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More extreme marine heatwaves in the China Seas during the global warming hiatus

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Abstract

Based on the satellite-derived global daily sea surface temperature (SST) data set with high resolution (0.25° by 0.25°), we analyzed changes in annual mean SST and extreme SSTs over the China Seas since 1982. Results show that the annual mean SST in the China Seas has experienced a remarkable declining trend during the global warming hiatus (1998–2013), which was dominated by the striking cooling of SST in boreal winter. Despite annual mean SST experienced warming hiatus after 1998, the regional averaged SST for 1998–2013 was still 0.5 °C above that for 1982–1997. The statistical distributions show that there are not only significant warmer climate shift in annual mean SSTs but also in annual extreme hot SSTs and cold SSTs. These changes can increase the likelihood of extreme oceanic warming events, known as marine heatwaves (MHWs). Further analyses reveal that, from 1982 to present, the MHW frequency increases at a rate of 1.13 events per decade, 2.5 times the global mean rate. For the period 1998–2013, the MHWs in the China Sea has never decreased in both of the frequency and intensity but has already become more frequent, longer duration and more intense than those metrics of MHWs during 1982–1997.

1. Introduction

Despite the continued increase of atmospheric greenhouse gases concentrations, the global surface mean temperature (GMST) has exhibited an unexpected shift from rapid to flat warming at 1998 and ending around 2014 (Medhaug *et al* 2017). This phenomenon was called the 'global warming hiatus', 'warming pause' or 'slowdown' (Meehl *et al* 2013, Trenberth *et al* 2014, Lewandowsky *et al* 2015) and has been ascribed to various possible causes: internal climate variability, reduced solar energy output, heat uptake in deep ocean, and strong shifts to La Niña states (Kosaka and Xie 2013, Trenberth *et al* 2014, Guan *et al* 2015). Several studies have attributed the warming hiatus to the 60-year-quasi-periodic natural climate variability —Pacific decadal oscillation (PDO) (Tollefson 2014). Though, there are still debates on the global warming hiatus, it is virtually certain that the warming hiatus were more noticeable in regional scales at the Northern Hemisphere (NH): for example, mainland China and Eurasian continents (Duan and Xiao 2015, Guan *et al* 2015, Li *et al* 2015, Garfinkel *et al* 2017, Sun *et al* 2017, Xie *et al* 2017, Shen *et al* 2018). Compared to the studies on the terrestrial warming hiatus, less focus has been given to warming hiatus at marginal seas.

Since the turn of the 21st century, special attention has been paid to extreme meteorological, hydrological, and oceanographic events such as heatwaves, cold snaps, storms, floods and tropical cyclones, which often trigger complex and, in some cases, catastrophic consequences (IPCC 2013, Oliver *et al* 2017, Herring *et al* 2019). Notable extreme ocean warm events or marine heatwaves (MHWs) have been observed in recent years (Hobday *et al* 2016, Oliver *et al* 2017, 2018), including events in the northern Mediterranean (Garrabou *et al* 2009), offshore of western Australia (Benthuysen *et al* 2018), in the northwest Atlantic (Chen *et al* 2014), and in the Tasman Sea (Oliver *et al* 2017), etc. MHWs are characterized as regions of large-scale and persistent at least five consecutive extreme hot days (EHDs) when daily SST exceeds a seasonally varying threshold (Hobday *et al* 2016). MHWs can be classified by multiple characteristics, such as intensity, frequency, duration, and timing similar to their terrestrial counterpart. MHWs with long duration and high intensity can cause serious marine ecological disasters and economic losses (Thomson *et al* 2015, Caputi *et al* 2016, Wernberg *et al* 2016, Frölicher and Laufkötter 2018), and are worthy of further attention.

The China Seas are one of the largest shelf seas of the world (its area is more than twice the size of the North Sea), with rich marine ecosystems and fishing grounds. As a warming hotspot where the warming rate has been considerably faster than the global average, the China Seas are more vulnerable, suffering from more frequent, longer lasting and stronger hot extremes (Belkin 2009, Wu *et al* 2012, Oliver *et al* 2018). Given the slowdown of GMST, it remains unclear what changes of annual or seasonal mean SSTs and extreme SSTs have occurred in this region and whether they are, and how if so, affected by the warming hiatus. After a wave of scientific publications and public debate, with GMSTs setting new records again after 2014 (World Meteorological Organization (WMO) 2019), it is time to take stock of what can be learned from the warming hiatus in the China Seas.

In this paper, we analyze the changes of annual mean SST and extreme warm SST events in the China Seas in the past decades, with an emphasis on the context of global warming hiatus. Data sets and methods are described in sections 2 and 3. Results are presented in section 4. Discussion on the causation and ecological impact of MHWs is given in section 5, and conclusions are shown in section 6.

2. Study region and data sets

2.1. Study region

The China Seas, including the Bohai Sea, the Yellow Sea, the East China Sea, the South China Sea, are bounded by mainland China, the Ryukyu (Nansei) Islands and the Korean Peninsula. The study region also covers a vicinity of the China Seas to show a better perspective for the analyzed SST variability, for example, the SST variability in the Kuroshio in the East China Sea. Thus, we approximated the area at (15°–45°N, 105°–130°E) (figure 1).

2.2. Data

The NOAA daily Optimum Interpolation (OI) SST v2 with high resolution (0.25° by 0.25°) in length (1982–2018) (OISST v2, Banzon *et al* 2016) was used to detect the warming hiatus at the China Seas. For comparison purposes, we also used other three global gridded monthly mean SST data sets with a horizontal resolution of 1° by 1° in the same period as OISST v2. The monthly mean SST data sets are from the Hadley Centre Sea Ice and SST data set (HadISST, Rayner *et al* 2003), the Centennial Observation-Based Estimates of SST version 2 (COBE SST2, Hirahara *et al* 2012) and the International Comprehensive Ocean-Atmosphere Data Set-SST section (ICOADS SST, Woodruff *et al* 2011). Due to the high spatial and temporal resolutions, OISST v2 is recommended for evaluating water extremes. The suitability of the database to identify extreme events was previously confirmed in literature (Lima and Wethey 2012, Oliver *et al* 2017, Benthuysen *et al* 2018). Statistical analyses of extreme SSTs and MHWs in our study were both based on this data set.

3. Methods

3.1. Extreme SSTs and marine heat wave (MHW)

In our study, the 90th (10th) percentile SST in each year (referred to as 90th (10th) SST) is used for the annual threshold of extreme hot (cold) SSTs, rather than the 95th (5th) or 99th (1th), so as to allow for the robust detection by applying a greater number of extreme SSTs. Daily SST anomalies are calculated to remove the seasonal cycle. This is achieved by subtracting from the SST of a certain day (e.g. January 1, 1982) the mean temperature of that day (January 1) over the climatic period 1983–2012.

We used the definition of Hobday *et al* to identify and quantify marine heatwaves (MHWs). In this definition, a MHW is defined as a discrete prolonged anomalously warm water event at a particular location. Specifically, 'discrete' implies the MHW is an identifiable event with clear start and end dates and 'prolonged' means it persists at least five consecutive EHDs. Here, the marine EHD was a day when daily temperature was above a defined threshold. The threshold was taken to be the seasonally varying 90th percentile climatology, following the recommendation of Hobday *et al* (2016). The climatological threshold and the mean were calculated for each calendar day of the year using daily temperature values across all years and within an 11-day window centered on the day, and were then smoothed using a 31-day moving window. The use of a seasonally-varying threshold allows for the detection of summer MHW as well as winter warm spells, both of which can have ecological impacts. This definition has been implemented in Python (available from https://github.com/ecjoliver/marineHeatWaves, also see Hobday *et al* 2016).

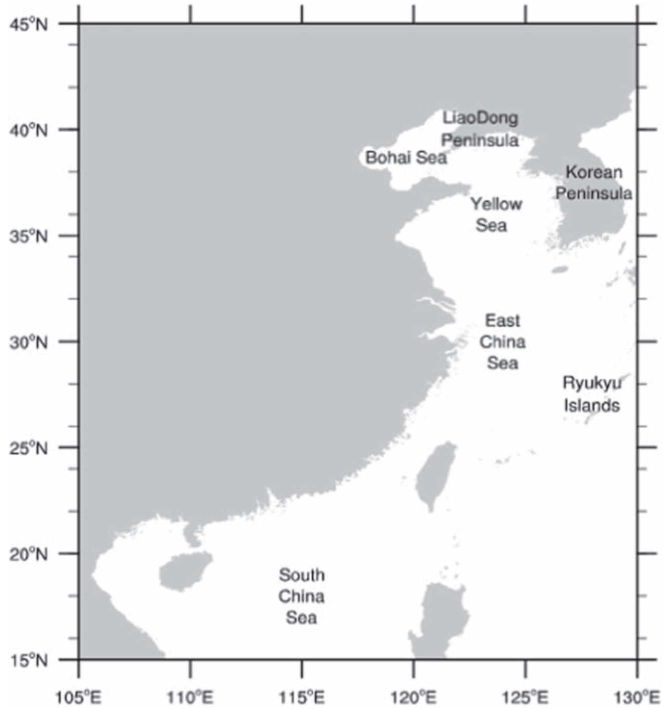

Figure 1. The location of the Bohai Sea, the Yellow Sea, the East China Sea, the South China Sea and the adjacent seas.

In our study, daily SSTs were spatially averaged over the China Seas (15°–45°N, 105°–130°E) to generate a regional daily SST time series covering 1982–2017. The MHW definition was then applied to the SST time series to detect all the MHWs in the China Seas. Following Oliver *et al* (2018), the implication of spatially averaging SSTs and then performing the MHW calculation, as opposed to detecting MHWs directly from the pixel-based data, can smooth away some of the high-frequency variability and thereby slightly increase average MHW duration at the expense of annual frequency. Annual statistics were then calculated including the frequency of events (i.e., the number of discrete events occurring in each year), mean annual duration and mean annual cumulative intensity. Here, 'duration' was the time between the event's start and end dates, 'maximum intensity' was the maximum temperature anomaly (measured relative to the climatological, seasonally-varying mean) over the duration of the event, and 'cumulative intensity' was the integrated temperature anomaly over the duration of the event, where units were °C days (more details in the table 2 of Hobday *et al* 2016).

3.2. Statistical methods

We used a nonparametric Kendall's tau based Sen's slope estimator (Sen 1968) to calculate trends, since the method does not assume a distribution for the residuals and thus is insensitive to the effect of outliers in the series, and it has been widely used in the studies of hydrological and extreme climate change. The significance of the Sen's slope was judged by using Mann-Kendall test method. A trend was considered to be statistically significant if it was significant at the 5% level ($p < 0.05$).

4. Results

4.1. Warming hiatus in the China Seas

The annual mean SSTA time series from four independent SST datasets are shown in figure 2(a). As a regional average, all of the four SSTA time series agree well during 1982–2013. Based on the observational evidence, SST over the China Seas switched from a previously accelerated warming period to a recent warming hiatus since 1998. There was a decreasing tendency in the accelerated warming period and an increasing tendency in the warming hiatus in the four accumulated SSTA series (figure 2(b)). We detected a significant temporal breakpoint at 1997/1998 in the four time series in the satellite era from 1982 to 2013 (figure 2(b)). Because of the shortness of the hiatus period, significance testing of the trends has limited relevance. Still, over the 16-year period from 1998 to 2013, decreases in ICOADS R2.5 SST, HadISST1, COBE SST2 and OISST are all significant at the 5% level (Mann–Kendall test), with the respective rates of −0.26, −0.24, −0.32, −0.37 °C per decade. Therefore, there was a remarkable shift in 1998 and the warming hiatus indeed existed in the China Seas. Moreover, during the warming hiatus, the annual mean SST over the China Seas experienced notable cooling. This remarkable hiatus phenomenon at the China Seas has shifted synchronously with the warming hiatus of GMST and mainland China (Trenberth *et al* 2014,

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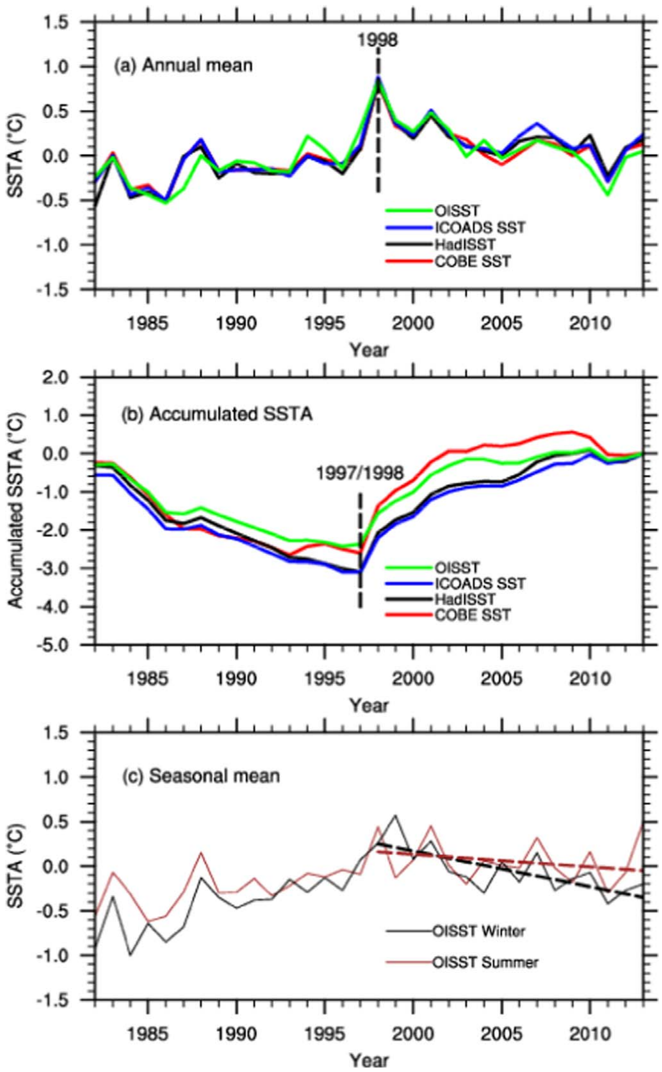

Figure 2. (a) Time series of the regional averaged annual mean SST anomalies (SSTAs) in the China Seas (15°–45°N, 105°–130°E) from COBE SST (red), HadISST1 (black), ICOADS R2.5 SST (blue) and OISST v2 (green) for period 1982–2013. (b) The same as (a), but for long-term variation of the accumulated anomalies. The black dashed line refers to their corresponding climate-jump year. (c) Time series of the regional averaged seasonal mean SSTAs in summer (brown line) and winter (black line) from OISST v2 during 1982–2013. The brown and black dashed lines are the linear trends based on the least squares estimator for 1998–2013 in summer and winter respectively. Anomalies are relative to the average of 1983–2012.

Duan and Xiao 2015, Xie *et al* 2017). Since 1998, the PDO switch from warm phase to the cool phase. The previously accelerated warming period in the China Seas was in the period when PDO was in the strong positive phase. The recent warming hiatus after 1998 was basically consistent with the period when PDO entered into its negative phase (figure omitted). Studies found that the PDO were suggested to influence the East Asian winter monsoon (EAWM) and deepening of East Asian trough (EAT), especially for the interdecadal variability (Ding *et al* 2014, Wang and Chen 2014, Xie *et al* 2017), which suggested the possible connections between the enhanced EAWM during the warming hiatus with the negative phase of PDO.

In our study, we find that the cooling tendency is not homogeneous or asymmetric in seasonal scale. Seasonally, the winter SSTA has experienced a significant cooling trend since 1998, while there is a slightly decreasing (trend very close to zero) in summer (figure 2(c)). Because the four SST gridded datasets displayed similar results, we just show the seasonal SST anomalies series during 1982–2013 from OISST v2. Previous studies reported that the most hiatus in global or regional warming was a seasonal phenomenon, prevalent in boreal winter (Cohen *et al* 2012, Trenberth *et al* 2014, Sun *et al* 2017). Figure 2(c) indicates that the annual mean SST decrease in the China Seas is also primarily from the contribution of cooling in boreal winter rather than in summer. The cooling of the winter SST during 1998–2013 is probably related to the combined influence from the recent strengthening of EAWM, weakening of Arctic oscillation (AO) and deepening of EAT (You *et al* 2013, Ding *et al* 2014, Sun *et al* 2017).

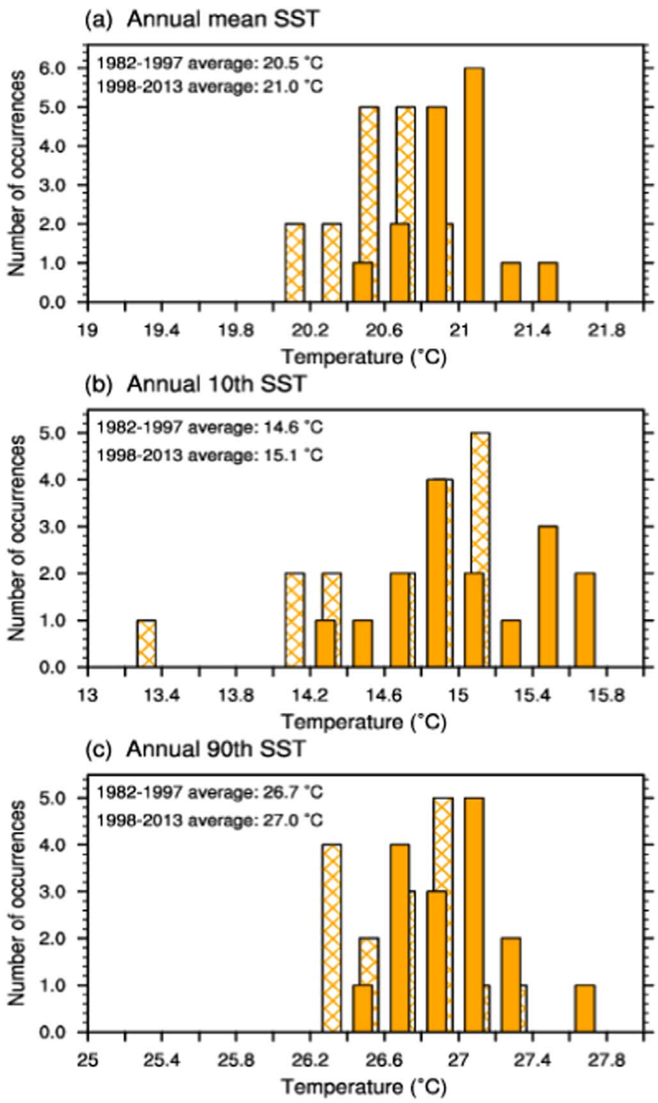

Figure 3. The regional averaged annual mean SST (a), 10th SST (b) and 90th SST (c) histograms for two periods: 1982–1997 (hatched bars) and 1998–2013 (orange bars).

4.2. Changes in extreme SST and MHWs

The statistical occurrences of the regional averaged annual mean SST, annual 10th SST and 90th SST at the 16-year periods are displayed in figure 3 for 1982–1997 (hatched bars) and 1998–2013 (orange bar). Although annual mean SST experienced a warming hiatus after 1998, the average SST for 1998–2013 (21.0 °C) is still 0.5 °C above that for 1982–1997 (20.5 °C) (figure 3(a)). All of these SST metrics appear to have remarkably shifted upward a warmer climate during the hiatus. The mean increase is higher for the 10th SST as it has shifted by 0.5 °C (from 14.6 °C to 15.1 °C) (figure 3(b)), compared to the shifting of the 90th SST by 0.3 °C (figure 3(c)).

The mean warming during 1998 to 2013 was also accompanied by changes in temperature extremes. The statistical occurrences of the regional average daily SST anomalies in 1982–1997 and 1998–2013 are illustrated in figure 4. Warm SSTAs (exceeding 90th percentile) that occurred around 2% of the total SSTAs during the period 1982–1997, occurred over 15% of the total SSTAs during the period 1998–2013 (figures 4(a), (b)). There are more frequent occurrences of warm SSTAs surpassing the threshold during warming hiatus. Compared to the significantly decreasing of cold SSTAs (below 10th percentile), the warm SSTAs experienced a general increase, and even the very hot SSTAs (exceeding 99th percentile) in annual and seasonal scales have occurred. Specially, the very cold SSTAs (below 1th percentile) disappeared in winter and summer and warm SSTAs have become common in winter after 1998 (figures 4(d), (f)). A more pointed and higher peak indicates the temperature closely around the mean value in winter and summer (figures 4(c), (e)), but the occurrences become more dispersed with the increase of warm events (figures 4(d), (f)).

As illustrated in figure 4, the hot regional average daily SST anomalies have greatly increased during 1998–2013. It indicated that more MHWs probably

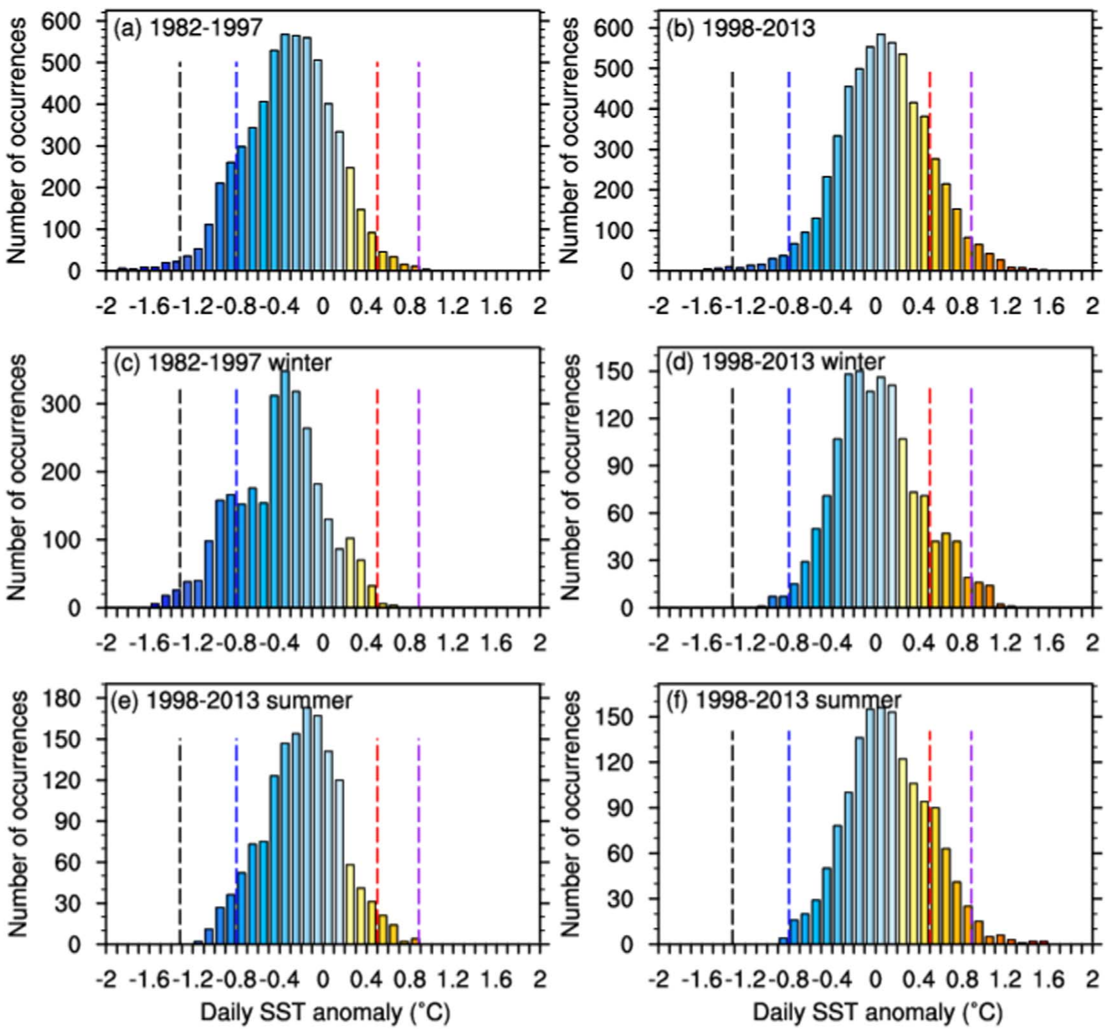

Figure 4. The daily mean SSTAs histograms for 1982–1997 (left) and 1998–2013 (right) for the whole year (a), (b), winter (c), (d) and summer (e), (f). The red and purple dashed line represents the 90th percentile and 99th percentile of climatological period (1983–2012). The blue and black dashed line represents the 10th percentile and 1th percentile of the climatological period 1983–2012.

occurred over the later period. Referring to Hobday *et al* (2016) (see Methods), we examined changes of regional average MHW with frequency, duration, and cumulative intensity during 1982–2013 (figure 5). An obvious ascending trend can be observed in all of the three metrics. As a regional average, annual mean MHW frequency significantly increased from about 0.5 events per year during 1982–1997 to 3.4 events per year during 1998–2013 (5.8 times increased). The regional averaged time series also showed general increases in MHW duration from about 4.8 EHDs to 11.8 EHDs (1.75 times increased), and cumulative intensity from 3.0 °C days to 9.8 °C days (2.27 times increased). It shows that, on average, not only was there no decrease in the frequency of MHWs over the China Seas during the global warming hiatus but the MHWs had already become more long-lasting, frequent and intense than those before 1997. Moreover, MHWs frequency in the China Seas increased significantly with a trend of 1.13 events per decade ($p < 0.01$), 2.5 times the global average rate (0.45 events per decade, Oliver *et al* 2018) in the same period of 1982–2016.

Three better-known MHW regions, Western Australia, the Mediterranean Sea and northwest Atlantic, have experienced 59, 70 and 67 MHWs during 1982–2014 (Hobday *et al* 2016). During the same period, a total of 65 events were also identified in the China Seas. Results suggest that, as a part of western boundary current extension region, the China Seas probably are also the high-risk region suffering from more frequent, longer lasting and stronger MHWs in the past decades. The latest studies show that, from 1925 to 2016, global average marine heatwave frequency and duration increased by 34% and 17% which largely is explained by increases in mean ocean temperatures (Frölicher *et al* 2018, Oliver *et al* 2018). Consistent with the previous works, the regional annual mean SST and mean MHW frequency, duration and the cumulative intensity over the China Seas are strongly correlated ($r_a = 0.83$; $r_b = 0.70$; $r_c = 0.72$, $p < 0.01$), with the highest correlation

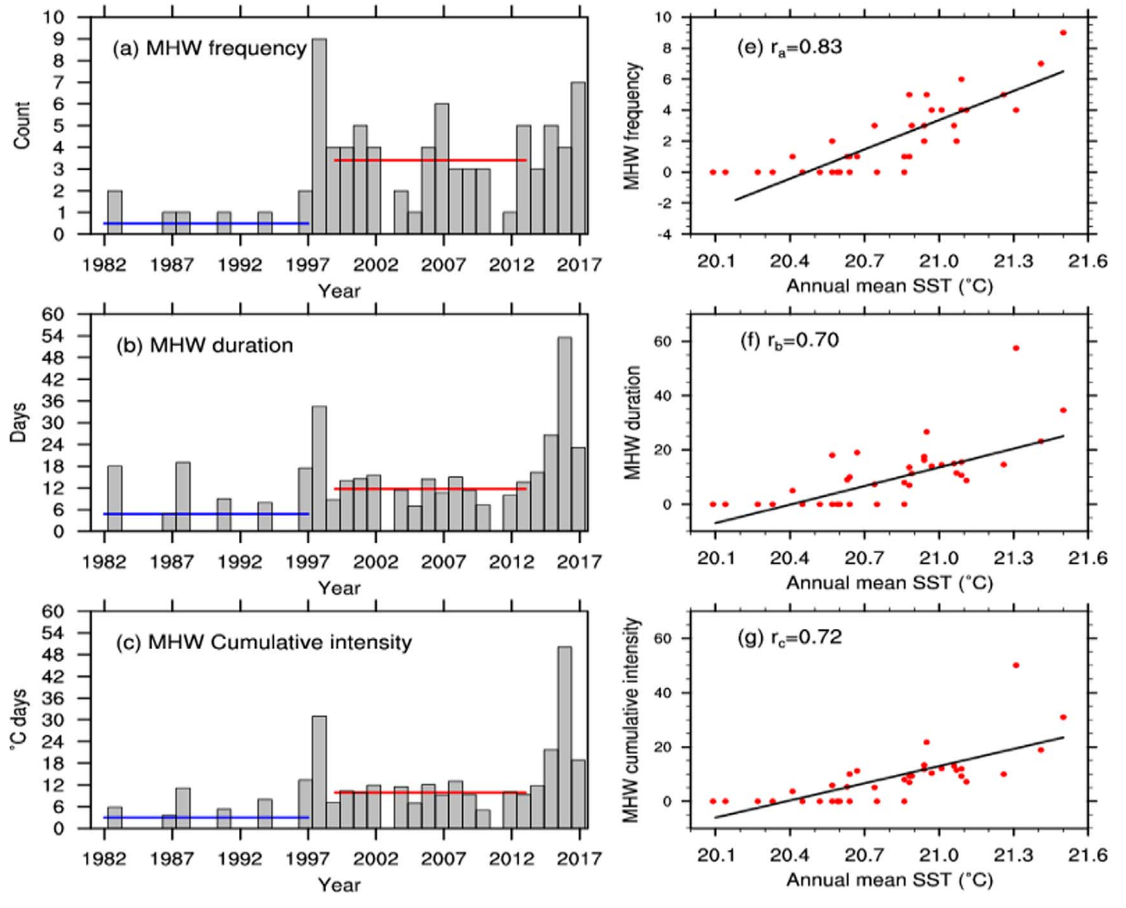

Figure 5. Regional averaged annual mean MHW frequency (a), duration (b) and cumulative intensity (c), and scatter plots of annual mean SST and MHW frequency (e), duration (f), and cumulative intensity (g), over the China Seas during 1982–2017. Red lines show the mean value over 1998–2013, blue lines show the mean value over 1982–1997, and black lines show the best-fit linear curve.

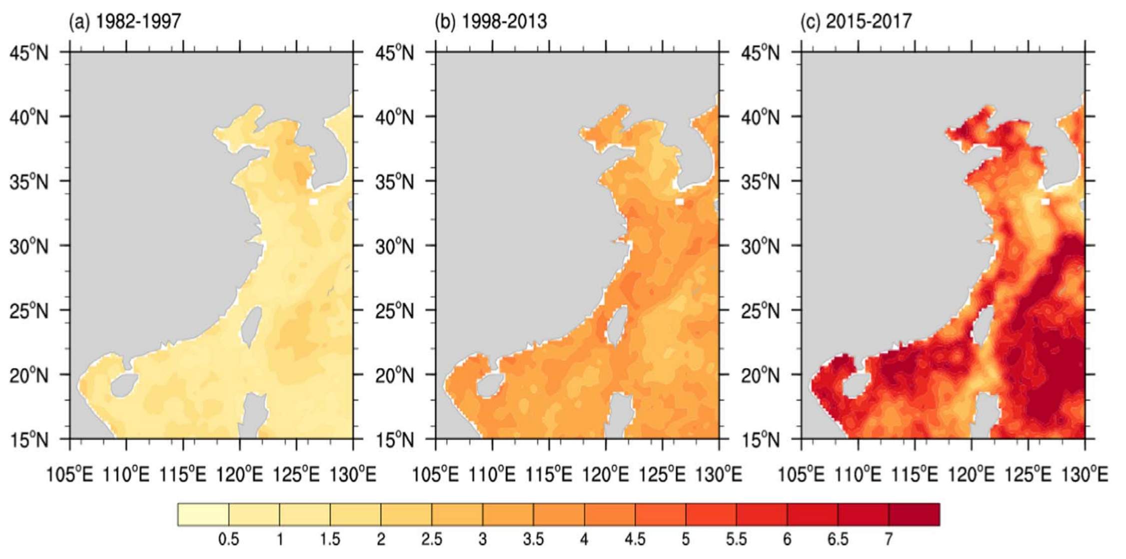

Figure 6. Annual mean MHWs frequency during the period of 1982–1997 (a), 1998–2013 (b) and 2015–2017 (c) in the China Seas.

found between SST and MHW frequency (figures 5(e)–(g)).

Spatial distributions of annual mean MHWs over different periods are shown in figure 6. The annual mean occurrences of MHWs ranged from about 0 to 2 events, depending on location (figure 6(a)). During 1998–2013, MHW frequency increased considerably across the whole China Seas (figure 6(b)), reaching 2 to 3 events on average. The larger increase occurred in the coastal areas of the China Seas and along the Kuroshio Current axis.

5. Discussion

While the characteristics, mechanisms and impacts of terrestrial heatwaves have been well explored, MHWs over the China Seas are generally understudied. In this work, we analyze the spatial and temporal pattern of the change in means and extreme events of SST in the China Seas. Analysis shows a significant increase in MHWs in the China Seas during 1998–2013. The increase is basically consistent with those reported for other oceanic regions. A recent study confirmed that an extreme strong and prolonged El Niño occurred during 2015–2016 and it probably ended the global warming hiatus (Hu and Fedorov 2017). Despite the warming hiatus, the globally mean temperatures of most years since 1998 were the warmest on record as the long-term warming trend continues; the frequency and intensity of both terrestrial and oceanic extreme events are also increasing globally (Herring *et al* 2019, World Meteorological Organization WMO (2019)). The more occurrences of extreme hot SSTAs are related to both rising mean temperatures and climate variability; the former would be the dominant driver of the increasing frequency of MHWs over most of the global ocean (Oliver 2019). In the China Seas, the regional mean SSTs 20.5 °C for 1982–1997, but 21.0 °C, for 1998–2013 following with 2015–2017, with the value of 21.2 °C. The regional mean SSTs were continuously rising in the three periods, though there was a warming hiatus during 1998–2013. The warm-side toward shift in mean temperature could be causing the increased MHWs.

Meanwhile, these events could be also influenced by additional processes. In this discussion, given the atmospheric priming of the MHW, we preliminarily analyzed the possible relationship between the warming and the large-scale atmosphere circulation modes. The Western North Pacific Subtropical High (WNPSH) indices of area and intensity have notably increased during 1982–2013, and the western edge of the WNPSH ridge has experienced a westward expansion (figure is omitted). The strengthening and westward extension of the WNPSH could cause strong descending motion and have contributed considerably to the surface warming in the study region. Thus, warming SST observed during 1982–2013 is probably related to the influence from the recent changes in the WNPSH. Meanwhile, it is also found that 500-hPa geopotential height (HGT500) exhibited a significant enhancing trend around Lake Baikal, which implies that the Baikal Ridge has been intensifying during the past decades (figure omitted). Influenced by this circulation pattern, the East China Seas was behind the deepened East Asian trough and before the enhanced Baikal Rridge, and therefore the descending movement and the northwesterly in the upper level were prevailing, which brought clear skies and more surface net solar radiation, was favorable for the abnormal hot and dry extremes (Wang *et al* 2017).

Besides, MHWs can also be affected by low-frequency oceanic modes, including the PDO, ENSO, and Indian Ocean dipole (IOD) (Benthuysen *et al* 2018, Oliver *et al* 2018, Tan and Cai 2018). However, there remain complex physical mechanisms between changes of large-scale atmospheric and oceanic systems and MHWs. These physical mechanisms are complicated by local processes, including the Yangtze River discharge, Kuroshio Current, Taiwan Warm Current, etc. (Wu *et al* 2012, Cai *et al* 2017, Pei *et al* 2017). Determining these causal factors, including anthropogenic forcing and natural variability modes, is still an area of ongoing research. → Copy 하자.

Spatially, in the period 2015–2017, much more MHWs occurred annually in the western China Seas, almost 2–4 more events annually than those occurred in the period before 2014 (figure 6(c)). Studies point out that MHWs will very likely become more common and more intense under future global warming (Frölicher *et al* 2018, Oliver *et al* 2018). Whatever the underlying causes are, the observed and expected increase of MHWs in the China Seas would exert a non-negligible impact on the marine ecosystem. Recently, the observed MHWs in the China Seas, especially in the western China Seas and the Yellow Sea have caused huge economic losses through impacts on fisheries and aquaculture. The 'Zhangzi Island scallops event in 2017' and 'Sea cucumber mortality event in 2018' are the two well-known marine fishery disasters. In July and August 2017, exceptionally warm SSTAs occurred at the northern Yellow Sea, with the temperature anomalies >1.0 °C covering approximately 5.8×10^5 km^2 (figure 7(a)). The northern Yellow Sea 2017 MHW lasted for 60 days from 30th June to 28th August (figure 7(b)). The date of the peak was 20th July with a maximum daily SSTA of 2.93 °C (figure 7(c)). The cumulative intensity of the event was up to 115 °C days. This local MHW was unprecedented as the longest event on record in this region, and it probably exceeded the marine ecosystem tolerance limits. This MHW event was considered as one of the most important factors leading to the mass emaciation and mortality of filter/suspension-feeding scallops (*Patinopecten yessoensis*) in Zhangzi Island (39.05°N, 122.75°E) in the 'Zhangzi Island scallops event in 2017'.

The impacts of these MHWs can be compared and contrasted with other major events that have occurred abroad recently. For example, the Tasman Sea 2015/16 MHW appeared to be restricted to sessile, sedentary or cultured species in the shallow coastal near-shore environment including outbreaks of disease in commercially viable species (Oliver *et al* 2017). The Alaskan Sea 2016 MHW favored some phytoplankton species, leading to harmful algal blooms, shellfish

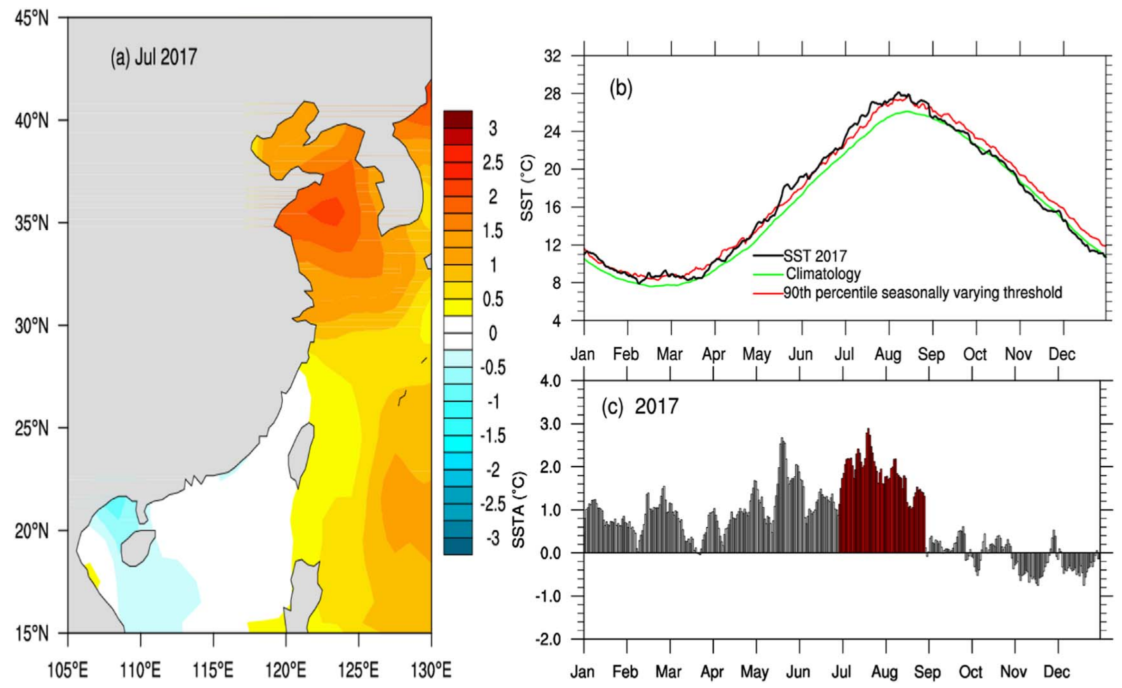

Figure 7. Pattern of monthly mean SST anomalies (SSTAs) from NOAA OISST v2 in July 2017 (a); domain-averaged SST time series for the northern Yellow Sea (30°–40°N, 117°–128°E), the 90th percentile seasonally varying threshold (red), and the climatology (green) (b); domain-averaged SST anomalies for the northern Yellow Sea (30°–40°N, 117°–128°E) (bar), with the red shaded regions indicating the northern Yellow Sea 2017 MHW detected using the definition of Hobday *et al* (2016) (c).

poisoning events and mortality events in seabirds (Walsh *et al* 2018). The examples described above indicate that a range of organisms and ecosystems can be impacted by MHWs. Considering the emerging risks from MHWs, we emphasize the importance of planning for strategies in the context of increased and intense MHWs in the China Seas. It is necessary and essential to take a more proactive approach to reduce the negative consequences of MHWs on food production from aquaculture and other marine ecosystems, such as setting up an early warning system and a seasonal prediction system.

6. Conclusions

We analyze the characteristics of the change in SST and MHWs in the China Seas, by using four global gridded SST data sets. One of the key findings of the analysis is that there is a remarkable warming shift in 1998 over the China Seas, which is consistent with change in GMST. During 1998–2013, the annual mean SST exhibits a declining tendency in the China Seas, with the rates at the range of $-0.37 \sim -0.24$ °C per decade. The annual mean SST declining after 1998 was mainly controlled by the remarkable cooling in boreal winter.

Importantly, despite the recent warming hiatus in the China Seas, the regional average annual mean SST for 1998–2013 is unexpectedly 0.5 °C above that for 1982–1997. The statistical distributions manifest that warm SSTAs and very hot SSTAs increased as the China Seas' mean climate shifts towards warmer during 1998–2013. Further analysis in this study finds that, not only there is no decrease in MHWs over the China Seas during the global warming hiatus, but actually they have become more frequent, intensive and longer during 1998–2013 compared to those during 1982–1997. In terms of spatial distribution, more frequent MHWs occurred in the coastal areas of the China Seas and along the Kuroshio Current axis during the warming hiatus, with the increase reaching two to three events annually.

Further investigation is needed to understand the underlying causes and the possible impacts of the observed increase in MHWs. In particular, we emphasize the importance of adaptation for local people to reduce the negative consequences of MHWs on fisheries, aquaculture and marine ecosystems.

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References

Banzon V, Smith T M, Chin T M, Liu C and Hankins W 2016 A long-term record of blended satellite and *in situ* sea-surface temperature for climate monitoring, modeling and environmental studies *Earth Syst. Sci. Data* **8** 165–76

Belkin I M 2009 Rapid warming of large marine ecosystem *Prog. Oceanogr.* **81** 207–13

Benthuysen J, Oliver E C J, Feng M and Marshall A G 2018 Extreme marine warming across Tropical Australia during austral summer 2015–2016 *J. Geophys. Res.* **123** 1301–26

Cai R S, Tan H J and Kontoyiannis H 2017 Robust surface warming in offshore China Seas and its relationship to the East Asian Monsoon wind field and ocean forcing on interdecadal time scales *J. Clim.* **30** 8987–9905

Caputi N *et al* 2016 Management adaptation of invertebrate fisheries to an extreme marine heat wave event at global warming hot spot *Ecol. Evol.* **6** 3583–93

Chen K, Gawarkiewicz G G, Lentz S J and Bane J M 2014 Diagnosing the warming of the Northeastern US Coastal Ocean in 2012: a linkage between the atmospheric jet stream variability and ocean response *J. Geophys. Res.* **119** 218–27

Cohen J L, Furtado J C, Barlow M, Alexeev A and Cherry J E 2012 Asymmetric seasonal temperature trends *Geophys. Res. Lett.* **39** L04705

Ding Y *et al* 2014 Interdecadal variability of the East Asian winter monsoon and its possible links to global climate change *J. Meteor. Res.* **28** 693–713

Duan A and Xiao Z 2015 Does the climate warming hiatus exist over the Tibetan Plateau? *Sci. Rep.* **5** 13711

Frölicher T L, Fischer E M and Gruber N 2018 Marine heatwaves under global warming *Nature* **560** 360–4

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

Garfinkel C L, Son S W, Song K, Aquila V and Oman L D 2017 Stratospheric variability contributed to and sustained the recent hiatus in Eurasian winter warming *Geophys. Res. Lett.* **44** 374–82

Garrabou J *et al* 2009 Mass mortality in Northwestern Mediterranean rocky benthic communities: effects of the 2003 heat wave *Glob. Change Biol.* **15** 1090–103

Guan X, Huang J, Guo R and Lin P 2015 The role of dynamically induced variability in the recent warming trend slowdown over the Northern Hemisphere *Sci. Rep.* **5** 12669

Herring S C, Christidis N, Hoell A, Hoerling M P and Stott P A 2019 Eds Explaining extreme events of 2017 from a climate perspective *Bull. Amer. Meter. Soc.* **100** S1–117

Hirahara S, Ishii M and Fukuda Y 2012 Centennial-scale sea surface temperature analysis and its uncertainty *J. Clim.* **27** 57–75

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

Hu S and Fedorov A V 2017 The extreme El Niño of 2015–2016 and the end of global warming hiatus *Geophys. Res. Lett.* **44** 3816–24

IPCC 2013 Climate change 2013: the physical science basis *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* (Cambridge: Cambridge University Press) p 1535

Kosaka Y and Xie S P 2013 Recent global-warming hiatus tied to equatorial Pacific surface cooling *Nature* **501** 403–7

Lewandowsky S, Risbey J S and Oreskes N 2015 On the definition and identifiability of the alleged 'hiatus' in global warming *Sci. Rep.* **5** 16784

Li Q *et al* 2015 China experiencing the recent warming hiatus *Geophys. Res. Lett.* **42** 889–98

Lima F P and Wethey D S 2012 Three decades of high-resolution coastal sea surface temperature reveal more than warming *Nat. Commun.* **3** 704

Medhaug I *et al* 2017 Reconciling controversies about the 'global warming hiatus' *Nature* **545** 41–7

Meehl G A, Hu A, Arblaster J M, Fasullo J and Trenberth K E 2013 Externally forced and internally generated decadal climate variability associated with the Interdecadal Pacific Oscillation *J. Clim.* **26** 7298–310

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

Oliver E C 2019 Mean warming not variability drives marine heatwave trends *Clim. Dyn.* **53** 1653–9

Pei Y H, Liu X H and He H L 2017 Interpreting the sea surface temperature warming trend in the Yellow Sea and East China Sea *Sci. China Earth Sci.* **60** 1558–68

Rayner N A, Parker D E, Horton E B, Folland C K, Alexander L V, Rowell D, Kent E C and Kaplan A 2003 Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century *J. Geophys. Res.* **108** 4407

Sen P K 1968 Estimates of regression coefficient based on Kendall's tau *J. Am. Stat. Assoc.* **63** 1379–89

Shen X J, Liu B and Lu X 2018 Weak cooling of cold extremes versus continued warming of hot extremes in China during the recent global surface warming hiatus *J. Geophy. Res. Atmos.* **123** 4073–87

Sun X B, Ren G Y, Ren Y Y, Liu Y L and Xue X Y 2017 A remarkable climate warming hiatus over Northeast China since 1998 *Theor. Appl. Climatol.* **9** 1–16

Sun Y *et al* 2014 Rapid increase in the risk of extreme summer heat in Eastern China *Nat. Clim. Change* **4** 1082–5

Tan H and Cai R 2018 What caused the record-breaking warming in East China Seas during August 2016? *Atmos. Sci. Lett.* **19** e853

Thomson J, Burkholder D D, Heithaus M, Fourqureen J, Fraser M, Statton J C and Kendrick G 2015 Extreme temperature, foundation species, and abrupt ecosystem change: an example from an iconic seagrass ecosystem *Glob. Change Biol.* **21** 1463–74

Tollefson J 2014 Climate change: the case of the missing heat *Nature* **505** 276–8

Trenberth K E, Fasullo J T, Branstator G and Phiilips A S 2014 Seasonal aspects of the recent pause in surface warming *Nat. Clim. Change* **4** 911–6

Walsh J E *et al* 2018 The high latitude marine heat wave of 2016 and its impacts on Alaska *Bull. Amer. Meteor. Soc.* **99** S39–43

Wang L and Chen W 2014 The East Asian winter monsoon: re-amplification in the mid-2000 s *Chinese Sci. Bull.* **59** 430–6

Wang S X, Yuan X and Li Y 2017 Does a strong El Niño imply a higher predictability of extreme drought? *Sci. Rep.* **7** 40741

Wernberg T *et al* 2016 Climate-drive regime shift of a temperature marine ecosystem *Science* **353** 169–72

Woodruff S D *et al* 2011 ICOADS Release 2.5: extensions and enhancements to the surface marine meteorological archive *Int. J. Climatol.* **31** 951–67

World Meteorological Organization (WMO) 2019 *WMO Statement on the State of the Global Climate in 2018.* (Switzerland) p 44

Wu L X, Cai W and Zhang L 2012 Enhanced warming over the global subtropical western boundary currents *Nat. Clim. Change* **2** 161–6

Xie Y, Huang J and Liu Y 2017 From accelerated warming to warming hiatus in China *Inter. J. Climatolo.* **37** 1758–73

You Q L, Ren G Y, Fraedrich K, Kang S, Ren Y Y and Wang P L 2013 Winter temperature extremes in China and their possible causes *Int. J. Climatol.* **33** 1444–55