWs.

In this study, we focus on the major atmospheric and oceanic modes responsible for summertime East Asian MHWs. Because regional atmospheric and ocean environments (inducible to MHWs) vary interannually through various teleconnection processes, our investigation of MHW modes was conducted within an interannual time frame. The ENSO may be a possible factor inducing a positive SST anomaly over East Asia, although its extratropical response depends on the properties of the ENSO (Wang *et al* 2001). In addition, the East Asian climate during the summer is correlated with convection activities over the WNP through a meridional wave train (e.g. Kwon *et al* 2005). Regarding atmospheric heatwaves in East Asia, Yeo *et al* (2019) recently revealed the importance of zonal waves across the Eurasian continent as well as meridional waves from anomalous convection over the subtropical WNP. In this study, we will explore interactions to determine how such well-known climate variabilities modulate the extreme ocean warming events over East Asia.

Zonal & meridional waves from convection?

The remainder of this paper is composed of five chapters. Chapter 2 describes the methods and data used for this study. Chapter 3 shows the multiyear variations in MHWs in East Asia and presents the two major modes associated with ocean and atmosphere systems. A discussion on the connection with a well-known climate phenomenon is presented in chapter 4. The final section provides some concluding remarks regarding the current findings.

2. Data and methodology

2.1. Data

To detect the frequency, duration, and intensity of MHWs, we used the National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation (OI) SST data (OISST; Reynolds *et al* 2002) available from 1982 to 2018. The daily data are at a 0.25° latitude × 0.25° longitude horizontal resolution. The present study focuses on July-August-September (JAS) as the summertime period when the SST of the East Asian Marginal Seas (EAMS) exhibits the highest peaks. Thus, summer MHWs along with atmospheric heatwaves have drawn substantial socioeconomic interest.

To understand the relationships between climate variabilities and MHWs, we used the Modern-Era Retrospective Analysis for Research and Application Version 2 (MERRA2; Gelaro *et al* 2017) data provided by the National Aeronautics and Space Administration (NASA) to analyze the geopotential height fields. The data are produced at a 0.5° latitude × 0.625° longitude horizontal resolution at 72 levels from the surface to 0.01 hPa. In addition, the Global Precipitation Climatology Project (GPCP) data were used for the relationship between subtropical precipitation and East Asian MHWs (Huffman *et al* 2009).

2.2. Detection of marine heatwaves

The current definition of MHWs follows that of Hobday *et al* (2016). Based on daily NOAA OISST data, an MHW event can be detected when the SST persists above the extreme-ocean warming threshold for more than 5 d. First, the seasonally varying 90th percentile thresholds were calculated using daily SSTs within an 11-day window centered on the time of the year. To obtain the baseline thresholds, we used 30 years of SST data from 1982 to 2011. Then, the 31-day moving average was applied to smooth the thresholds.

The seasonal mean of the 90th percentile SSTs (i.e. the MHW detection threshold) in figure 1(b) was compared with the seasonal SST climatology (figure 1(a)). Given the large meridional gradients in both SST maps, the threshold SST values (figure 1(a)) were approximately 27.5 °C over the Korea Strait but approximately 25 °C over the Yellow and East/Japan Seas. The MHW threshold values tended to be approximately 1 °C–2 °C higher than the seasonal mean values (figure 1(b)). Thus, the detected MHWs indicate an extremely high SST condition that has a clear distinction with a positive SST anomaly only above the seasonal mean.

For detection of an MHW event, the single event is defined as the sum of MHW days from the start to the end dates. This means that both the 3- and 10-day MHW durations are regarded as a single event. Thus, this study mainly used the ‘total MHW duration’ to indicate how long an MHW event occurred among 92 d in summer. Over the EAMS, the averaged total MHW durations range from 7 to 8 d (not shown) and do not show significant spatial variability by adopting regionally varying thresholds.

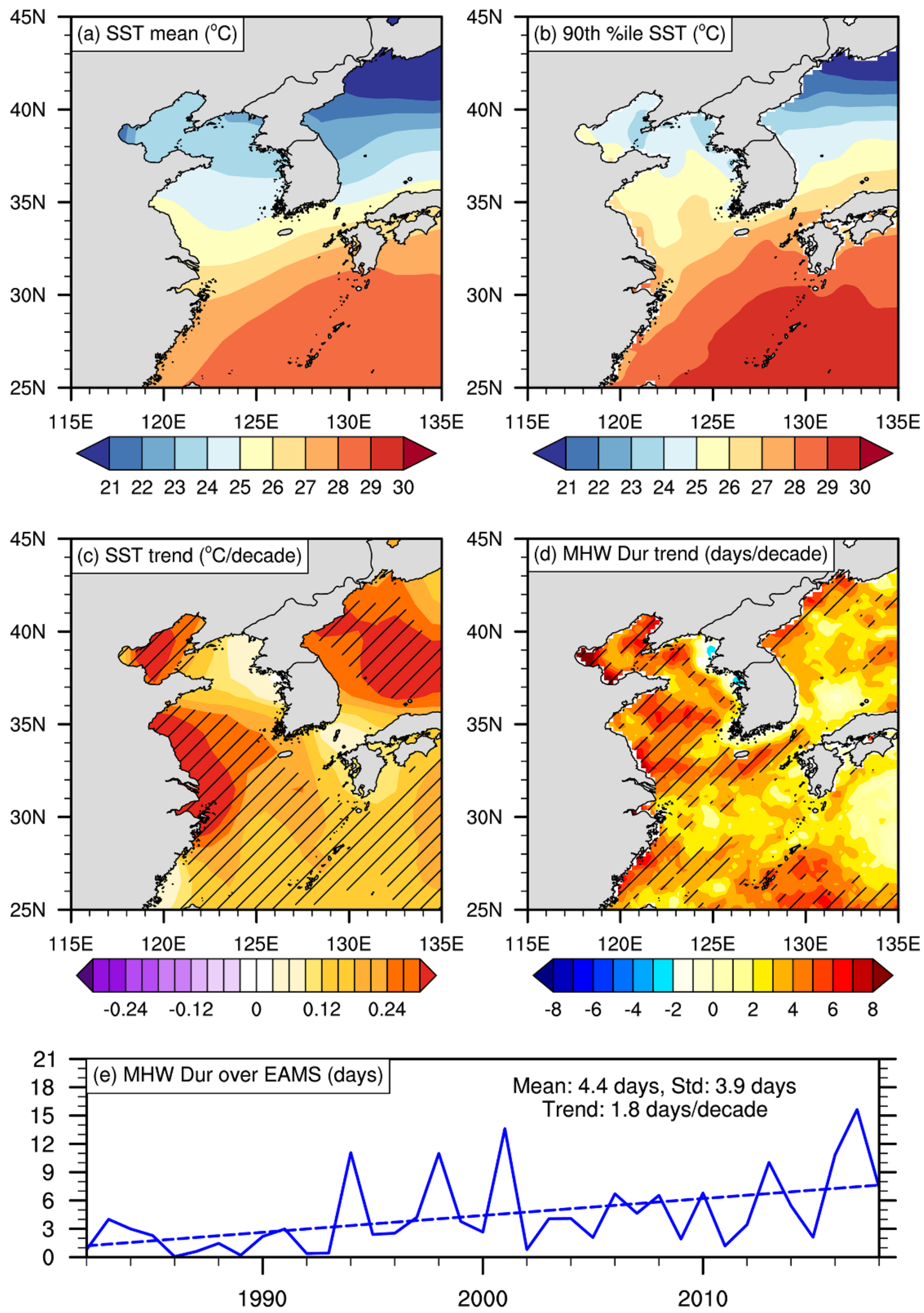

Figure 1. Seasonal mean of (a) SST and (b) 90th percentile of daily SST using OISST data for 1982—2011, and long-term trends of (c) seasonal mean and (d) total MHW duration days for 1982—2018. (e) Time series of total MHW duration (solid line) with a least-square linear fit (dashed line). The dashed regions in (c) and (d) indicate the area where the trends of SST and MHWs are significant with a 95% confidence level.

3. Results

3.1. Interannual variation in East Asian marine heatwaves

Herein, we first show the long-term trends of the mean seasonal SST for 1982–2018. Overall, the increasing trend in the mean SST is dominant, except for that a small area along the west coast of Korea (figure 1(c)). However, such an increase in the mean SST is not significant over most sea areas around the Korean Peninsula. Only the northern East/Japan Sea and the East China Sea reveal statistically significant positive trends ($p < 0.05$). The insignificance of the SST trend is consistent with the findings of Kim *et al* (2011), who showed that the SST warming trend is obvious only in winter, not in summer.

By contrast, it is remarkable that the MHW durations (figure 1(d)) tend to increase, with a 95% confidence level. The largest increase was found in the East China Sea (+3.92 d per decade), and the minimum increase occurred in the southern East Sea/Japan Sea (+2.14 d per decade). The increases over the Korea Strait and the Yellow Sea are +2.67 and +3.09 d per decade, respectively. Oliver *et al* (2018) explained that, over the global scale, longer MHWs can be largely explained by an increase in the mean

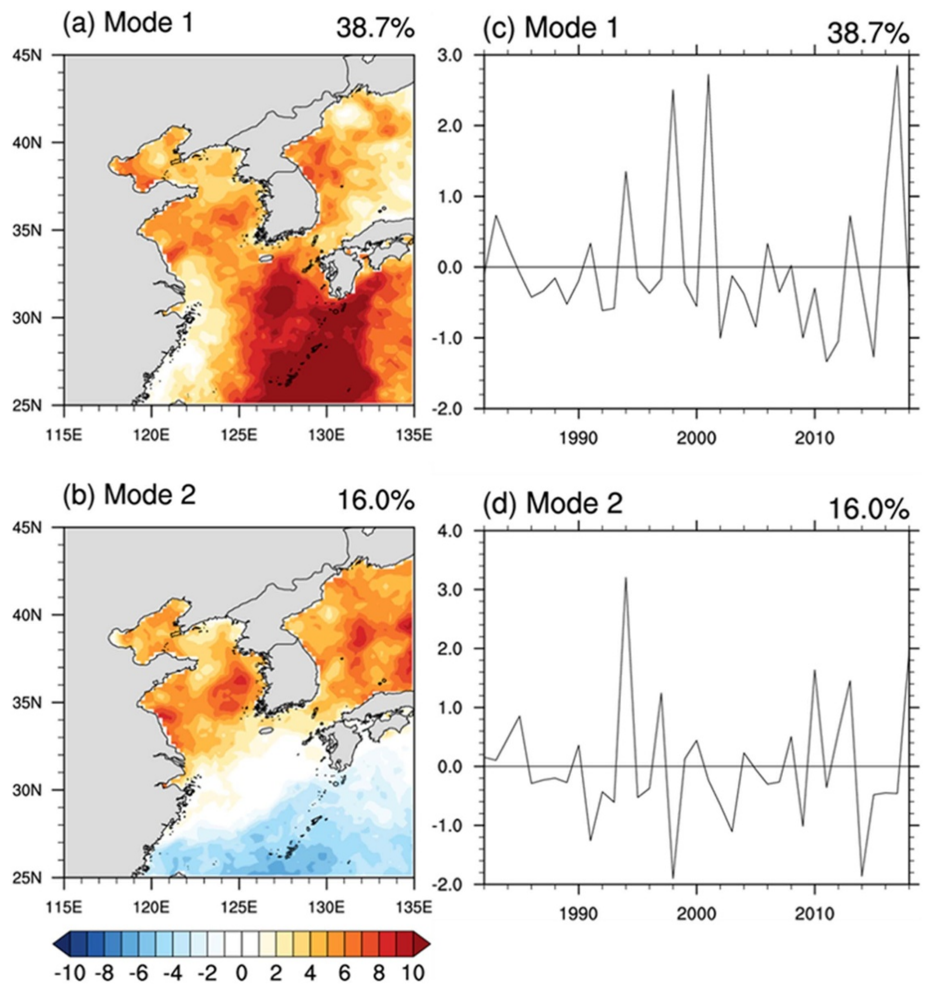

Figure 2. Spatial patterns of the two primary modes of the EOF of East Asian MHW duration in the left panels ((a) and (b)) and the associated PC time series of two principal components in the right panels ((c) and (d)).

ocean temperature. The current increase in the East Asian MHW properties, despite the insignificance in the mean SST trends, may indicate a greater impact of global warming on ocean extreme events than the mean climate.

The time series of MHWs (figure 1(e)) exhibit a strong interannual variation as well as a positive trend. For example, it show 18 MHW days in 1994 but 1 or 2 MHW days in 1992–1993, with a large standard deviation (4.3 d) compared to the mean duration (5.5 d). The current interannual variation in MHWs differs from that of atmospheric heatwaves in Korea (figure 5) (Lee and Lee 2016). In contrast to the positive trend in MHWs (figure 1(e)), no trend regarding atmospheric heatwaves can be found. In addition, the current time series show several major peaks in the MHW duration (all for approximately 30 d in 1994, 1998, 2013, 2017, and 2018). However, the heatwave time series (Lee and Lee 2016) show an exceptional peak year (25 d) in 1994, which is significantly larger than that of other secondary peak years (heatwave duration of less than 15 d).

In summary, the increasing trends in MHWs in East Asia may also be a part of global warming, but 37 years seems insufficient to clearly separate the effects of decades of variability from global warming. For the remainder of the study, we will focus on oceanic and atmospheric modes to modulate the MHWs over the interannual timescale.

3.2. Two major modes of East Asian marine heatwaves

To intensify the major modes responsible for the interannual variation in MHW (figure 1(e)), we applied an empirical orthogonal function (EOF) analysis to the detected MHW dataset. Figure 2 shows the spatial patterns of the two leading eigenvectors and the corresponding principal component (PC) time series. The two primary modes of EOF (EOF1 and EOF2) account for 40.5% and 16.8% of the total, respectively. These two modes are well separated from one another according to the criterion of North *et al* (1982).

Overall, the primary EOF modes for East Asian MHWs reveal two distinct spatial patterns. The first EOF pattern indicates that the East Asian MHW varies coincidentally with the subtropical WNP that is located below 30°N. This subtropical WNP-to-East Asia MHW mode (hereafter, called basin-wide warming mode) shows peaks in 1998, 2001, and 2017, as

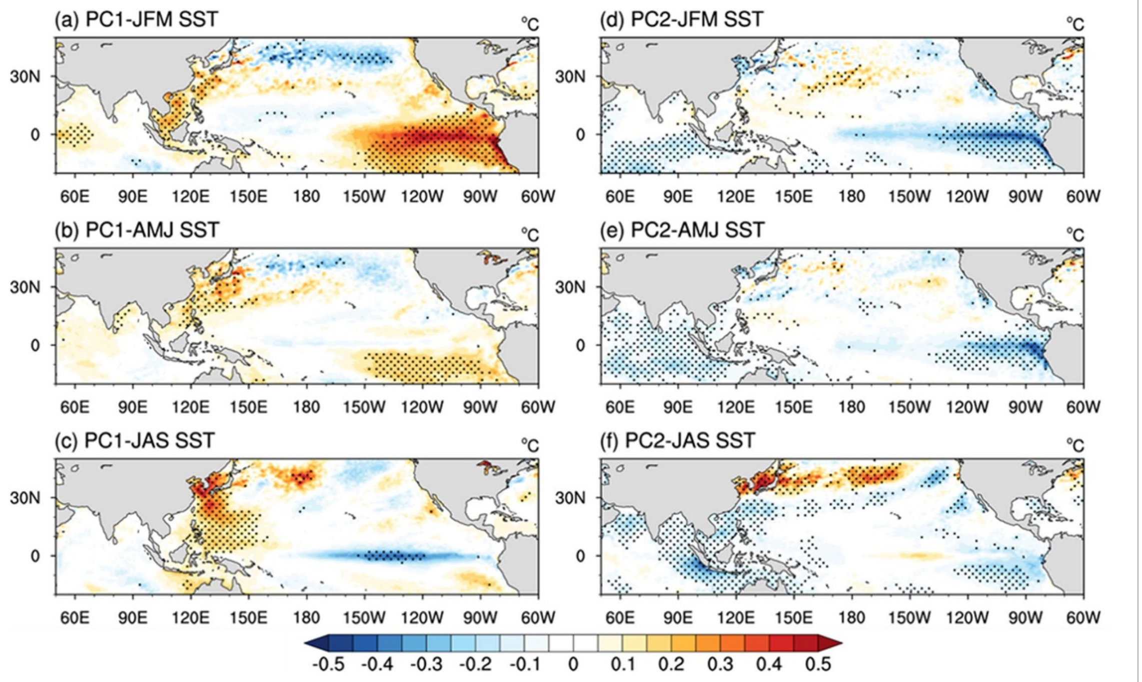

Figure 3. Regression maps of SSTs for the preceding winter (JFM, (a) and (d)), preceding spring (AMJ, (b) and (e)), and simultaneous summer (JAS, (c) and (f)) with respect to the summer MHW duration PC1 (left panels) and PC2 (right panels) time series shown in figure 2. The dotted regions indicate the areas where the regression of the SSTs exceeded the 95% confidence level.

in the time series of PC1 (figure 2(c)). In contrast, the second MHW EOF mode shows a dipole pattern between the mid-latitude and subtropical regions (figure 2(b)). In the time series of PC2, an exceptional peak of the dipole mode (figure 2(d)) was found for 1994, which was the year experiencing a well-known atmospheric heatwave, as described by Lee and Lee (2016).

Next, we try to understand the relationship between summer MHW modes and global-scale SST patterns. We hypothesize that the large-scale SSTs during earlier seasons can provide a precondition for summertime MHWs over East Asia. As shown in figure 3, we analyzed regression maps of SSTs for the preceding winter (January-February-March, JFM) and spring (April-May-June, AMJ) as well as the simultaneous summer (JAS) with respect to PC1 and PC2.

그럼 겨울에는 왜 시작될?

겨울에서 부터 시작된 것?

Associated with the first MHW mode (figure 2(a)), basin-wide ocean warming from subtropical WNP to East Asia (approximately 120–140°E/20–40°N, figure 3(c)) starts to emerge from the previous winter (figure 3(a)). Throughout spring to summer, a positive SST anomaly (figures 3(b), (c)) is established over the longitudes of 120–160°E across the Maritime continent, Philippine Sea, and East Asia. The results imply that East Asian warm ocean memory had accumulated for several months until summer. This persistence of a slightly warmed ocean state can provide a favorable background for initiating extreme ocean warming events in East Asia during summer.

ocean memory 인거 아닌지 어떻게 알지?

In the second MHW mode (figure 2(b)), a negative SST pattern developed earlier over the Yellow and East/Japan Seas from the previous winter through spring (figures 3(d), (e)). In addition, no prominent ocean warming was observed over the subtropical WNP region. However, abrupt increases in the SST are remarkably shown in the zonal direction around East Asia during summer (figure 3(f)). The abrupt ocean warming of the second mode has a clear distinction from the persistent, favorable ocean conditions of the first mode.

The east-to-west elongation across the International Date Line in Pacific (180°E) of a positive SST anomaly (+0.5 °C) was confined only to the mid-latitude regions, which results in a dipole pattern (positive MHWs over East Asia but negative MHWs over the subtropical WNP). It is questionable how the second MHW mode can develop despite the earlier unfavorable ocean conditions. It is our hypothesis that the second mode may require more favorable atmospheric forcing to increase ocean temperatures up to extreme ocean thresholds, which will be examined in the next subsection.

3.3. Governing processes of the two MHW modes

The ocean and atmospheric conditions in East Asia are known to interplay with various climate variabilities through a Rossby wave response from anomalous convection over a subtropical WNP (Nitta 1987, Lee and Lee 2016), during the decaying phase of El Niño (Yun et al 2015), and/or through the mid-latitude wave train across the Eurasian continent (Park and

겨울은 favorable background 다
VS
long term scale 현상이 겨울/여름 MHW를 일으킨다.

실제로 여름보단 겨울에 많음!

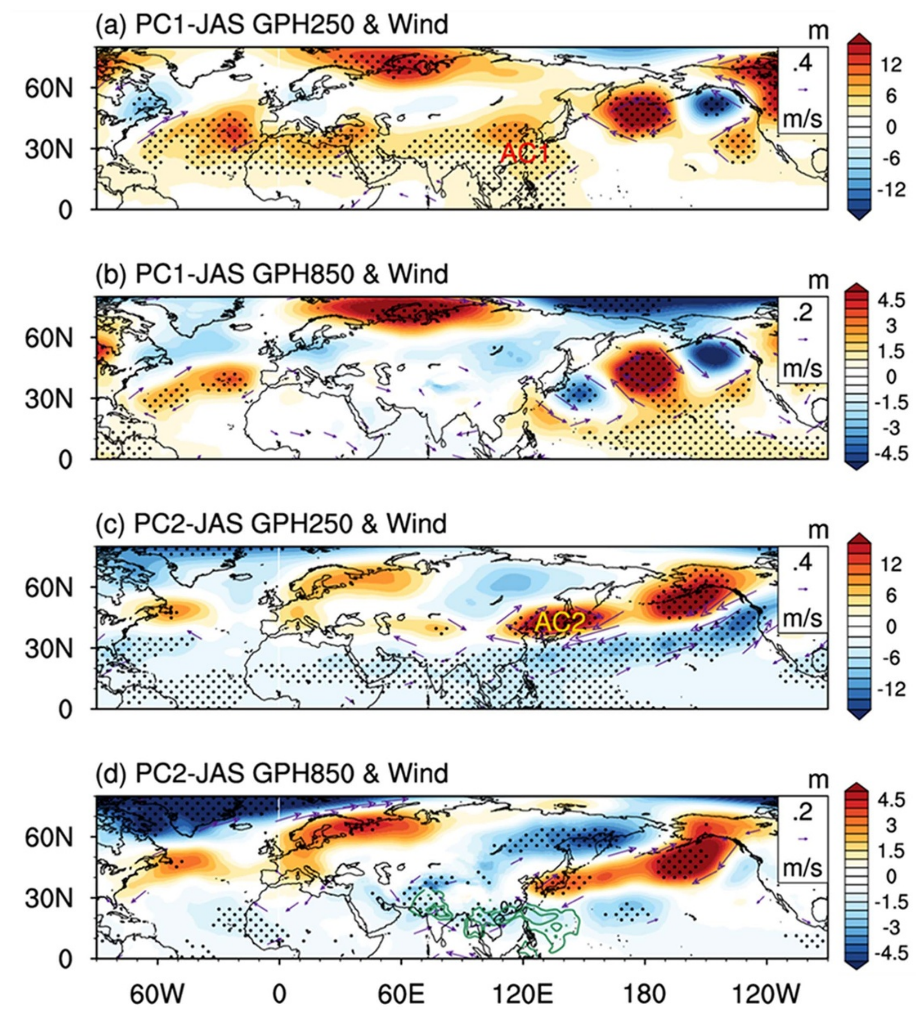

Figure 4. Regression maps of 250-hPa and 850-hPa geopotential heights (MERRA2, unit: m) and winds (m s^{-1}) on the JAS, with respect to PC1 (in (a) and (b)) and PC2 (in (c) and (d)) from 1982 to 2018, with the area exceeding the 90% confidence level (dotted). In (d), an enhanced convection feature (with GPCP monthly rainfall intervals of 0.2 and 0.5 mm day^{-1}) across the Indian monsoon and the western North Pacific is indicated by the green contour line. For the wind and precipitation, only those areas exceeding the 90% confidence level are indicated.

Schubert 1997, Yeo *et al* 2019). This section will examine global-scale SST evolution (figure 3) and atmospheric circulation (figure 4). Schematic figures as to how the aforementioned climate variabilities affect the two major MHW modes will be shown (figure 5).

3.3.1. The first mode processes

The basin-wide ocean warming associated with the first MHW mode may be preconditioned by equatorial SST evolution related to ENSO. Whereas the SST anomaly over the tropical Eastern Pacific is strongly positive during the mature phase of El Niño (figure 3(a)), it weakens during spring (figure 3(b)). Then, during summer, the equatorial central Pacific changes to a cooling pattern (figure 3(c)). In contrast, anomalous warming in the South China Sea and along the East Asian coast, versus a weak cooling anomaly in the eastern WNP, is maintained from winter to the succeeding summer. While this seasonal subsequence seems to correspond to the well-known SST variations over the Indo-western Pacific domain from El Niño and matures until its decay during summer (Wang *et al* 2003), this study clearly focuses on the connection between ENSO and the extreme events in the oceans of East Asia.

A wide anomalous anticyclonic circulation (AC1 in figure 4(a)) over the WNP is known to be a key component of ENSO for impact on East Asian MHWs. The WNP-to-East Asia basin-wide, anomalous anti-cyclonic circulation during an El Niño mature winter may possibly be driven through local air-sea feedback in response to the zonal dipole pattern of SST anomalies (Wang *et al* 2003). In addition, central Pacific cooling (figure 3(c)) may have an important role in maintaining anticyclonic circulation during the summer of rapid El Niño decay or La Niña development/persistence (Xiang *et al* 2013, Wu *et al* 2017).

Given the subtropical to mid-latitude anticyclonic anomalous, a more enhanced geopotential height peak at 250 hPa (AC1 in figure 4(a)) is found in mid-latitudes. Successive high- and low-pressure

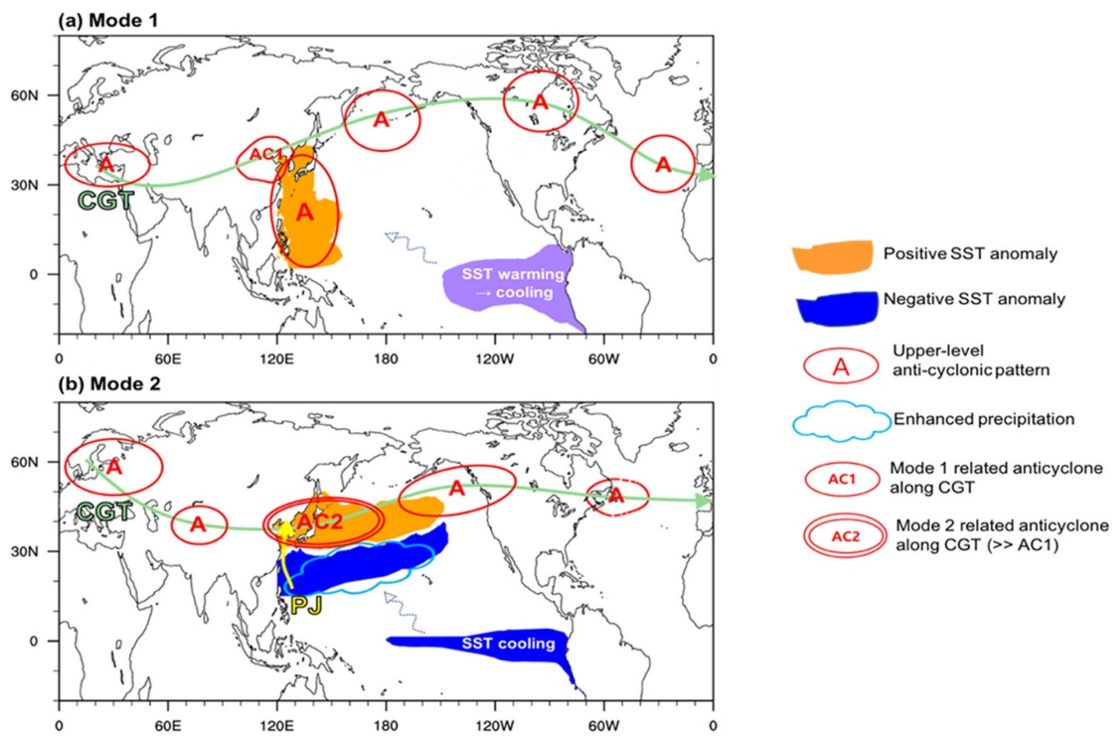

Figure 5. Schematic pictures illustrating how two primary modes of East Asian marine heatwaves are affected by global-scale climate variabilities (CGT, WNP convection, and the equatorial SST pattern): (a) Mode 1 (basin-wide warming pattern) and (b) Mode 2 (dipole warming pattern).

areas are zonally elongated across the North Atlantic Ocean, Eurasian continent, Pacific, and North America (figures 4(a), (b)). In particular, East Asia is located in a high geopotential height phase along the wave trains. The zonal wavenumber-5 upper-level variations, peak locations, and barotropic structures are mostly consistent with the Circumglobal Teleconnection (CGT) pattern identified by Ding and Wang (2005). In general, the CGT pattern occurs in the summer mid-latitudes of the Northern Hemisphere. Ding and Wang (2005) documented that the Indian summer monsoon (ISM) acts as a conductor inducing the CGT. An enhanced ISM affects the upper-level anomalous high through Rossby wave dispersion over Europe, India, East Asia and North America.

Accordingly, a certain intensity of an atmospheric high-pressure anomaly (AC1; figures 4(a), 5(a)) in the mid-latitude CGT pattern (green arrow; figure 5(a)) has a critical role in finally inducing summertime MHWs in cooperation with the pre-conditioning of the basin-wide ocean warming (orange shading; figure 5(a)). The concurrent, large-scale anticyclonic pattern responsible for the basin-wide warming may be related to the fast decay of ENSO. However, our individual year case analysis (not shown) implies that due to the diversities in ENSO evolution, the ENSO impact on WNP warming can vary every year.

3.3.2. The second mode processes

In the second mode, the west-to-east extended anticyclonic anomaly (AC2 in figures 4(c),(d)) is much stronger than that for the first process (AC1 in figures 4(a),(b)). The typical CGT-type positive and negative waves along East Asia toward the west coast of North America are transformed into a significantly intensified positive geopotential height phase with the absence of negative phases, as shown in figure 4(c).

This significant intensification of high-pressure and anticyclonic circulation is attributed to the teleconnection from the subtropical WNP. This subtropical to mid-latitude impact was well emphasized in previous studies on atmospheric heatwaves in Korea by Lee and Lee (2016) and Yeo *et al* (2019). In the current study, figure 4(d) also shows that diabatic heating associated with enhanced precipitation over the subtropical WNP can further intensify the anomalous anticyclone circulation (AC2 in figure 4(c)) over East Asia through Rossby wave trains. Nitta (1987) called this WNP-East Asian connection the Pacific-Japan (PJ) pattern linked between anomalous convection over the WNP and East Asia. Wang *et al* (2001) mentioned that the enhanced western North Pacific summer monsoon suppressed convection and precipitation over the East Asian region. In our results, the correlation between the current PC2 time series and the PJ index is 0.46 with $p < 0.05$, which confirms the role of subtropical convection activities in the second MHW.

Accordingly, as seen in figure 5(b), the abrupt ocean warming over East Asia is induced by a much stronger, zonally-extended anticyclonic anomaly (AC2 in figure 5(b)) along the CGT wave train, whereas the WNP remains cool, possibly in association with La Nina. It was suggested that the mid-latitude anticyclone intensification may be attributed to the enhanced convection over the WNP (figure 5(b)).

4. Summary and discussion

Recent prominent ocean warming events and their global-wide impacts on marine ecosystems and fisheries have been explored as a new area of extreme climate events, namely, MHWs (Oliver *et al* 2018). A single MHW process has been identified over the Mediterranean Sea (Olita *et al* 2007), around Australia (Pearce and Feng 2013), and in the northeastern Pacific (Di Lorenzo and Mantua 2016). Given the well-known interannual variabilities of ocean and atmospheric environments in East Asia (Wang *et al* 2001), it has been hypothesized that major atmospheric and ocean processes of MHW can change each year. This study revealed the significant interannual variation in the total MHW days (figure 1) over East Asian seas, with overall increasing trends using NOAA OISST data for a 37-year period from 1982 to 2018 (see section 3.1). We then conducted analyses of the EOF of the satellite-detected total MHW duration (figure 2) and the regression maps of the large-scale SSTs and atmospheric fields (figures 3 and 4).

In conclusion, we presented two major basin-wide and dipole patterns of East Asian MHWs (section 3.2). The first MHW mode was mainly involved with a 'persistent ocean state' (positive ocean temperature anomaly emerging from an earlier winter), and the second mode was accompanied by an 'abrupt atmospheric forcing' (atmospheric high intensification) despite the persistence of unfavorable ocean conditions. Through an additional analysis on the relationship between the two MHW modes and heat flux (supplementary figure 1, available online at: stacks.iop.org/ERL/15/074008/mmedia), we found strong upward versus downward heat fluxes for modes 1 and 2, respectively. This result further confirms a much stronger atmospheric impact on warming the ocean for the second mode than for the first mode.

It has been known to the public that extreme ocean warming can occur in response to atmospheric heatwaves. The second MHW mode shows peaks in the well-known heatwave years of 1994 and 2018 (Yeo *et al* 2019). Here, we emphasize the accumulated effect of persistent ocean (Pearce and Feng 2013) and abrupt atmospheric forcing (Olita *et al* 2007) conditions.

As an additional critical point, various global-scale teleconnection processes (ENSO, CGT, and convection activities over the subtropical WNP) can act as local MHW mechanisms. We newly emphasized the role of ENSO on East Asian MHWs by determining persistent, favorable ocean conditions (figure 3). For the first MHW mode, the large-scale basin-wide SST warming along with an anomalous anti-cyclonic circulation can be sustained for several months from an El Niño mature winter to a La Niña summer and/or equatorial SST cooling in the summer. In the second MHW mode, the anomalous cold SST is maintained from winter to summer over the tropical Eastern Pacific, similar to La Nina.

In addition, the interaction between mid-latitude CGT-type waves and subtropical convection activities has a critical role in inducing immediate atmospheric forcing, both causing an anomalous atmospheric high structure in East Asia. This interaction for the second MHW is consistent with Yeo *et al* (2019), who emphasized the zonal (CGT-type) and meridional (subtropical) wave types of atmospheric heatwaves in East Asia. By contrast, the first ocean mode of this study confirmed the distinctive processes of an MHW that differed from those of atmospheric heatwaves. However, for a mixture of both modes, the current ideal EOF modes should be applied cautiously to real MHW cases. For example, 1994 is the representative year of the second mode, but it also reveals a small positive value of PC1 (figure 2(d)). In this case, the atmospheric and ocean influences and the global teleconnection patterns cannot be explained through a single ideal MHW mode.

Acknowledgments

This research was a part of the project titled 'Investigation and prediction system development of marine heatwave around the Korean Peninsula originated from the subarctic and western Pacific (20190344)', funded by the Ministry of Oceans and Fisheries, Korea. The authors would also like to thank Professor Baek-Min Kim at Pukyong National University and Mr. Nakbin Choi at Ulsan National Institute of Science and Technology for the helpful comments regarding the current results.

Data availability statement

The data that support the findings of this study are openly available. The OISST and GPCP data were from their web site at www.esrl.noaa.gov/psd/; MERRA2 at https://gmao.gsfc.nasa.gov/reanalysis/MERRA2/data_access/.

References

Di Lorenzo E and Mantua N 2016 Multi-year persistence of the 2014/15 North Pacific marine heatwave *Nat. Clim. Chang.* **6** 1042

Dian-Xiu Y, Ji-Fu Y, Zheng-Hong C, You-Fei Z and Rong-Jun W 2014 Spatial and temporal variations of heat waves in China from 1961 to 2010 *Adv. Clim. Change Res.* **5** 66–73

Ding Q and Wang B 2005 Circumglobal teleconnection in the Northern Hemisphere summer *J. Clim.* **18** 3483–505

Feng M, Mcphaden M J, Xie S P and Hafner J 2013 La Niña forces unprecedented Leeuwin current warming in 2011 *Sci. Rep.* **3** 1277

Frölicher T L and Laufkötter C 2018 Emerging risks from marine heat waves *Nat. Commun.* **9** 650

Gelaro R *et al* 2017 The modern-era retrospective analysis for research and applications, version 2 (MERRA-2) *J. Clim.* **30** 5419–54

Hobday A J *et al* 2016 A hierarchical approach to defining marine heatwaves *Prog. Oceanogr.* **141** 227–38

Huffman G J, Adler R F, Bolvin D T and Gu G 2009 Improving the global precipitation record: GPCP version 2.1 *Geophys. Res. Lett.* **36**

IPCC 2018 Global warming of 1.5 °C: an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. intergovernmental panel on climate change *Sustainable Development, and Efforts to Eradicate Poverty* (Geneva: IPCC) (www.ipcc.ch/sr15/)

Kim S J, Woo S H, Kim B M and Hur S D 2011 Trends in sea surface temperature (SST) change near the Korean peninsula for the past 130 years *Ocean Polar Res.* **33** 281–90

Knutson T R *et al* 2010 Tropical cyclones and climate change *Nat. Geosci.* **3** 157

Kwon M H, Jhun J G, Wang B, An S I and Kug J S 2005 Decadal change in relationship between east Asian and WNP summer monsoons *Geophys. Res. Lett.* **32**

Lee W S and Lee M I 2016 Interannual variability of heat waves in South Korea and their connection with large-scale atmospheric circulation patterns *Int. J. Climatol.* **36** 4815–30

Mcwilliams J P, Côté I M, Gill J A, Sutherland W J and Watkinson A R 2005 Accelerating impacts of temperature-induced coral bleaching in the Caribbean *Ecology* **86** 2055–60

Meehl G A *et al* 2000 An introduction to trends in extreme weather and climate events: observations, socioeconomic impacts, terrestrial ecological impacts, and model projections *Bull. Am. Meteorol. Soc.* **81** 413–6

Nitta T 1987 Convective activities in the tropical western Pacific and their impact on the Northern Hemisphere summer circulation *J. Meteor. Soc. Japan* **65** 373–90

North G R, Bell T L, Cahalan R F and Moeng F J 1982 Sampling errors in the estimation of empirical orthogonal functions *Mon. Weather Rev.* **110** 699–706

Olita A, Sorgente R, Natale S, Ribotti A, Bonanno A and Patti B 2007 Effects of the 2003 European heatwave on the Central Mediterranean Sea: surface fluxes and the dynamical response *Ocean Sci.* **3** 273–89

Oliver E C J *et al* 2017 The unprecedented 2015/16 Tasman Sea marine heatwave *Nat. Commun.* **8** 16101

Oliver E C J *et al* 2018 Longer and more frequent marine heatwaves over the past century *Nat. Commun.* **9** 1324

Park C K and Schubert S D 1997 On the nature of the 1994 East Asian summer drought *J. Clim.* **10** 1056–70

Pearce A F and Feng M 2013 The rise and fall of the 'marine heat wave' off Western Australia during the summer of 2010/2011 *J. Mar. Syst.* **111** 139–56

Perkins S E, Alexander L V and Nairn J R 2012 Increasing frequency, intensity and duration of observed global heatwaves and warm spells *Geophys. Res. Lett.* **39** 20

Reynolds R W, Rayner N A, Smith T M, Stokes D C and Wang W 2002 An improved in situ and satellite SST analysis for climate *J. Clim.* **15** 1609–25

Sparnocchia S, Schiano M, Picco P, Bozzano R and Cappelletti A 2006 The anomalous warming of summer 2003 in the surface layer of the Central Ligurian Sea (Western Mediterranean) *Ann. Geophys.* 443–52

Stott P 2016 How climate change affects extreme weather events *Science* **352** 1517–18

Wang B, Wu R and Lau K M 2001 Interannual variability of the Asian summer monsoon: contrasts between the Indian and the western North Pacific–East Asian monsoons *J. Clim.* **14** 4073–90

Wang B, Wu R and Li T I M 2003 Atmosphere–warm ocean interaction and its impacts on Asian–Australian monsoon variation *J. Clim.* **16** 1195–211

Wernberg T *et al* 2013 An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot *Nat. Clim. Chang.* **3** 78

Wu B, Zhou T J and Li T 2017 Atmospheric dynamic and thermodynamic processes driving the western North Pacific anomalous anticyclone during El Niño. Part II: formation processes *J. Clim.* **30** 9637–50

Xiang B, Wang B, Yu W and Xu S 2013 How can anomalous western North Pacific subtropical high intensify in late summer? *Geophys. Res. Lett.* **40** 2349–54

Yeo S R, Yeh S W and Lee W S 2019 Two types of heat wave in Korea associated with atmospheric circulation pattern *J. Geophys. Res.: Atmos.* **124** 7498–511

Yun K S, Ha K J, Yeh S W, Wang B and Xiang B 2015 Critical role of boreal summer North Pacific subtropical highs in ENSO transition *Clim. Dyn.* **44** 1979–92