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Sea Surface Temperature Extremes of Different Intensity in the China Seas During the Global Warming Acceleration and Hiatus Periods

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Abstract: Based on the daily OISST V2 with 0.25º horizontal resolutions, the present study looks into the variations of sea surface temperature (SST) extremes in the China Seas for different segments of the period 1982–2013. The two segments include the warming acceleration period from 1982 to 1997 and the hiatus period from 1998 to 2013 when the global mean surface temperature (GMST) did not significantly increase as expected, or even decreased in some areas. First, we construct the regional average time series over the entire China Seas (15°–45°N, 105°–130°E) for these SST extremes. During the hiatus period, the regionally averaged 10th, 1th and 0.1th percentile of SSTs in each year decreased significantly by 0.40°C, 0.56°C and 0.58°C per decade, respectively. The regionally averaged 90th, 99th and 99.9th percentile of SSTs in each year decreased slightly or insignificantly. Our work confirm that the regional hiatus was primarily reflected by wintertime cold extremes. Spatially, the trends of cold extremes in different intensity were non-uniformly distributed. Cold extremes in the near-shore areas were much more sensitive to the global warming hiatus. Hot extremes exhibited non-significant trend in the China Seas during the hiatus period. In short, the variations of the SST extremes in the two periods were non-uniform spatially and asymmetric seasonally. It is unexpected that the hot and cold extremes of each year during 1998–2013 were still higher than those extremes during 1982–1997. It is obvious that compared with the warming acceleration period, hot extremes were far more likely to occur in the recent hiatus as a result of a 0.3°C warmer shift in the mean temperature distribution. Moreover, hot extremes in the China Seas will be sustained or amplified with the end of warming hiatus and the continuous anthropogenic warming.

Key words: sea surface temperature; linear trend; regional climate change; extreme

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1 INTRODUCTION

Observational evidence indicates that since 1998, the global mean surface temperature (GMST) has experienced a notable climatic shift from rapid warming to unexpected deceleration, which is called "global warming hiatus". The "global warming hiatus" often refers to the period from about 1998 and to around 2013, during which the average annual increase in GMST did not seem to be as large as the continuous increase in anthropogenic greenhouse gas concentration (Medhaug et al. [1]). This phenomenon has attracted broad interest from the climate variability and climate change communities (Kosaka et al. [2]; Fyfe et al. [3]; Guemas et al. [4]; Johnson et al. [5]; Liu et al. [6]; Hu et al. [7]), though there are still some disputes over the terms “warming hiatus” or “hiatus” and some even believe that this phenomenon does not exist (Karl et al. [8]).

Regionally, researchers from China confirmed that the Chinese mainland experienced a remarkable cooling since 1998 due to the global warming hiatus (Li et al. [9]; Sun et al. [10]; Xie et al. [11]). The China Seas are important marginal seas located between the Chinese mainland and the northwest Pacific Ocean with rich marine ecosystems and resources. As a part of the western boundary current, the China Seas is one of the most significant warming regions in the world (Belkin [12], Wu et al. [13]). Recent study shows that though the annual mean sea surface temperature (SST) in the China Seas also experienced a remarkable decline during the global warming hiatus, more extreme marine heatwaves (MHWs) occurred (Li et al. [14]). Compared with terrestrial extreme events, oceanic extreme events have received less attention, yet still can cause shifts in species ranges, local extinctions, and economic loss on

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aquaculture and seafood industries through declines in important fishery species (Zhi et al. [15]; Caputi et al. [16]; Hobday et al. [17]; Oliver et al. [18]; Le et al. [19]; Frölicher et al. [20]). Nevertheless, whether and how the temperature extremes changed in different intensity categories, i.e., the 90th, 99th, 99.9th percentiles SST of each year and the 10th, 1th, 0.1th percentiles SST of each year during the hiatus period are still unevaluated. In the present study, we apply SST extremes definitions on daily-resolution SST data during 1982–2013. The purpose of this study is to explore the patterns of the changes in temperature extremes in the China Seas, particularly for the warming hiatus period after 1998.

2 DATASETS AND METHODS

2.1 *Datasets*

The daily gridded SST data from the National Oceanic and Atmospheric Administration Optimum Interpolation SST v2 (OISST v2) with a horizontal resolution of 0.25º for the period 1982–2013 (Banzon et al. [21]) was used in our study (available online www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.highres.html). OISST v2 uses Advanced Very High Resolution Radiometer (AVHRR) infrared satellite SST data from the Pathfinder satellite combined with buoy data, ship data, and sea ice data SST data sets (Reynolds et al. [22]). The suitability of the data base to identify extreme SSTs was previously confirmed in many literatures (Lima et al.[23]; Benthuysen et al. [24]; Wang et al. [25]). The SST data was separated into two different periods (1982–1997, hereinafter referred to as warming period; 1998–2013, hereinafter referred to as hiatus period) for analysis. Statistical analyses of extreme SSTs in our study were based on this data set. The China Seas is located at the western rim of the Pacific Ocean, including the Bohai Sea, the Yellow Sea, the East China Sea and the South China Sea. The Kuroshio Current is the most important western boundary current in this area. In this study, we approximated the area at (15°–45°N, 105°–130°E) (Fig. 1).

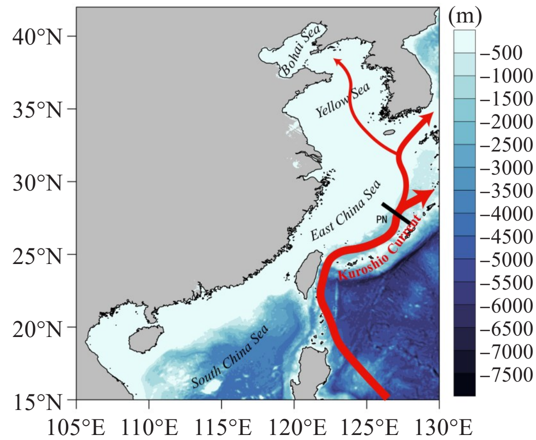

Figure 1. The location of the China Seas and its adjacent seas. The schematic pathway of the Kuroshio Current is shown in red line. The location of the Pollution Nagasaki (PN) section is also shown here.

Compared with the average temperatures, changes of the summertime hot and wintertime cold extremes are more closely related with marine ecosystems and aquaculture (Frölicher et al. [26]; Smale et al. [27]). Following previous studies (Frölicher et al. [20]; Stramska et al. [28]), our study focused on two extreme ends of the probability distribution of temperatures, i. e. the 90th, 99th, 99.9th percentiles SST of each year (in them 99.9th and 99th percentiles representing very hot extremes) and the 10th, 1th, 0.1th percentiles SSTs of each year (0.1th and 1th percentiles representing very cold extremes) (Table 1). Here, threshold values of each year are defined based on the 90th, 99th, 99.9th (10th, 1th, 0.1th) percentile values of SSTs in each year which are arranged in descending order. Then, the linear trends of annual percentils of extremes are given.

Table 1. The hot and cold extremes in this study.

Descriptive name	Definition	Units
Summertime hot extremes	The 90th percentile SST in each year	°C
	The 99th percentile SST in each year	°C
	The 99.9th percentile SST in each year	°C
Wintertime cold extremes	The 10th percentile SST in each year	°C
	The 1th percentile SST in each year	°C
	The 0.1th percentile SST in each year	°C

2.2 *Methods*

The SST analysis in our study was conducted on both a regional basis and a per-grid basis. Regional average is calculated by area-weighted averaging the grid data using latitude cosine as weights. Trends were calculated as the Sen's estimator of the slope (Sen et at. [29]), which was widely used in detecting monotonic trend in hydrometeorological time series (Sheffield et al. [30]; Dorigo et al. [31]). The nonparametric Mann-Kendall test was performed for the statistical significance of trends. Note that we obtained similar results by using the linear regression and Student's *t*-test in this paper. The probability density functions (PDFs) of SST in histogram format are computed for both the summertime (June-July-August) and wintertime (December-January-February) during the warming period (1982–1997) and the hiatus period (1998–2013).

3 RESULTS

Previous study found that the annual mean SST in the China Seas has experienced a remarkable decline during the global hiatus period (1998–2013) (see Fig. 2 in Li et al. [14]). Here, we make a detailed analysis of spatial characteristics of annual mean SSTs trends based on the same dataset (Fig. 2). In the warming period (1982–1997), western of the China Seas has experienced significant rapid warming (Fig. 2a). In the hiatus period, trends of decreasing annual mean SST have been detected at most parts of the China Seas (Fig. 2b). Both of the significant warming in 1982–1997 and significant cooling in 1998–2013 were located along the nearshore area. Thus, as shown in Fig. 2c, the largest differences of the trends between 1998–2013 and 1982–1997 were mainly concentrated along the nearshore areas, especially at the coastal area of the East China Seas, exceeding 1.4°C per decade (Fig. 2c). The coastal SST in China experienced a conspicuous shift from a notable warming to cooling. It suggests that in the context of the global warming hiatus, the coastal SST were much more sensitivity than these of the open oceans.

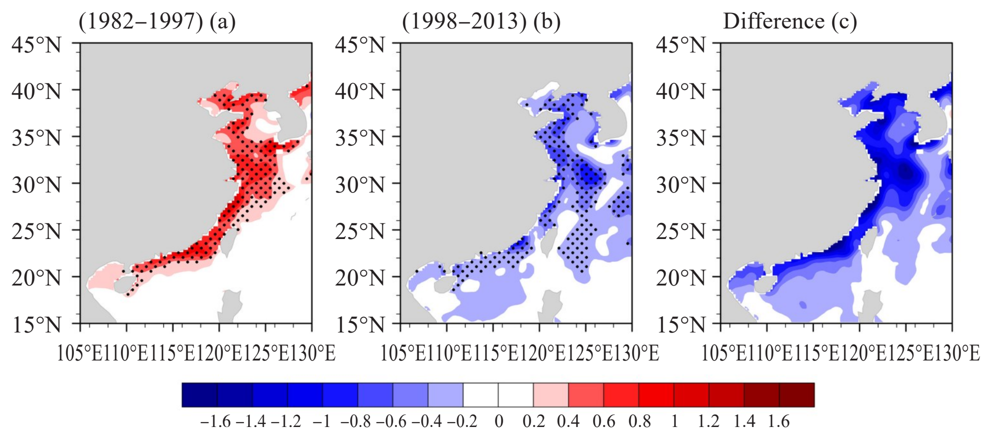

Figure 2. Spatial distribution of trends of annual mean SST during 1982–1997 (a), and 1998–2013 (b), where the green dots represent the trends that are significant at the 95% confidence level ($p<0.05$) using the Mann-Kendall test. (c) shows the trend differences between the two periods (1998–2013 minus 1982–1997) (Units: °C per decade).

To our knowledge, annual mean SSTs can be significantly affected by extreme SST values, including hot and cold extremes. We estimate trends for hot extremes in summertime and cold extremes in wintertime in different intensity categories of each year (Table 1). The time series of regional average different percentiles SST in each year showed fluctuant variations from 1982 to 2013 (Fig. 3). Because of the shortness of the warming and hiatus period, significance testing of the trends has limited relevance. Still, over the 16-year period from 1982 to 1997, all of these cold extremes exhibited significant increase, consistent with global warming (statistically significant at the 95% confidence level, $p<0.05$). The 0.1th, 1th and 10th percentiles SST in each year have been increasing much faster than the hot extremes, with the rate of 0.58°C per decade, 0.56°C per decade and 0.40°C per decade, respectively. During 1998 to 2013, hot SSTs showed insignificant decreasing, with a high level of uncertainty (non-significant at the 95% confidence level, $p>0.05$). In contrast, cold extremes exhibited a significant decline (all of them significant at the 95% confidence level, $p<0.05$). Results confirm that the recent lapse in global warming also occurred in extreme SSTs in the China Seas, but the cooling tendency was obvious only in wintertime cold extremes and thus was a seasonal phenomenon. Furthermore, there were significant correlations between all extreme indices and annual mean SST over the China Seas for the study period 1982–2013, i.e., r_{90th}=0.68, r_{99th} =0.67, $r_{99.9th}$=0.67, r_{10th}=0.85, r_{1th}=0.82, and $r_{0.1th}$=0.80; all the correlation coefficients exceed the 99% confidence level. These results indicate that the variability of cold extreme was much more subject to the influence of the hiatus of annual mean SSTs in the China Seas, rather than hot extreme.

Figure 4 and Fig. 5 show the spatial patterns of the trends of summertime hot and wintertime cold extremes in the China Seas. During 1982–1997, hot extremes increased only in the Bohai and Yellow Seas, but most of them were nonsignificant (Fig. 4a, 4c, 4e). During 1998–2013, all of the hot extremes decreased slightly (trends were very close to zero or were zero) (Fig. 4b, 4d, and 4f). Trends for extreme hot SSTs were low and statistically not significant in most areas, such as the east of the East China Sea and the south of the Yellow Sea. On the contrary, in the majority of the west of the Kuroshio Current, cold extremes revealed striking opposite trends between the warming and hiatus period, particularly in the near-shore areas (Fig. 5). The warming rates of cold extremes during 1982–1997 exceeded 0.8 °C per decade, and the larger warming occurred in the near-shore areas, exceeding 1.2 °C per decade (Fig. 5a, 5c, 5e). In the hiatus period, there were remarkable rapid decreases in the west of the Kuroshio Current, with the largest cooling in the near-shore areas (Fig. 5b, 5d, and 5f). In general, the above evidence suggests that the hiatus phenomenon that has occurred since 1998 can be more strongly associated with the substantial decreases in the cold extremes than to the decreases in hot extremes. This conclusion is also supported by time series of annual extreme SSTs averaged in the study regions shown in Fig. 3. Furthermore, the trends of summertime hot and wintertime cold extremes during the two periods displayed substantial spatial heterogeneity. The notable warming hiatus appeared in the western China Seas, especially in the near-shore areas.

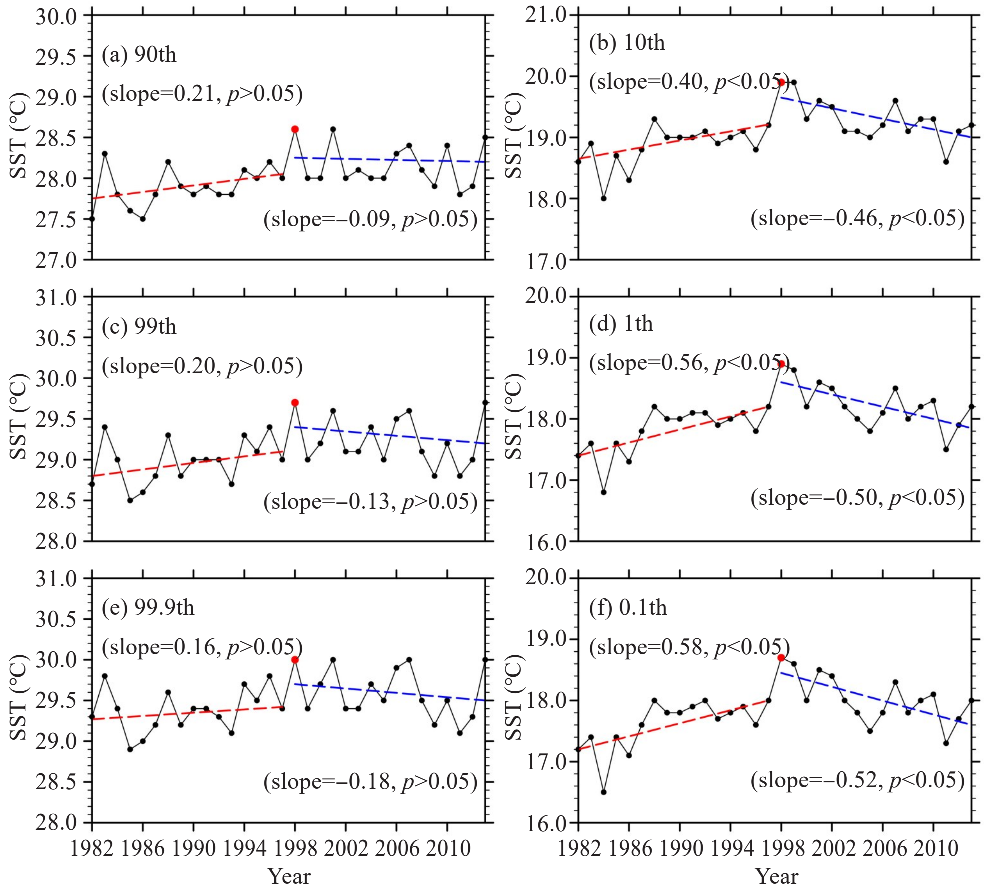

Figure 3. Temporal variations of regionally averaged 90th, 99th, 99.9th percentiles in annual SST data and 10th, 1th, 0.1th percentiles in annual SST data from 1982 to 2013. The red dots represent the year of 1998, the red dashed line represents the linear trend in the warming period and the blue dashed line represents the linear trend in the hiatus period.

The cooling of the winter SST during 1998–2013 was probably related to the combined influence from the recent strengthening of EAWM, weakening of Arctic Oscillation (AO) and deepening of EAT (You et al. [32]; Ding et al. [33]; Cai et al. [34]). In fact, extreme SST variability was not only associated with large-scale climate oscillation, but also effected by local processes, for example upwelling currents, local ocean forcing, Kuroshio Current and so on (Cai et al. [34]; Belkin and Lee [35]; Pei et al. [36]; Shu et al. [37]). Among them, the Kuroshio Current is one of the most well-known subtropical western boundary currents globally and the most important poleward heat transport pathways to adjusting the regional climate especially the China Seas (Wu et al. [13]; Wang et al. [38]; Cai et al. [34]). The Kuroshio Heat Transport (KHT) through the Pollution Nagasaki (PN) section from 1982 to 2013 is calculated using the method shown in Pei et al. [36]. Result shows that the KHT began to rise in the early 1980s and continued until the late 1990s, and then began to weaken (figure omitted). The KHT experienced a sharp climatic jump around 1998, which corresponded to the warming shift of the annual mean SST and the cold extremes. It is possible that there might be close relationship between the KHT and the trends of SST extremes in the China Seas under global warming. Further investigations are still needed for a deep understanding of the underlying physical process between the regional climate change and natural variability modes as well as local processes.

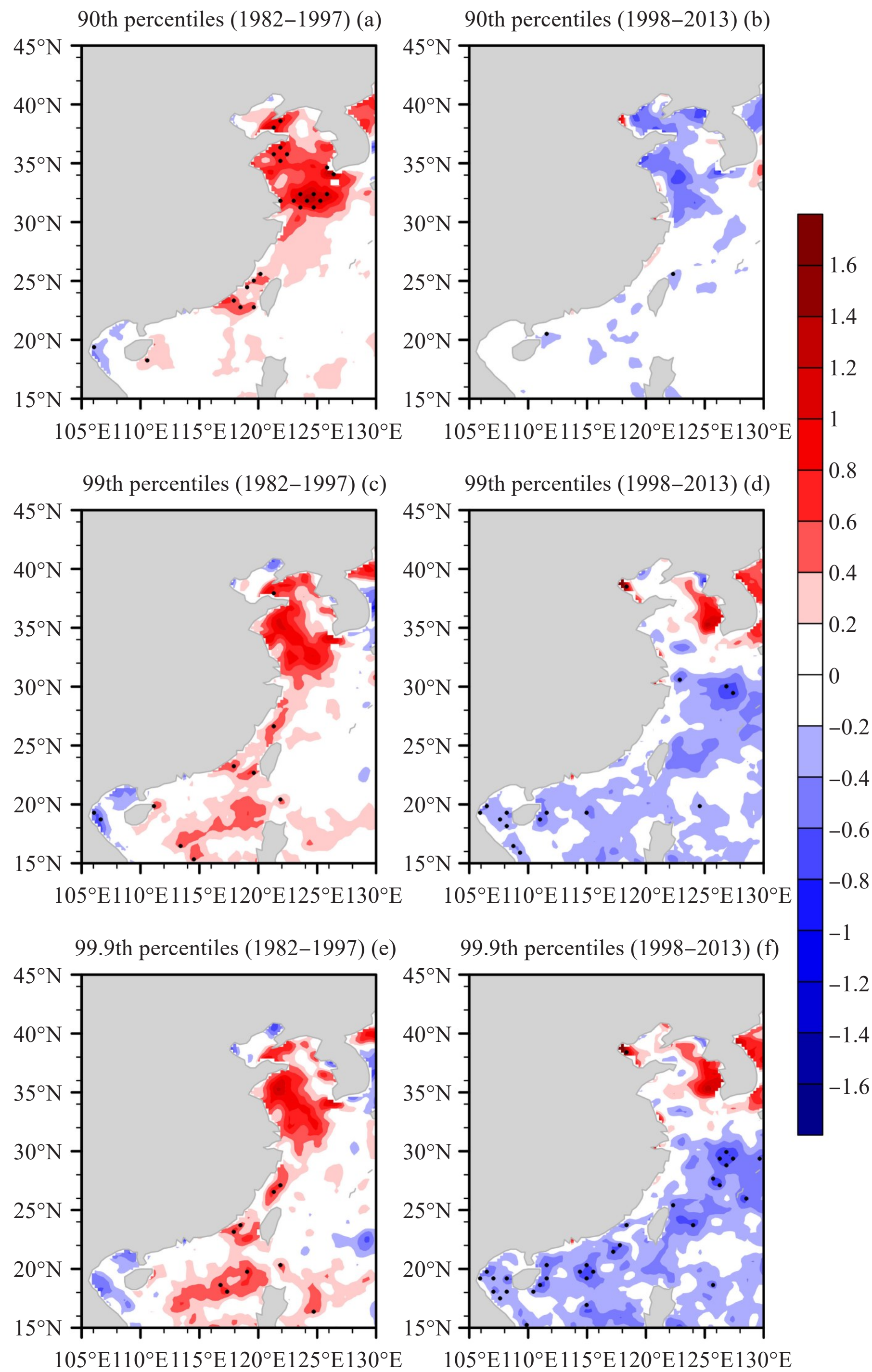

Figure 4. Trends of 90th (a), 99th (c) and 99.9th (e) percentiles in the annual SST data from 1982 to 1997; and trends of 90th (b), 99th (d) and 99.9th (f) percentiles in the annual SST data from 1998 to 2013 in the China Seas, where the stippling indicates a 95% confidence level (p<0.05) using the Mann-Kendall test (Units: °C per decade).

Interestingly, although summertime hot extremes experienced non-significant cooling tendency and wintertime cold extremes experienced a significant cooling tendency after 1998, all of these extremes during 1998–2013 were still higher than these during 1982–1997 (Fig. 2). The distributions of the differences of summertime hot extremes and wintertime cold extremes between the recent and early periods are displayed in Fig. 6. There were regionally varying positive temperature differences over most of the China Seas. In summertime, the strongest warming was mostly in the Yangtze River Estuary (30°–35°N, 120°–125°N), with the center value of ~0.8℃ which was lower than value of cold extremes. The warming was strongest in western East China Sea, especially the 0.1th and 1th percentiles, with the center value of ~1.2℃. Thus, the temperature

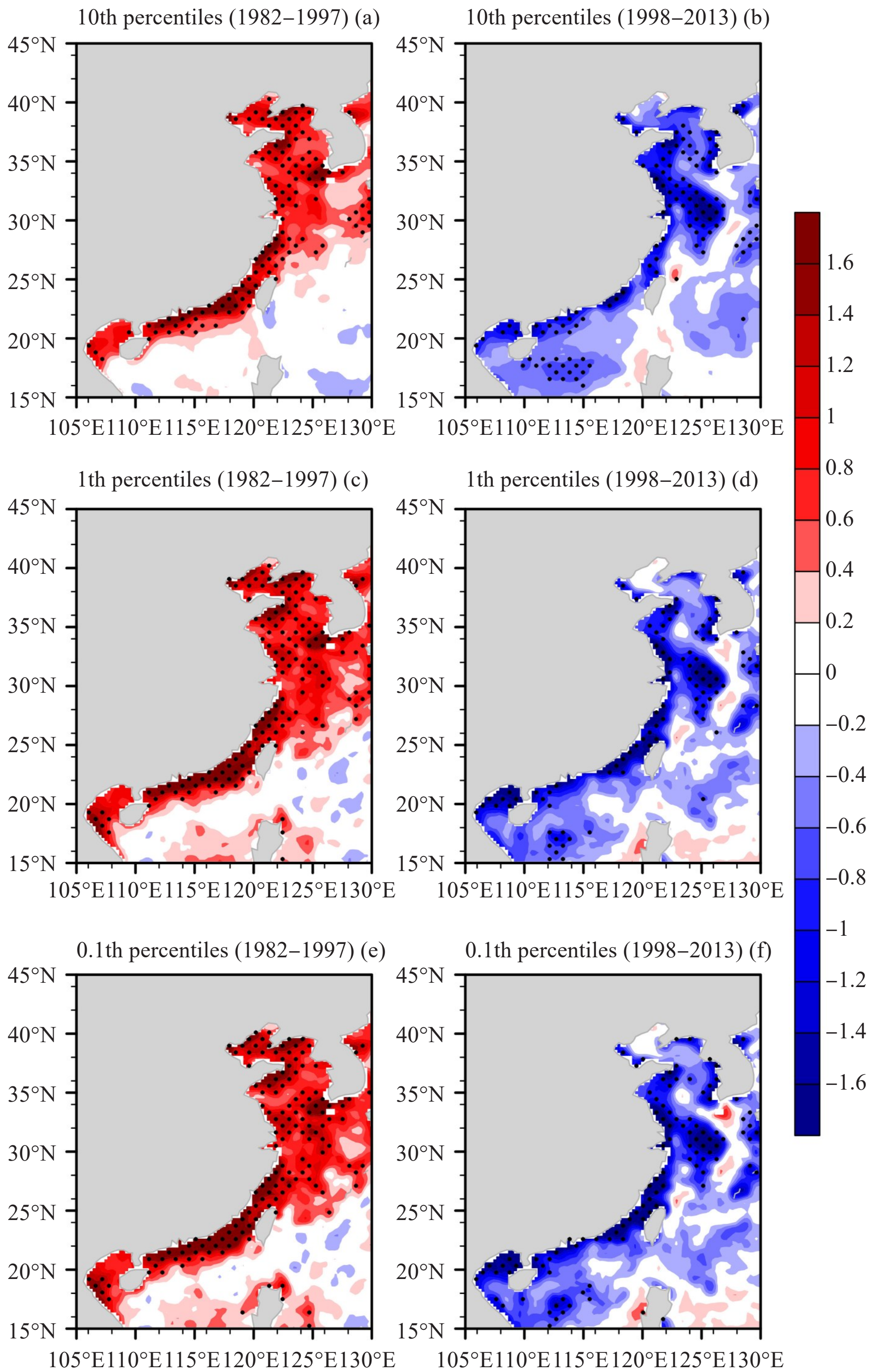

Figure 5. Trends of 10th (a), 1th (c) and 0.1th (e) percentiles in the annual SST data from 1982 to 1997; and trends of 10th (b), 1th (d) and 0.1th (f) percentiles in the annual SST data from 1998 to 2013 in the China Seas, where the stippling indicates a 95% confidence level (p<0.05) using the Mann-Kendall test (Units: °C per decade).

changes in the two periods were spatially non-uniformed across the China Seas and asymmetric through the year, with larger differences in the very cold extremes of wintertime.

To analyze the characteristics of the period shifts in the distribution of region SST, Fig. 7 shows the histogram of regional averaged SST of wintertime (Fig. 7a) and summertime (Fig. 7b) for the warming period (hatched grey bars) and hiatus period (blue bars) binned by 0.2 °C intervals. SSTs showed a positive shift of 0.3°C in the mean of the probability density function (PDF) for both winter and summer from warming to hiatus periods. Shifts in the temperature variability as diagnosed from the standard deviation were much smaller (0.01) relative to the overall magnitude in the regional average. With the marked shift, marine

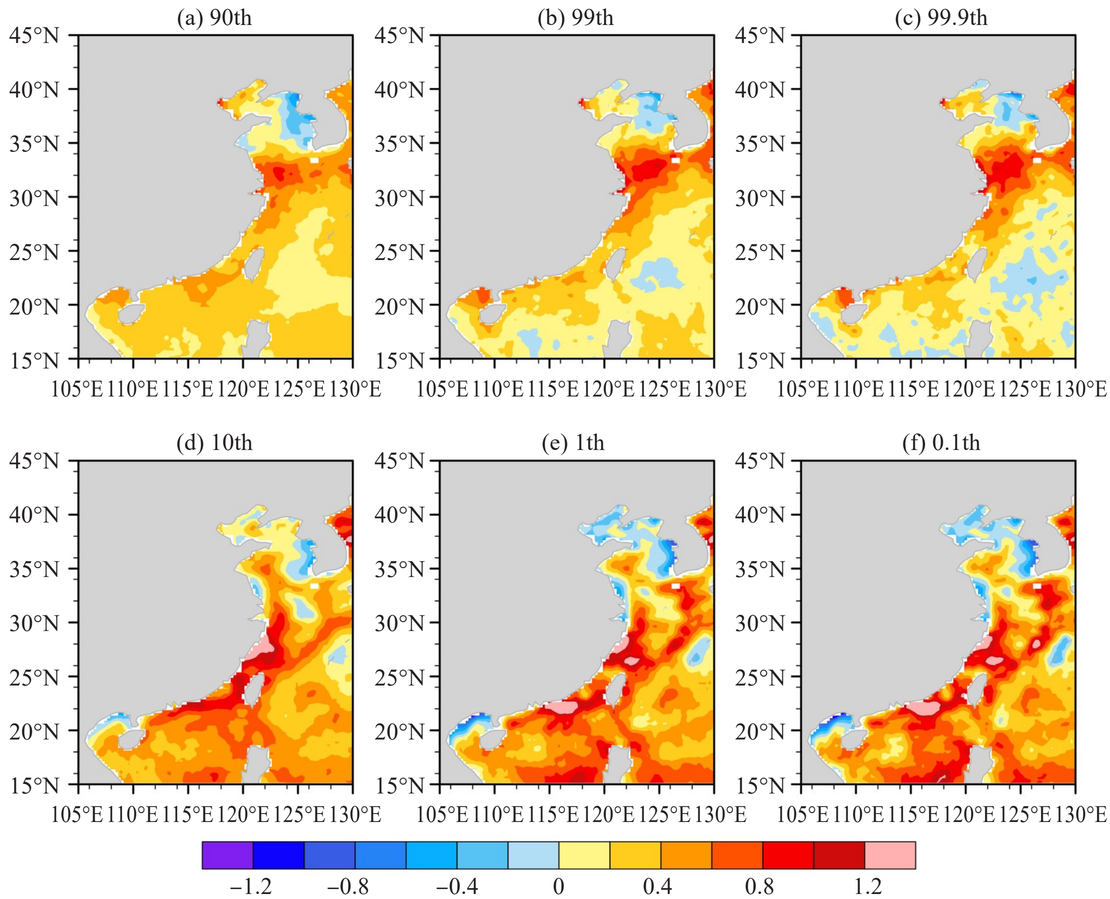

Figure 6. Spatial differences of 90th (a), 99th (b), 99.9th (c), 10th (d), 1th (e), 0.1th (f) percentiles for the periods of 1998–2013 minus 1982–1997 (Units: °C).

heatwave days (MHWDs) (the day when daily SST exceeds 90th percentile of the entire 1982–2013 as the baseline period) that accounted for 22.9% of the total MHWDs during the warming period, took up 77.1% of the total during the hiatus period. There are more frequent occurrences of hot extreme during the hiatus period. However, occurrences of marine cold-spells days (MCSDs) (the day when daily SST is below 10th percentile of the entire 1982–2013 as the baseline period) significantly declined from 79.6% to 20.4% of the total MCSDs. Specially, the very stronger MCSDs (below 1th percentile) disappeared in wintertime during the hiatus period. This would suggest that SST changes in the China Seas from 1982 to 2013 were primarily due to a shift in the mean SST and not an increase in temperature variability. And hot extremes are far more

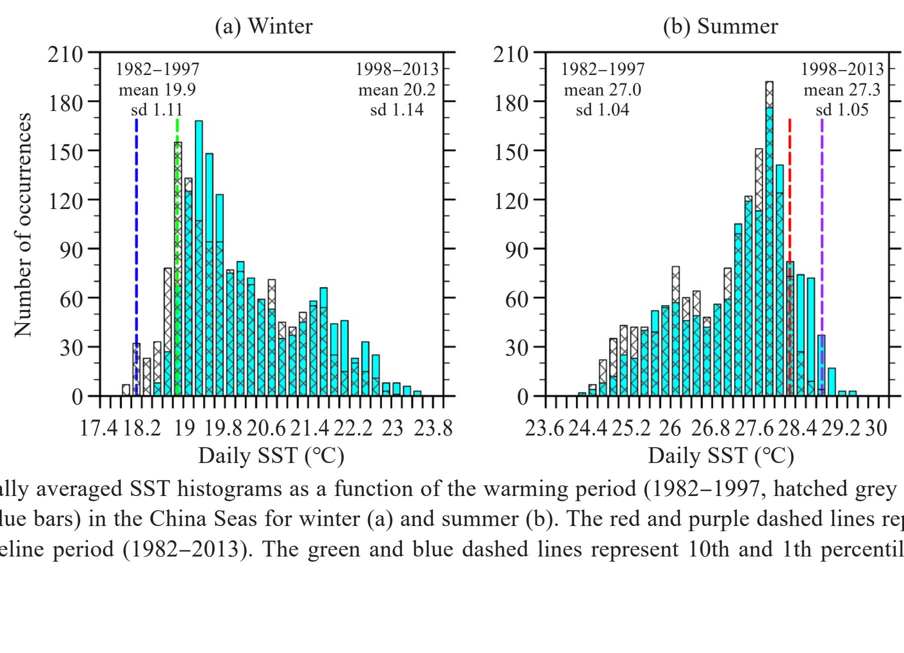

Figure 7. Regionally averaged SST histograms as a function of the warming period (1982–1997, hatched grey bars) and hiatus period (1998–2013, blue bars) in the China Seas for winter (a) and summer (b). The red and purple dashed lines represent 90th and 99th percentiles of baseline period (1982–2013). The green and blue dashed lines represent 10th and 1th percentiles of baseline period (1982–2013).

likely to occur at present as a result of a mean shift in the temperature distribution.

4 CONCLUSIONS AND DISCUSSION

In this research, based on the high resolution daily SST data, we study the variations of SST extremes in the China Seas in the warming acceleration (1982–1997) and hiatus (1998–2013) periods. Results show that the trends of wintertime cold extremes in the China Seas displayed exceptional trend reversals before and after 1998. These significant reverse patterns (i. e., from warming to cooling) mainly concentrated in the western of the China Seas, especially in the near-shore areas, consistent with annual mean SST trends. It indicates that under the background of the global hiatus, coastal cold extremes are much more sensitivity than those in the open oceans. However, summertime hot extremes trends exhibited non-significant tendency in the China Seas during the hiatus period. In short, the variations of the SST extremes in the two periods were non-uniform spatially and asymmetric seasonally.

An other intriguing phenomenon is that although there is reverse SST variability from warming to cooling in response to the global hiatus, the hot and cold extremes are still higher than those extremes in the warming acceleration period. Higher hot extremes are far more likely to occur in the recent hiatus as a result of a 0.3 °C warmer shift in the mean temperature distribution. To our knowledge, the change of global temperature is influenced not only by anthropogenic global warming, but also by the natural oscillation dominated by internal variability in the climate system (Tollefson et al.[39], Hu et al.[40]). A WMO report shows that closely following the warming hiatus period, GMST has been rapidly increasing, making three astonishing high temperature records in 2014, 2015 and 2016 consecutively which might be intensified by the super strong and prolonged El Niño (2014–2016) (WMO [41-42]; Hu et al. [43]; Su et al. [44]). Thus, this temperature rise has effectively ended the global warming hiatus since 1998. Meanwhile, as the Pacific Decadal Oscillation (PDO) struggled back to a new accelerated warming period, higher frequencies of record high temperatures would occur in the near future globally (Su et al. [44]). As a part of western boundary currents, there is hotspot of greater increase than global mean SSTs rising (Wu et al.[13]). This means that with the warming hiatus break off and the continued ocean temperature rising, which is projected to occur under current greenhouse gas emission levels, there will be more frequent and intense hot extremes in the China Seas, particularly around Yangtze River Estuary. Even if the 1.5°C IPCC target is achievable (IPCC [45]), the anthropogenic warming in the coming decades may exacerbate future hot extremes. It is expect that without forward-looking measures, the implied economic damage in the aquaculture can be huge in some region. Meanwhile, significant increase of hot extremes can also drive up the disaster risk on the local marine ecosystems, such as coral reefs and mangrove.

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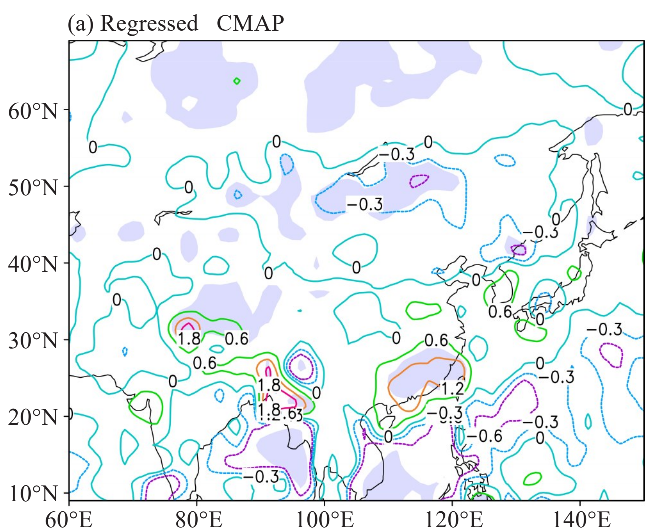
Notice

In the article titled “An Interdecadal Change of Summer Atmospheric Circulation over Asian Mid-High Latitudes and Associated Effects” by Zhou et al. published in the *Journal of Tropical Meteorology*, Vol 26, Issue 3, Figure 6a on page 368 was incorrect and the correct one should be the following figure.



We hereby correct it and sincerely apologize for the mistake.

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