



Classifications and Characteristics of Marine Heatwaves in the Northern South China Sea

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The classifications and associated characteristics of marine heatwaves (MHWs) in the northern South China Sea (SCS) have been investigated. Based on the ratio of the area with MHWs to the total area of the northern SCS, the MHWs are divided into three categories, i.e., narrow coverage, moderate coverage, and wide coverage. Different kinds of MHWs (i.e., narrow coverage, moderate coverage, and wide coverage) contribute around 64, 28, and 8% to the total days with MHWs, respectively. Narrow coverage MHW scatters over the northern SCS continental shelf, and moderate (wide) coverage MHWs are concentrated east of Hainan Island (mid of northern SCS continental shelf). Wide coverage MHWs contribute more than 50% to the total MHW cumulative sea surface temperature (SST) anomalies. The cumulative days and temperature anomalies of all kinds of MHWs exhibit significant long-term trends and decadal variability.

Keywords: northern South China Sea, marine heatwaves, classification of MHWs, long-term trends and decadal variability, probability of space occupancy

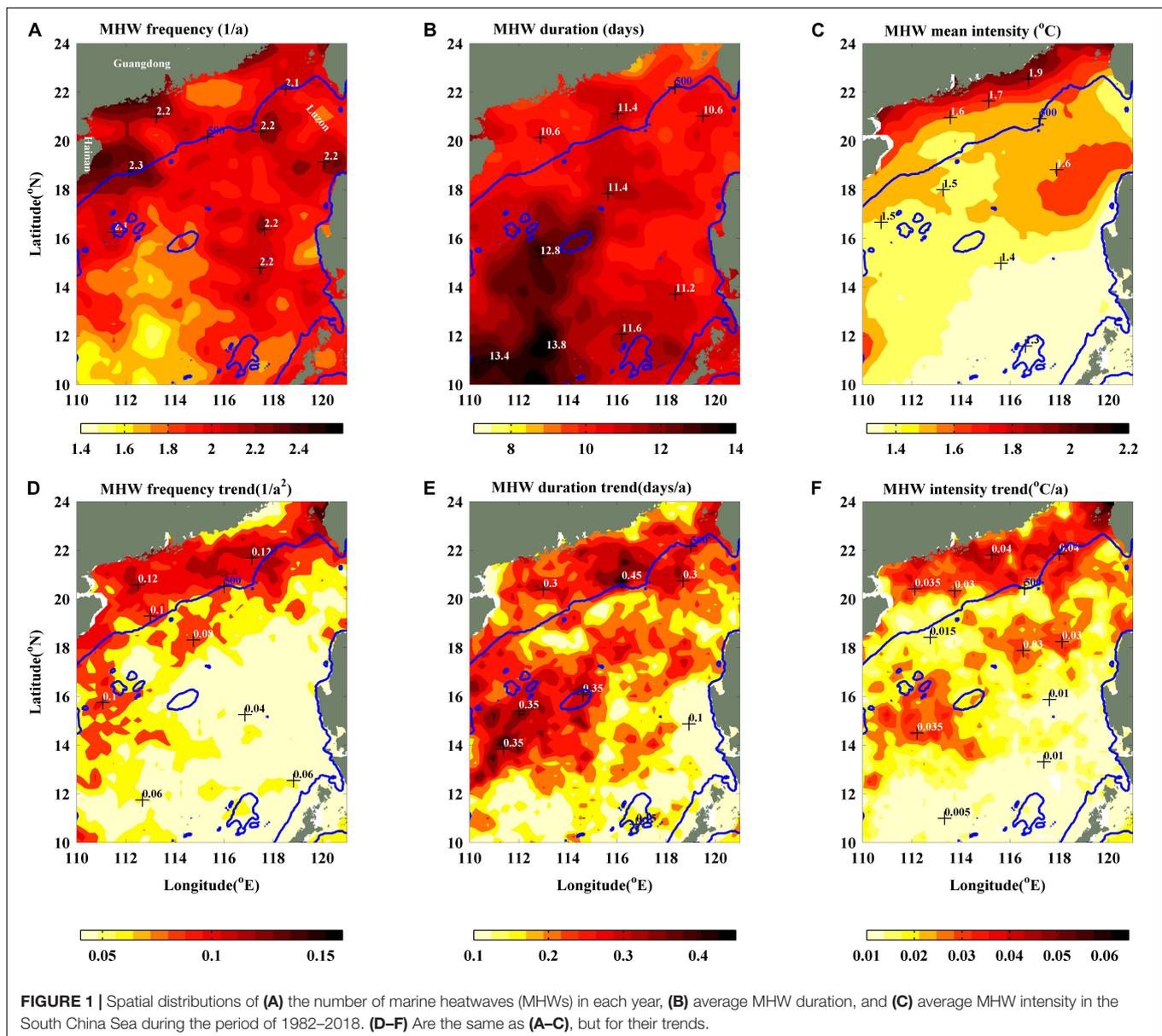
INTRODUCTION

Marine heatwave (MHW) is defined as an anomalously warm, discrete, and prolonged event, which has drawn great attention due to its extraordinary influences on ecosystem structure and functioning (Wernberg et al., 2013; Hobday et al., 2016; Gao et al., 2020). Many MHW events have been recorded, and they mainly occur off the coast (Garrabou et al., 2009; Feng et al., 2013; Mills et al., 2013; Bond et al., 2015; Oliver et al., 2017; Schlegel et al., 2017; Benthuisen et al., 2018; Tan and Cai, 2018; Gao et al., 2020). As a consequence of climate change, the frequency and intensity of MHWs in the world oceans are increasing (Hobday et al., 2018). Both the sea surface heat flux and the oceanic process can contribute to the generation and evolution of MHWs, and their contributions vary in different oceans (Chen et al., 2014; Schlegel et al., 2017). Like the northeast Pacific MHWs, the importance of the contribution of sea surface heat flux and vertical entrainment varies at different developmental stages (Chen et al., 2021a,b).

The South China Sea (SCS) is the largest semi-enclosed marginal sea, which connects the North Pacific and the East Indian Ocean. Due to the East Asian monsoon, SCS upper layer circulation exhibits distinct seasonal shifts (Qu et al., 2000; Gan et al., 2006; Wang et al., 2020a,b,c). Driven by the northeasterly winter (southwest summer) monsoon, a mature basin-scale cyclonic (anticyclonic) circulation is formed. Its sea surface temperature (SST) also presents a significant seasonal cycle, and air-sea heat flux plays a leading role while ocean circulation advection plays a secondary role (Qu, 2001). The SCS temperature interannual variability and long-term change have been widely studied, and the circulation advection effect is one of the major contributions (Wang, 2002; Liu et al., 2004, 2014; Xiao et al., 2018, 2020; Wang et al., 2021). Additionally, the surface heat fluxes are also key factors modulating the SST anomalies

in the SCS (Wu et al., 2014; Wang and Wu, 2021). However, the short-term extreme event-based research still lacks, and the short-term extreme events actually exert a more important influence on ecosystems due to substantially higher temperatures than normal temperature (Smith, 2011; Li et al., 2019), such as harmful algae blooms, which are closely related to extreme warm events or MHWs (Cai et al., 2016, 2017). Under global warming, there is a long-term increase of MHWs in marginal seas in China (Yao et al., 2020).

Recently, summer MHWs in the SCS have been reported (Yao and Wang, 2021). Under the influence of intensification of the western North Pacific subtropical high, upwelling in the mid-western SCS weakens and then causes basin-wide severe summer MHWs. Due to the MHWs in the SCS, the symbiotic relationship between corals and algae has been disrupted (Hughes et al., 2017;



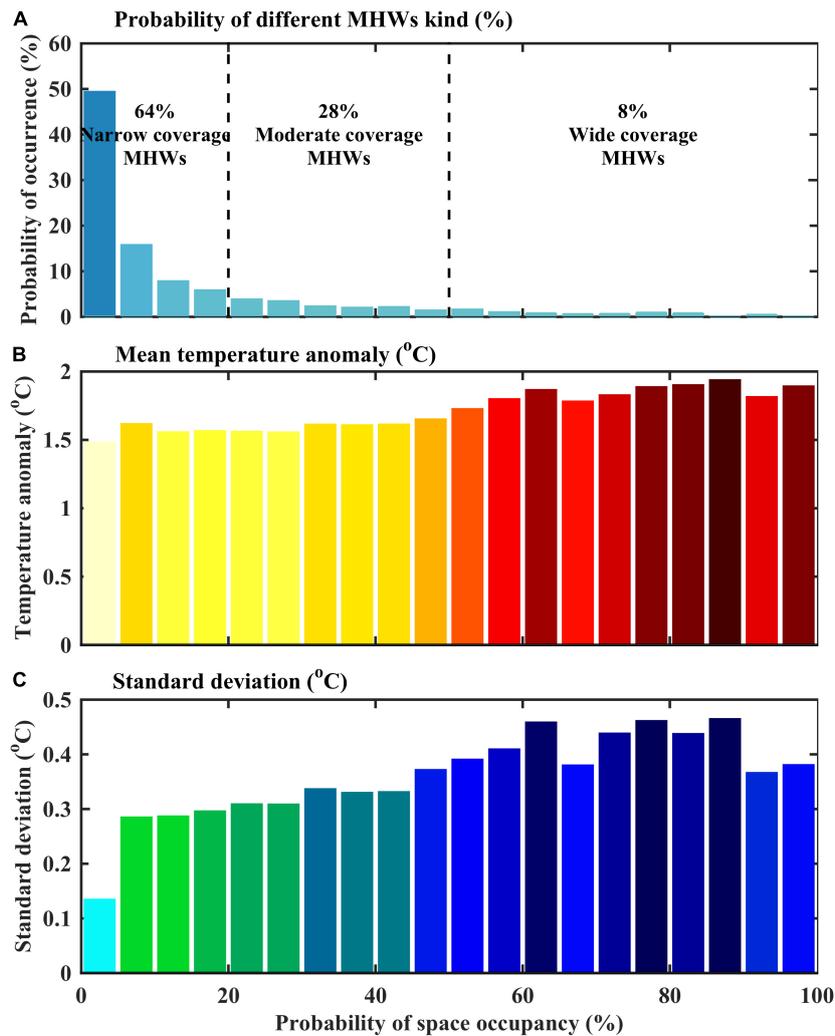


FIGURE 2 | (A) Occurrence probability of different MHWs, which is classified by the ratio of the area with MHWs to the total area of the northern South China Sea continental shelf bounded by the 500 m isobaths (see the text for the details of the definition). **(B)** Average sea surface temperature (SST) anomalies of different MHWs. **(C)** Average spatial SD of different MHWs.

Eakin et al., 2019). Then, the coral reefs in the SCS sharply declined (Zhang et al., 2017). Extreme warming of SCS can also modulate the Southern China winter rainfall (Wang et al., 2018).

Marine heatwaves in the SCS have not been widely studied earlier. Therefore, a detailed examination of the MHWs in the northern SCS is presented in this study, which will add to our knowledge of extreme events in the SCS and carry implications for ecological studies in the SCS.

DATA AND METHODS

Data

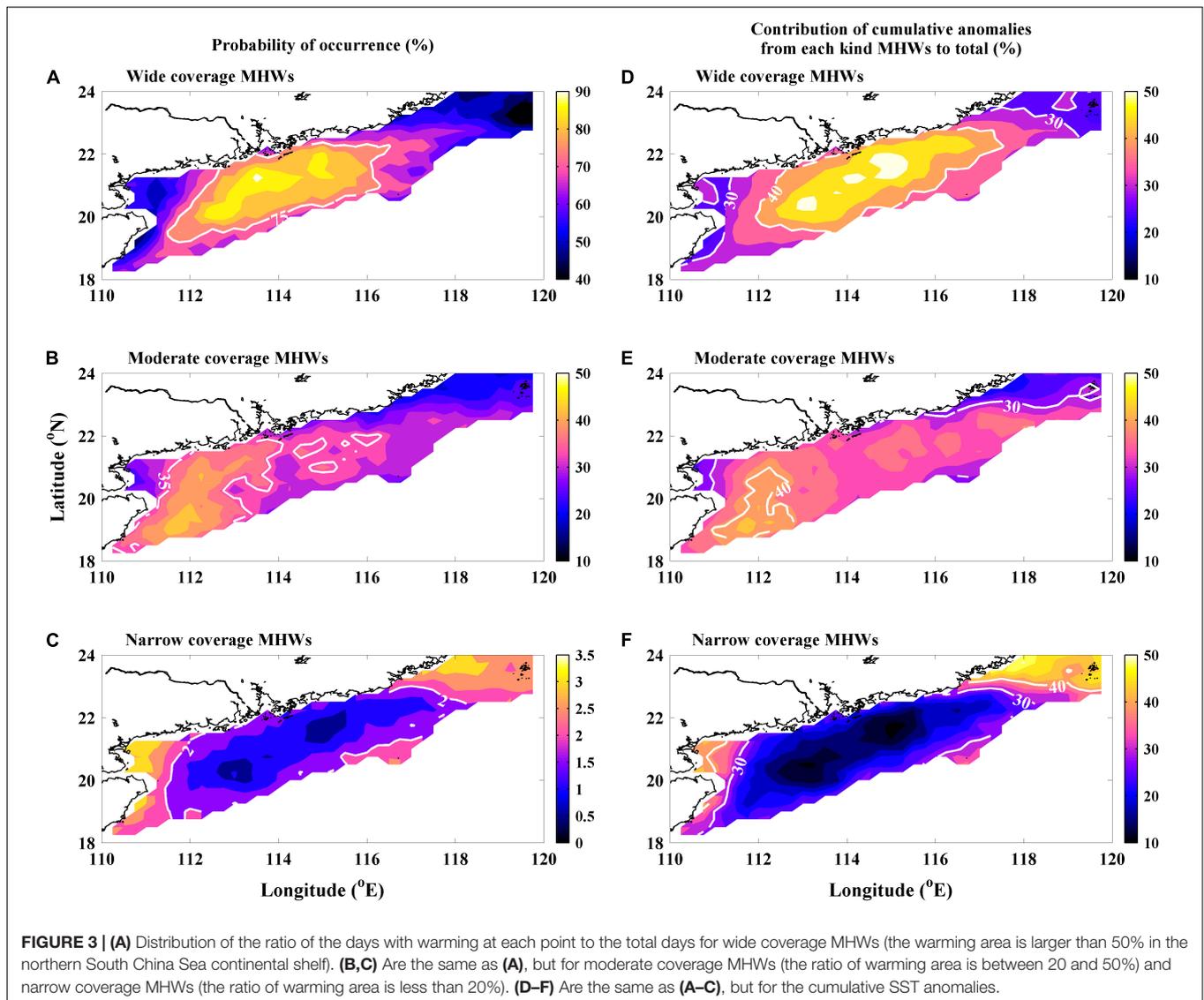
The SST data are obtained from the United States National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation SST (OISST) version 2 (Reynolds et al., 2007), which is a daily and $0.25 \times 0.25^\circ$ gridded product from Advanced

Very High-Resolution Radiometer (AVHRR) satellite data, with bias correction using ship and buoy data. The period 1982–2019 is used in this study. Since the SST anomaly basically obeys the Gaussian distribution, the raw SST data are utilized.

Definition of Indices

Following the study by Hobday et al. (2016), an MHW event is defined as warming exceeding the threshold lasting at least for 5 persistent days. The threshold is defined as the 90th percentile of the samples within an 11-day window centered on a specific day in all years. To measure the influence period of an MHW, a metric of duration was utilized. The duration is defined as the days between the start and end dates, and the intensity is the average of daily intensity anomalies relative to the climatology.

The northern SCS continental shelf is a whole area of shelf, geographically. However, MHW events do not fully occupy the entire continental at the same time. To evaluate its influence,



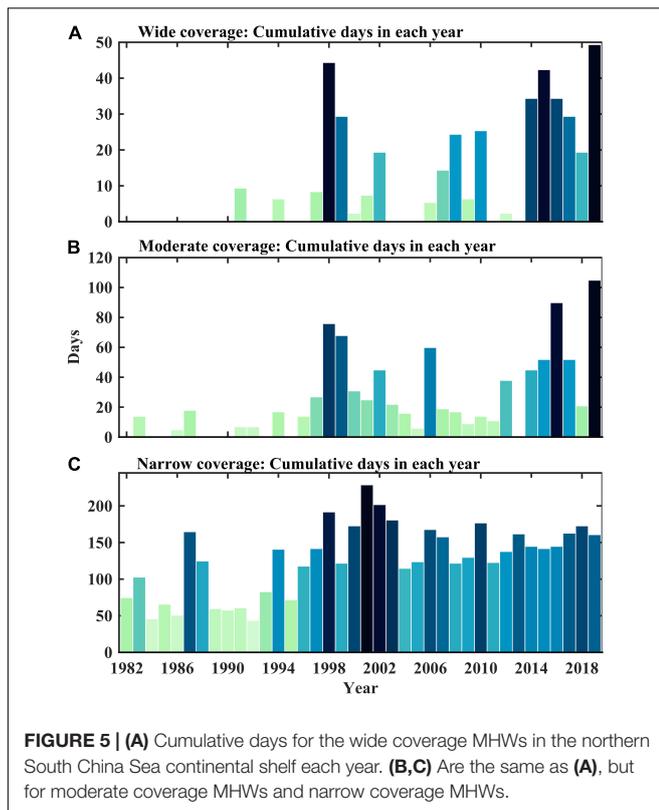
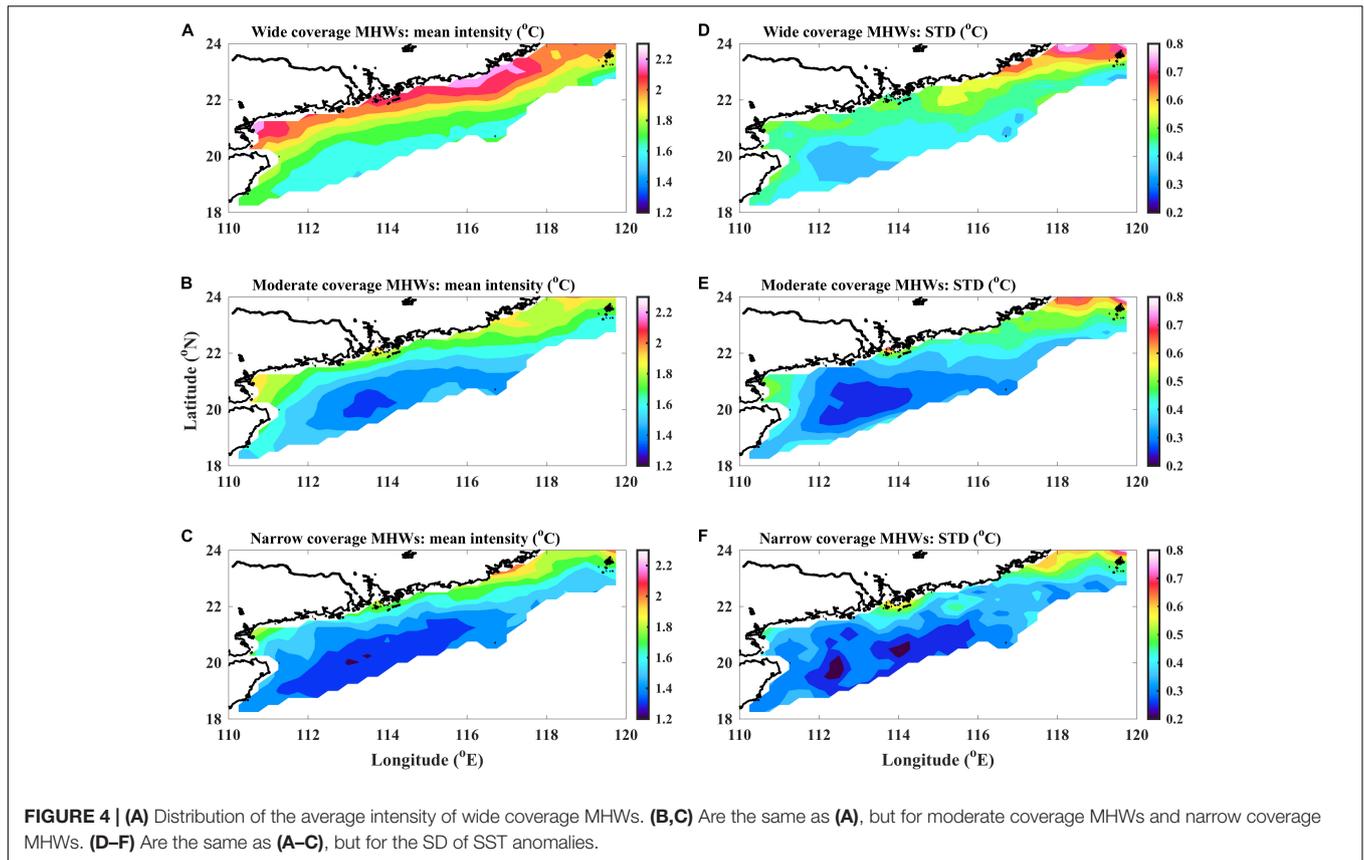
its space occupancy and associated characteristics need to be known. The probability of space occupancy (PSO) is defined as the percentage of MHW area in the total area in the northern SCS continental shelf every day (bounded by the 500 m-isobath, 110°E, and 24°N). The probability of occurrence with different PSOs is defined as the ratio of days within a range of PSO (5% is utilized in this article) to the total days with MHWs. Narrow coverage MHW day is defined as the PSO smaller than 20%, and moderate coverage MHW day is between 20 and 50%, and wide coverage MHW day is larger than 50%.

CHARACTERISTICS OF MARINE HEATWAVES IN THE NORTHERN SOUTH CHINA SEA

Marine heatwave occurs most frequently to the east of Hainan Island with 2.2–2.4 events per year, and secondarily along the

coast of Guangdong and west of Luzon Strait with 1.9–2.2 events per year (**Figure 1A**). On the western margin of SCS, the duration of MHW is the longest, ranging from 12 to 14 days (**Figure 1B**). On the northern SCS continental shelf, the duration of MHW is between 10 and 11 days. Although there was a spatial difference in the MHW frequency and duration distribution, the differences were not significant. The mean intensity of MHW exhibits a belt distribution parallel to the coast of Guangdong, declining outward sea (**Figure 1E**). On the northern SCS continental shelf, the mean intensity of MHW is higher than 1.5°C. In the open sea, the MHW is mainly below 1.5°C, except for a 1.6°C area west of the Luzon Strait.

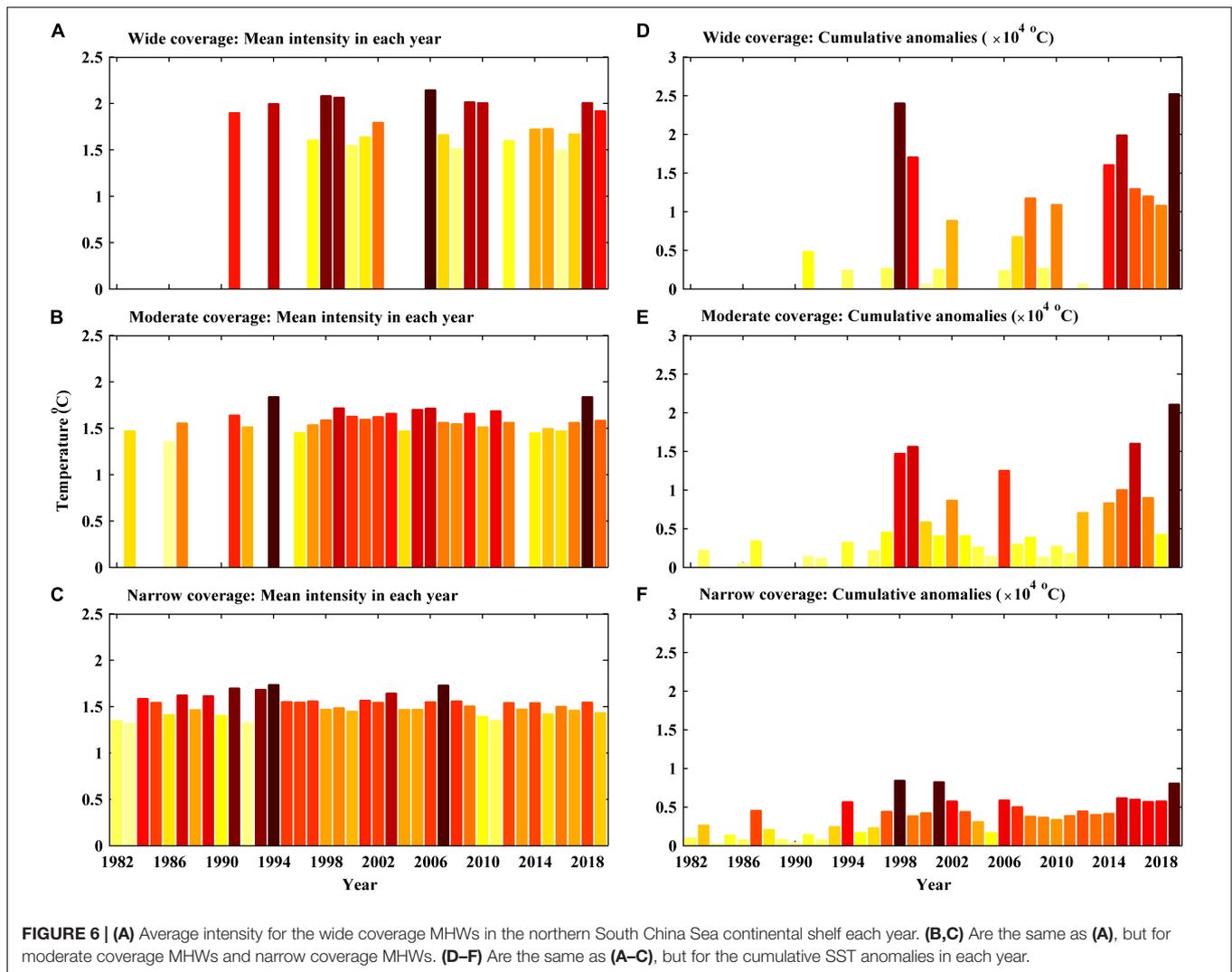
The significant long-term trend of MHW occurrence and intensity mainly centers in the northern SCS continental shelf and the western margin (**Figures 1D–F**). On the northern SCS continental shelf, the number of MHW occurrences increases by 0.1–0.14 per year. In the open sea, the long-term trend is mainly less than 0.06 per year. On the northern SCS continental shelf



and the western margin, the long-term duration trend is 0.3–0.4 d/a. The enhancement of MHW intensity is also mainly in the northern SCS continental shelf with an amplitude of around 0.04°C/a.

Narrow coverage MHWs dominate the northern SCS continental shelf, contributing around 64% to the total MHW days (**Figure 2A**). Moderate coverage MHWs occupy around 28%, and wide coverage is only around 8%. These results mean that the MHWs are mainly scattered in the northern SCS continental shelf. The average intensities of narrow- and moderate-coverage MHWs are equivalent and are both significantly lower than those of wide coverage MHWs (**Figure 2B**). The distribution of different MHW SDs is similar to that of average intensity (**Figure 2C**).

The probability of MHW occurrence is utilized to analyze the distribution of different kinds of MHWs (**Figure 3**). The wide coverage MHWs mainly occupy the mid-northern SCS continental shelf (**Figure 3A**). The moderate coverage MHWs are mainly concentrated at the east of Hainan Island (**Figure 3B**). The distribution of narrow coverage MHWs is very scattered, with a relatively large value region in the eastern and western parts (**Figure 3C**). Although the wide coverage MHW percentages are very low (**Figure 2A**), the contribution of this kind of MHWs to the cumulative SST anomalies is the largest with approximately 50% at the mid-northern SCS continental shelf (**Figure 3D**). The contribution of moderate coverage MHWs ranges from ~30 to 40% (**Figure 3E**). The contribution of narrow coverage MHWs



is also concentrated at the eastern and western northern SCS continental shelf with about 40% (**Figure 3F**).

The spatial distributions of the average intensity of all kinds of MHWs are similar to the total intensity (**Figures 1C, 4A-C**). The band-like average intensity decreases from the coast to the open sea. The average intensity of wide coverage MHWs is the largest, followed by moderate- and narrow-coverage MHWs. The SD of all kinds of MHWs is large at the eastern northern SCS continental shelf and small at the western SCS (**Figures 4D-F**).

VARIABILITY OF DIFFERENT KINDS OF MARINE HEATWAVES IN THE NORTHERN SOUTH CHINA SEA

There was an increasing long-term trend of cumulative days for all kinds of MHWs (**Figure 5**). In the 1980s, no wide coverage MHWs and rare moderate coverage MHWs occurred (**Figures 5A,B**). After the 1980s, the cumulative days of these two kinds of MHWs both increased rapidly and presented significant

decadal variability. For the narrow coverage MHWs, decadal variance is also present (**Figure 5C**).

The average intensity of all kinds of MHWs does not present a significant long-term trend or decadal variability (**Figures 6A-C**). However, the yearly cumulative SST anomalies still present a significant long-term trend and decadal variability (**Figures 6D-F**) induced by the variability in yearly cumulative days (**Figure 5**).

CONCLUSION

Based on the long time series of SST, the features of MHWs in the northern SCS continental shelf are studied. Using the daily ratio of the area with MHWs to the total area of the northern SCS continental shelf, the MHWs are divided into three categories, i.e., narrow coverage, moderate coverage, and wide coverage.

The occurrence days of narrow coverage MHWs contribute around 64% to the total days with MHWs. This kind of MHW is scattered over the northern SCS continental shelf, with a lower

temperature anomaly and SD. Moderate coverage MHWs occupy around 28%, with a slightly higher mean temperature anomaly than narrow coverage MHWs. This kind of MHW is mainly concentrated at the east of Hainan Island. The wide coverage MHWs contribute around 8%, mainly occupying the mid of northern SCS continental shelf. However, the contribution of this category of MHW to the cumulative SST anomalies is largest with around 50% at the mid of the northern SCS continental shelf.

The cumulative days and temperature of all kinds of MHWs exhibit significant long-term trends and decadal variability. However, their mean intensities in each year do not present such significant variability.

Many factors, such as the air-sea heat flux, ocean currents, and large-scale air-sea interaction, could modulate the generation and evolution of MHWs. Their variability and spatial distribution potentially contribute to the spatial characteristics of MHWs. Therefore, the classifications and characteristics of MHWs may be potentially affected by these factors. The details of the relationship between them remain to be revealed in the future.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

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AUTHOR CONTRIBUTIONS

YW analyzed and wrote the manuscript. JZ and ZW collected the data and analyzed the variability. SL, ST, FY, QC, and YH participated in the discussion and analysis. All authors contributed to the article and approved the submitted version.

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