Journal of
Marine Science and Engineering

MDPI

Article

Spatial Patterns and Evolution Features of Marine Cold Spells in the Arabian Sea during the Past Three Decades

Qianqian Wang [1], Zhihua Zhang [1,*] and M. James C. Crabbe [2]

[1] Climate Modeling Laboratory, School of Mathematics, Shandong University, Jinan 250100, China
[2] Wolfson College, Oxford University, Oxford OX1 2JD, UK; james.crabbe@wolfson.ox.ac.uk
* Correspondence: zhangzhihua@sdu.edu.cn

Abstract: Marine Cold Spell (MCS) events are cold sea states with potentially devastating impacts on marine environments and ecosystems. In this study, we analyzed different MCS types with various severe categories in the Arabian Sea during 1994–2023. We found that all four types of MCS events shared a similar spatial pattern in terms of frequency, mean duration, mean intensity, and total days, but the frequency of 1-MCS events had a sharply decreasing trend compared with any other type of MCS events, indicating that ocean warming mainly led to the significant disappearance of short-period MCS events. Moreover, the MCS events in offshore Somalia had the highest occurring frequency, longest duration, largest intensity, and maximal total days, and were significantly different from those in other regions of the Arabian Sea. This is originated from that the cold–warm changes of the Somali current make larger fluctuations in the sea surface temperatures of the waters off Somalia, enhancing the occurring probability of MCS events, especially during the summers.

Keywords: marine cold spell; Arabian sea; spatial patterns; statistical indicators; severe categories

check for updates

Citation: Wang, Q.; Zhang, Z.; Crabbe, M.J.C. Spatial Patterns and Evolution Features of Marine Cold Spells in the Arabian Sea during the Past Three Decades. *J. Mar. Sci. Eng.* **2024**, *12*, 1439. https://doi.org/10.3390/jmse12081439

Academic Editor: Eugen Rusu

Received: 6 August 2024
Revised: 17 August 2024
Accepted: 18 August 2024
Published: 20 August 2024

1. Introduction

Global warming is one of the greatest threats to the global environment and ecosystem. The main factor causing global warming is the increase in anthropogenic carbon emissions from industrial and energy sectors since the Industrial Revolution. As of July 2024, the concentration of carbon dioxide in the atmosphere has reached 422.9 ppm at the Mauna Loa Observatory in Hawaii while the pre-industrial level was only 278 ppm [1]. The oceans, a major component of the Earth's climate system, cover more than 71% of the Earth's surface and provide a huge reservoir for the absorption and storage of excess heat and carbon emissions in the atmosphere [2]. Over the last few decades, the oceans have played a key role in slowing down the speed of atmospheric warming through absorbing more than 90% of excess heat in the atmosphere, but at the same time, it has also contributed to ocean warming [3].

The Sixth Assessment Report (AR6) of the United Nations Intergovernmental Panel on Climate Change (IPCC) indicated that sea surface temperatures have risen by about 0.9 °C since the industrial revolution [4]. Venegas et al. (2023) revealed further that global sea surface temperature (SST) increased by 0.11 °C between 1950 and 2020 [5]. The World Meteorological Organization's State of the Climate in Asia 2023 report revealed that the mean sea surface temperature in the Northwest Pacific in 2023 was the largest on record, and that warming of the upper ocean (0–700 m) was particularly strong in the northwestern Arabian Sea, the Philippine Sea, and east of Japan, and was more than three times the global average [6]. Roxy et al. [7] found that sea surface temperatures in the Indian Ocean have shown a persistent warming trend since the 1950s and were stronger than in most of the tropical Pacific and Atlantic Oceans. In addition to anthropogenic forcing by direct radiation from increasing carbon emissions, such persistent warming possibly relied on the localized ocean–atmosphere coupling mechanisms in the Indian Ocean; some studies believe that warming has been exacerbated by weakened monsoons over the Indian Ocean, while others have shown that weakened monsoons have accelerated the warming [8–10]. Pedro et al. (2020) showed that a few degrees increase or decrease in global mean temperature can trigger an imbalance in surface temperature in the equatorial regions of the Indian Ocean, leading to a more variable climate and resulting in El Niño and La Niña phenomena [11]. Meanwhile, Du et al. (2009) revealed that El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) have a significant role in modifying sea surface temperatures in the tropical Indian Ocean [12].

The rate and magnitude of ocean warming vary considerably across spatial and temporal scales, resulting in large variations in the occurrence and trends of extreme marine heat/cold events. Under the scenario of continued warming, wide investigations into marine heat waves have been carried out [13–16], while only very limited studies on marine cold spells (MCS) have been conducted. Ibrahim et al. (2021) examined the long-term evolutionary trends of MCS events in the southern North Sea over the past four decades (1982–2021) and found a rapid decrease in the total days of MCS events (-16.54 ± 9.06 days/decade) and a higher frequency of MCS events in only two of the last two decades (2010 and 2013). These were attributed to the strong negative phase of the North Atlantic Oscillation (NAO) [17]. Kumar et al. (2024) used a fully coupled regional Earth system model to predict future tropical Indian Ocean MCS events and found that under both RCP4.5 and RCP8.5, MCS events disappear first from the north regions of the tropical Indian Ocean, and, finally, that MCS events will become rare in the future [18]. Li et al. (2023) studied the temporal and spatial variations in oceanic cold and heat events in the China seas, and found that during 1982–2020, the frequencies of cold weather and MCS events dramatically decreased to 7.5 days/decade and 0.72 times/decade, respectively, and severe MCS events became weaker, with trends of -0.24 °C/decade and -2.80 days/decade, respectively [19]. Yao et al. (2022) examined the means and trends of MCS events in coral reef zones and found that the total days of MCS events in most coral reef zones decreased by more than 10 days/decade in 1982–2021. Mean duration increased in southern Sumatra, northwestern Australia, and the Caribbean, with frequencies decreasing at an average rate of -1.0 to -2.4 days/decade during 2022–2070 [20].

The Arabian Sea, located between India and the Arabian Peninsula, has a significant feature of deep water that is maintained close to land. Meanwhile, the Arabian Sea plays a core role in sea–air interaction processes through providing the water necessary for wet storms and then contributing to a monsoonal climate in the surrounding regions. Therefore, in this study, we focused on MCS events in the Arabian Sea during 1994–2023 and revealed their spatial patterns, category distributions, and seasonal features.

2. Study Area and Data

The Arabian Sea (40° E–80° E, 0° N–25° N), covering a total area of about 3,862,000 km^2, is located in the northern Indian Ocean, east of Somalia in Africa, southeast of Arabia, and west of India, bordered by Bahrain, India, Iran, Iraq, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia, Somalia, United Arab Emirates, and Yemen, and connected to the Red Sea through the Gulf of Aden in the west, and to the Sea of Oman and the Persian Gulf in the east, and the southern portion is directly connected to the vast Indian Ocean (Figure 1). Since the maritime Silk Road in ancient China, the Arabian Sea has become an economically important sea crossroad for transportation, and is rich in oil and gas. Due to its proximity to the Suez Channel and the Persian Gulf, the Arabian Sea is known as the busiest shipping lane in the world [21–23].

In the context of frequent extreme climate events, MCS events, such as extreme ocean cold water events, have severe and long-lasting impacts on marine ecosystems, including large-scale die-offs of fish and invertebrates [24], coral bleaching [25,26], changes in species distribution (e.g., range shifts), and phenology (e.g., start of the growing season). In order to investigate spatial patterns and evolution features of MCS events in the Arabian Sea, we used the sea surface temperature observations from the Optimal Interpolation Sea Surface

Temperature (OISST) V2.1 dataset of the National Oceanic and Atmospheric Administration (NOAA). This dataset spans the period from 1 January 1994 to 31 December 2023 and has a spatial resolution of 0.25° × 0.25° [27,28].

Figure 1. Topography of the Arabian Sea.

3. Marine Cold Spells: Definition, Indicators, and Categories

Marine cold spells (MCS) events are discrete, persistent, abnormally cold events occurring in a specific sea area. In this study, we adopted the qualitative definition of MCS events proposed by Schlegel et al. (2021) [29], but extended it to consider different periods of abnormally cold persistence:

- ➢ 7-MCS is an event in which the sea surface temperatures are below the 10th percentile seasonally varying threshold for at least seven consecutive days; if two successive events have a gap of three days or less, they are combined as a single event.
- ➢ 5-MCS is an event in which the sea surface temperatures are below the 10th percentile seasonally varying threshold for at least five consecutive days; if two successive events have a gap of two days or less, they are combined as a single event.
- ➢ 3-MCS is an event in which the sea surface temperatures are below the 10th percentile seasonally varying threshold for at least three consecutive days; if two successive events have a gap of one day, they are combined as a single event.
- ➢ 1-MCS is an event in which the sea surface temperatures are below the 10th percentile seasonally varying threshold for at least one day.

All MCS events can be quantitatively characterized in terms of frequency, duration, mean intensity, and total days of cold spells [29,30]. Their detailed description is shown in Table 1.

The severe level of MCS events has significantly different impacts on marine climate and environment. Four severity categories of MCS events, which are based on multiples of the difference between the local climatological mean and 10th percentile [31], include moderate (1–2, Category I), intense (2–3, Category II), severe (3–4, Category III), extreme (>4, Category IV).

Table 1. Definitions of Four Statistical Indices.

Index	Definition	Formulas	Unit
Frequency	Annual number of MCS events	N	Times
Duration	Annual mean duration of MCS events	$\sum_{i=1}^{N} (D_i)/N$	Days/time
Mean-Int	Annual mean intensity of MCS events	$\sum_{i=1}^{N} \sum_{j=1}^{D_i} \left(\widetilde{T}_{ij} - T_{ij} \right) / N$	°C/time
Days	Annual total days of MCS events	$\sum_{i=1}^{N} D_i$	Days/times

For the i_{th} MCS event, D_i is its duration, and T_{ij} and $\widetilde{T}_{ij}$ is the observed SST and associated climatological mean for day j, respectively.

4. Results

4.1. Analysis of 7-MCS Events

The annual mean statistical indices for all 7-MCS events during 1994–2023 in the Arabian Sea, including frequency, duration, mean intensity, and total days are shown in Figure 2. Generally, 7-MCS events occurred 0.3–1.5 times every year over the whole Arabian Sea. The high frequency of 7-MCS events appeared in offshore Somalia (1.2–1.5 times/year) and offshore Oman, offshore Yemen, and offshore India (0.9–1.2 times/year), while the lowest frequency appeared in the southeastern Arabian Sea (<0.3 times/year). The annual mean duration of 7-MCS events was approximately 10–17 days over the whole sea. It reached up to 17 days in the waters off Oman, Somalia, and Mumbai (India); however, the frequency of 7-MCS events in the waters off Oman and Mumbai (India) was much less than that in the waters off Somalia. The annual mean intensity of 7 MCS events was about 1.0–1.5 °C in the central and eastern Arabian Sea and the strongest mean intensity (2.2–2.5 °C) appeared in offshore Somalia. The annual mean total days of 7-MCS events demonstrated similar spatial patterns to frequency and mean intensity. The longest total days also appeared in offshore Somalia (16–22 days).

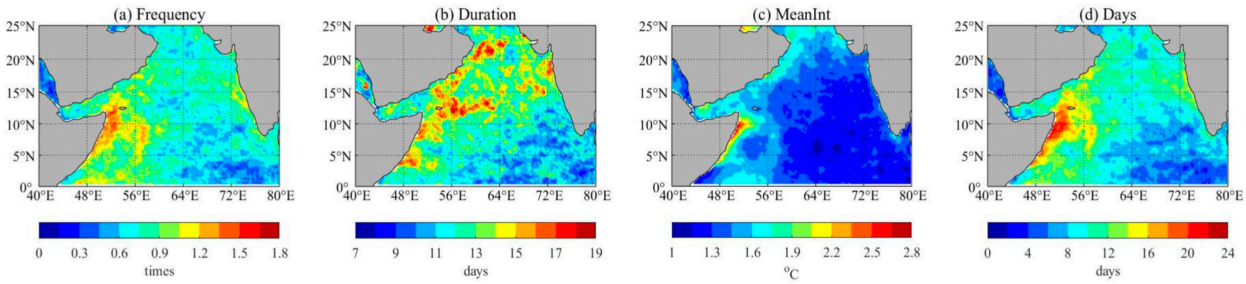

Figure 2. Spatial patterns of annual mean statistical characteristics of 7-MCS events during 1994–2023.

Regarding seasonal variabilities, Figure 3 demonstrates the spatial distribution of seasonal average total days of 7-MCS events in four seasons of the period 1994–2023. In spring, average total days in most of the Arabian Sea reached 1–3 days, and the eastern Arabian Sea had slightly higher total days than the western Arabian Sea. However, in summer, the average total days of 7-MCS events showed a clear spatial pattern of high in the southwest and low in the northeast, with the highest value mainly occurring in offshore Somalia (7–10 days). In the autumn, the average total days in most of the Arabian Sea were about 1–4 days, except for the waters off Somalia and Mumbai in India (3–5 days). The total days in winter demonstrated a similar pattern to those in autumn, but were slightly higher in the waters off Somalia, Oman, and North India (4–6 days). In general, the seasonal average total days had significant seasonal and spatial distribution differences, which were large in summer and relatively smaller in spring, autumn, and winter, especially in the western Arabian Sea. The longest duration of 7-MCS events appeared in summer, followed by autumn and winter, but the longest duration in the northeastern Arabian Sea appeared in winter and summer, followed by autumn and spring.

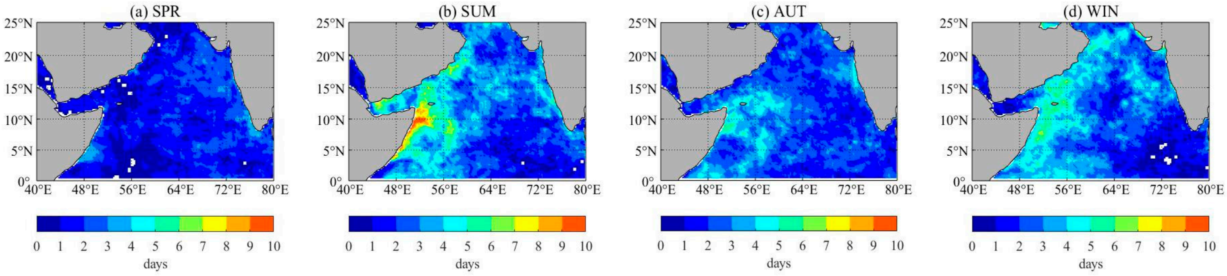

Figure 3. Seasonal variabilities in total days of 7-MCS events during 1994–2023.

Figure 4 demonstrates the annual trend of 7-MCS events during 1994–2023 in terms of frequency, mean duration, mean intensity, and total days. The frequency of 7-MCS events showed a decreasing trend (−1.2 to −0.2 times/decade) in most of the Arabian Sea, except for some small regions in offshore Somalia (0.2–0.8 times/decade) and offshore Oman (0–0.2 times/decade). The duration of 7-MCS events had a statistically significant trend in most of the Arabian Sea (−3 to 3 days/decade). The mean intensity showed a significant but slight trend (−0.2 to 0.2 °C/decade) in almost all of the Arabian Sea. The annual trend for total days had a similar spatial pattern as that of the frequency. It was dominated by a decreasing trend (−12 to −3 days/decade), except for offshore Somalia (3–15 days/decade).

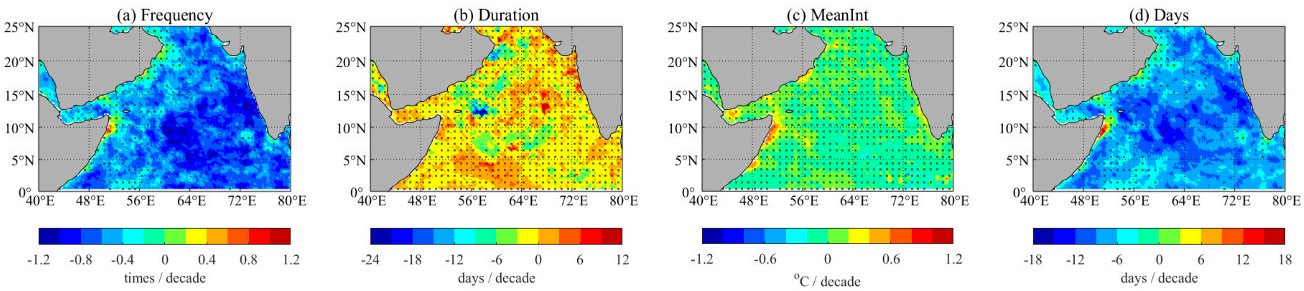

Figure 4. Annual trends of four statistical indices for 7-MCS events during 1994–2023, where the dots denote statistical significance at the $p < 0.05$ level.

Figure 5 demonstrates the probability of the occurrence of different categories of 7-MCS events in the Arabian Sea for the period 1994–2023. Over almost the whole Arabian Sea, about 40–80% of 7-MCS events belonged to Category I and about 10–40% of 7-MCS events belonged to Category II, especially in the northern edge of the Arabian Sea, almost all 7-MCS events belonged to Category I. The probability of Categories I and II was much higher than that of Categories III and IV. Moreover, Category III occurred only in about 31% of the Arabian Sea, mainly located in the western and northern Arabian Sea, while Category IV events rarely occurred.

In order to reveal seasonal differences, Figure 6 demonstrates the probability of occurrence of different categories of 7-MCS events in four seasons (spring, summer, autumn, and winter) of 1994–2023. Since Category IV events rarely occurred, here we only investigated Categories I–III. Compared with spring, autumn, and winter, Category I events occurred more frequently in summer. Specifically, 50–70% of Category I events in the Western Arabian Sea and offshore India occurred in the summer. Following summer, winter was the second season with frequent Category I events. The probability of Category I events in winter reached 40–50% in offshore India. In contrast to summer and winter, Category I events occurred less frequently in spring and autumn. Moreover, there were no Category I events in the central Arabian Sea during autumn and in the northern edge and southeast of the Arabian Sea during spring.

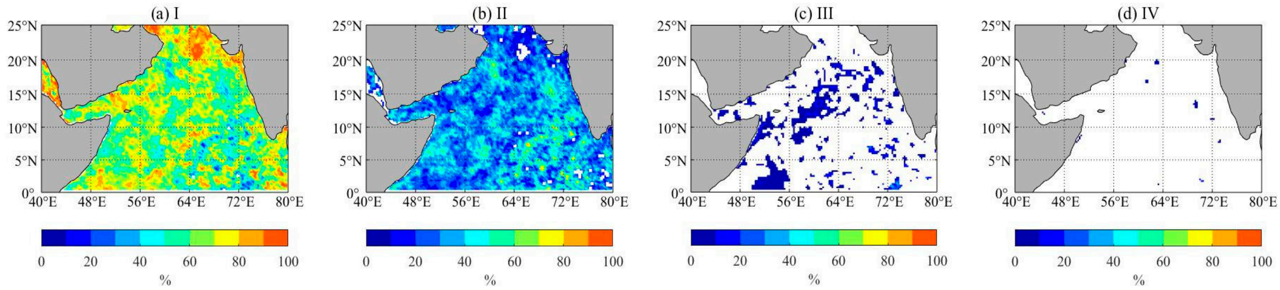

Figure 5. Probability of different categories of 7-MCS events during 1994–2023 (blank areas indicate that no 7-MCS events occurred).

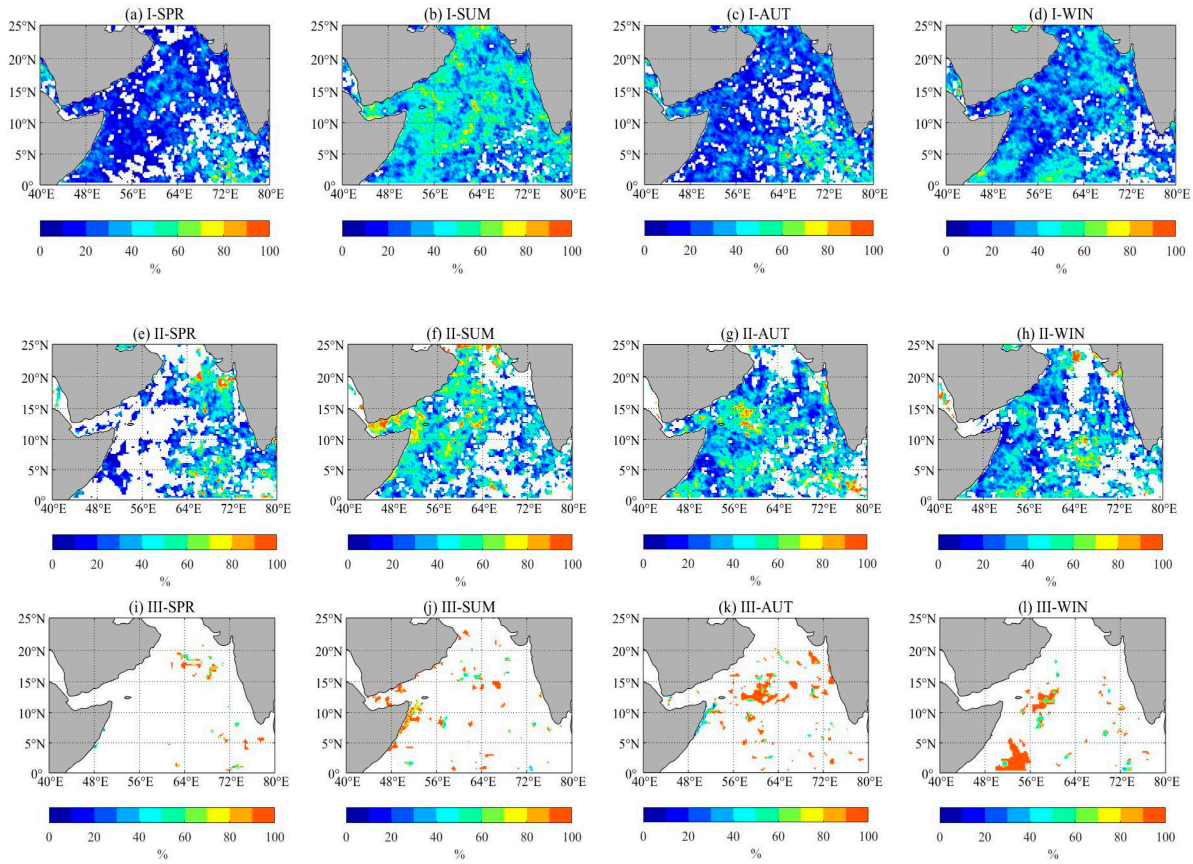

Figure 6. Probability of different categories of 7-MCS events in spring, summer, autumn, and winter of 1994–2023.

Category II events occurred more frequently (>50% share) in offshore India during spring, the western Arabian Sea during summer, offshore Yemen during autumn, and the southeastern Arabian Sea during winter. It is worth noting that Category II events rarely occurred in the western Arabian Sea during spring. Category III events sparsely occurred in all seasons. In offshore Somalia and Yemen, the frequency of Category III events was higher in summer (>80%), followed by autumn (40–50%), and almost zero in spring and winter. In some regions of the central Arabian Sea and offshore India, the frequency of Category III events was higher in autumn (>60%), followed by summer and autumn, and lowest in spring.

4.2. Analysis of 5-MCS Events

We analyzed statistical indices of 5-MCS events in the Arabian Sea during 1994–2023 (Figure 7). In most of the Arabian Sea, 5-MCS events occurred on average 0.9–1.8 times every year. The highest occurring frequency appeared in offshore Somalia (1.8–2.1 times/year) and offshore India (1.5–1.8 times/year). The mean duration of 5-MCS events in most of the Arabian Sea was 9–12 days, and a high duration of 12 days or more appeared in some waters off Somalia, Oman, and Yemen. The mean intensity of 5-MCS events showed significant spatial variations, being high in the waters off Somalia, Oman, and Yemen and low in the southeast; the mean intensity in offshore Somalia was over 2.5 °C. The spatial pattern of total days was similar to that of frequency; significantly high total days (20–28 days) occurred in offshore Somalia while significantly low total days (6–12 days) occurred in the southeastern Arabian Sea. Overall, 5-MCS events in offshore Somalia were demonstrated to be the highest frequency, longest duration, maximal intensity, and longest total days, while those in the southeastern Arabian Sea had the lowest frequency, shortest duration, minimal intensity, and shortest total days.

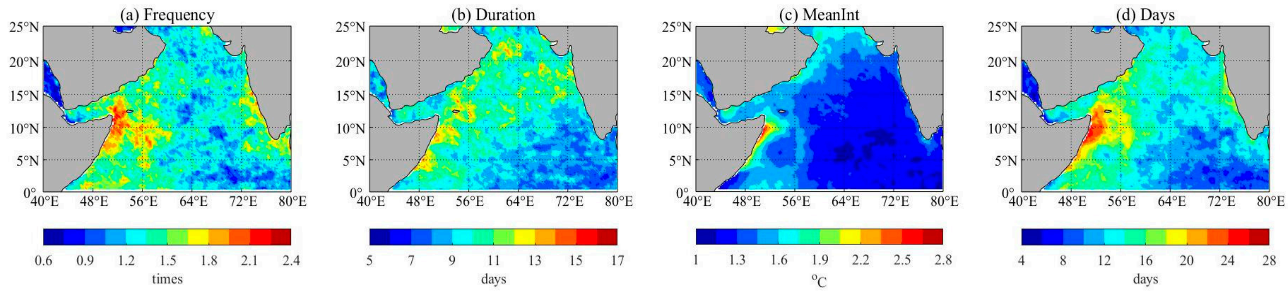

Figure 7. Spatial patterns of annual mean statistical characteristics of 5-MCS events during 1994–2023.

The seasonal variabilities of the total days of 5-MCS events in the Arabian Sea during 1994–2023 are shown in Figure 8. Among all four seasons, total days in spring had no significant spatial variability throughout the whole Arabian Sea, while total days in summer demonstrated the largest spatial variability with 9–10 days in offshore Somalia and 1–3 days in the southeastern Arabian Sea. The spatial patterns of total days in autumn and winter were similar to those in summer but were very different from those in spring. The longest total days in autumn and winter also appeared in offshore Somalia but were shorter than those in summer. The southeastern Arabian Sea had slightly longer total days in autumn than in summer and winter, while the northeastern Arabian Sea had slightly longer total days in summer and winter than in autumn.

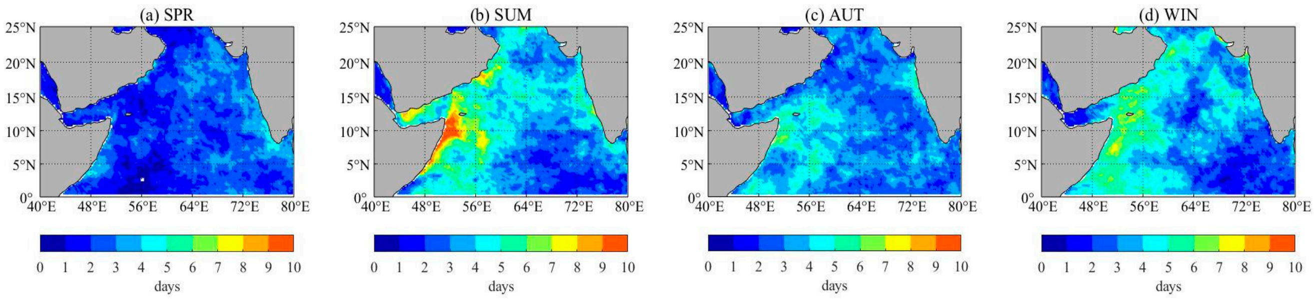

Figure 8. Seasonal variabilities in total days of 5-MCS events during 1994–2023.

The annual trend of 5-MCS events in the Arabian Sea during 1994–2023, in terms of frequency, mean duration, mean intensity, and total days, is demonstrated in Figure 9. The statistically significant trends in the frequency of 5-MCS events appeared only in offshore Oman (up to 0.8 times/decade) and offshore Somalia (up to 1.2 times/decade). Although the frequency of 5-MCS events in other areas of the Arabian Sea showed decreasing trends

(−1.6 to −0.4 times/decade), these annual trends did not pass the statistical significance test. Different from frequency, the mean duration of 5-MCS events was found to have a statistically significant trend (−3 to 3 days/decade) in almost the whole Arabian Sea. The mean intensity of 5-MCS events had similar trend patterns as mean duration, but the trend magnitude was slight, except for offshore Somalia (up to 0.6 °C/decade). The spatial pattern of the evolution trend in total days was similar to that in frequency. The statistically significant trends in total days of 5-MCS events appeared only in offshore Somalia (12–28 days/decade). Although decreasing trends (−12 to −6 days/decade) in total days were detected in other areas of the Arabian Sea, these annual trends did not pass the statistical significance test.

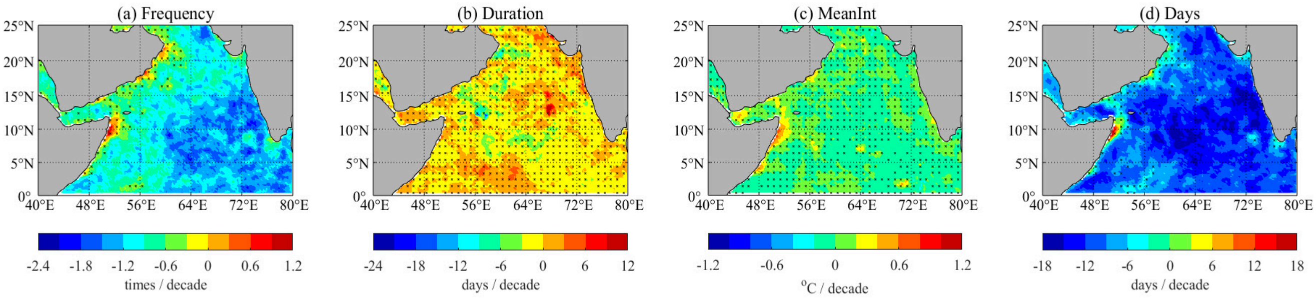

Figure 9. Annual trends of four statistical indices for 5-MCS events during 1994–2023, where the dots denote statistical significance at the $p < 0.05$ level.

The probability of Categories I–IV of 5-MCS events occurring in the Arabian Sea during 1994–2023 is shown in Figure 10. Both Category I and II MCS events occurred in the whole Arabian Sea, and the probability of Category I (50–90%) was much higher than that of Category II (10–50%). Category III MCS events only occurred in approximately 36% of the Arabian Sea and had a probability of <20%, and Category IV rarely occurred.

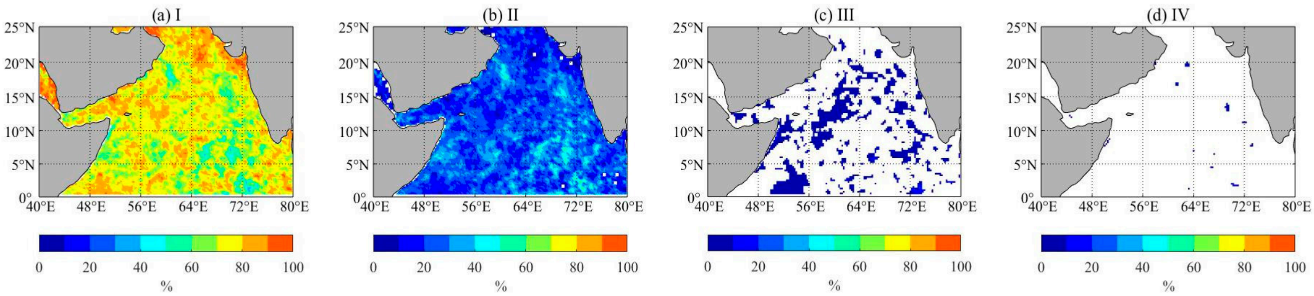

Figure 10. Probability of different categories of 5-MCS events during 1994–2023 (blank areas indicate that no 5-MCS events occurred).

We analyzed the seasonal difference in Category I–III 5-MCS events (Figure 11). The spatial variability in the probability of Category I events was relatively small for each season. The probability of category I events (40–60%) in summer was much higher than that in spring, autumn, and winter in the Arabian Sea, except for its south edge. A further analysis of the southern Arabian Sea revealed that 40–50% of category I events occurred in the southeast during autumn or spring and in the southwest during winter.

The probability of Category II events demonstrated significant spatial heterogeneity. Approximately 50–80% of Category II events occurred in the spring in the northeastern Arabian Sea, the summer of the western Arabian Sea, and the autumn/winter of the southern Arabian Sea. It is worth noting that there were almost no Category II events in spring in the western Arabian Sea. Category III events were relatively sporadic and had a high probability in autumn and winter.

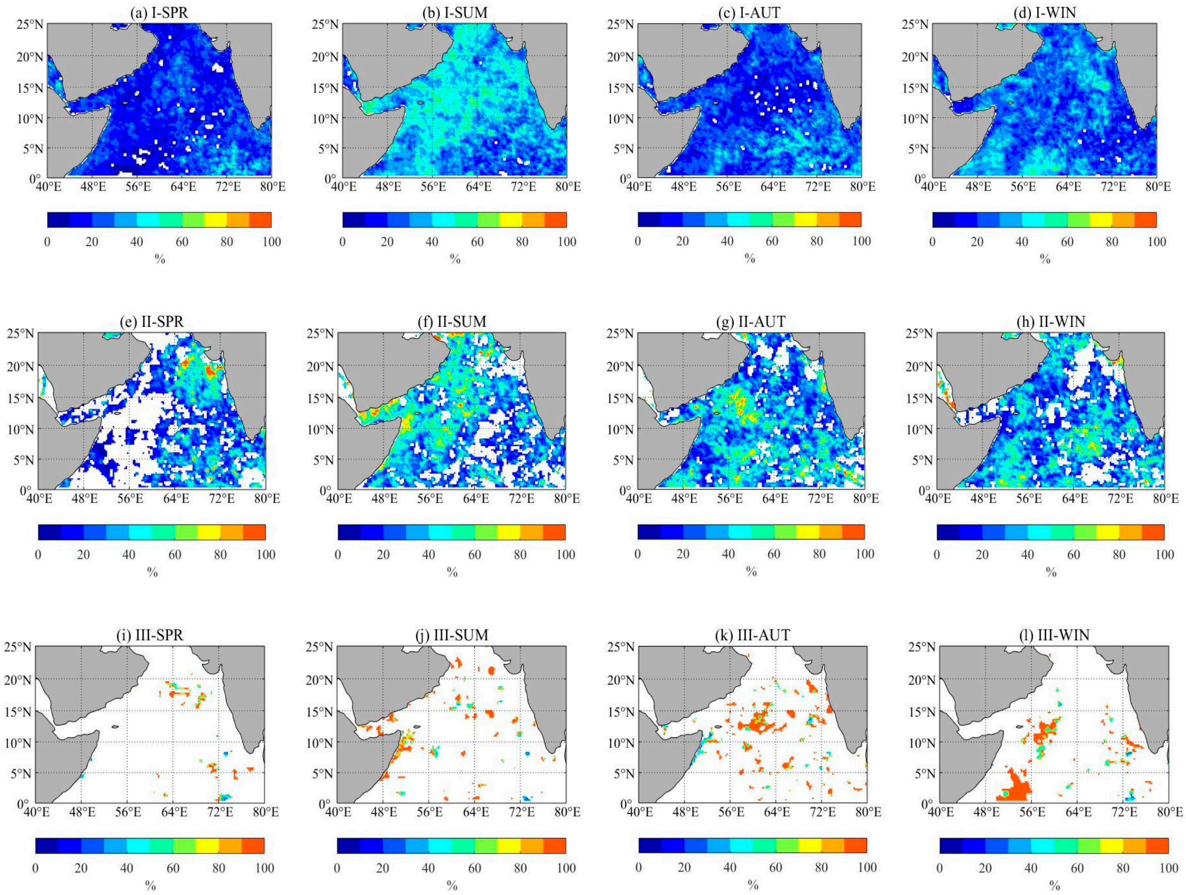

Figure 11. Probability of different categories of 5-MCS events in spring, summer, autumn, and winter of 1994–2023.

4.3. Analysis of 3-MCS Events

The spatial patterns of annual mean statistical characteristics of 3-MCS events during 1994–2023 are shown in Figure 12. 3-MCS events occurred mainly 1.8–3.2 times every year, and more frequently in the water off Oman, Yemen, Somalia, and south India. The highest frequency (3.2–3.6 times/year) appeared in offshore South India, while the lowest frequency (1.8–2.4 times/year) appeared in the northern Arabian Sea. The mean duration of 3-MCS events was approximately 5–8 days in most of the Arabian Sea and the longest mean durations (>8–10 days) appeared in the waters off Oman and Somalia, while the shortest mean duration (4–6 days) appeared in the southeastern Arabian Sea. The mean intensity of 3-MCS events demonstrated significant spatial variabilities. The mean intensity was the lowest (1–1.3 °C) in the southeastern Arabian Sea, gradually increased to the northern and western Arabian Sea, and reached the highest (2.2–2.5 °C) in offshore Somalia. The total days of 3-MCS events were approximately 10–17 days in most of the Arabian Sea, and were significantly high in offshore Somalia (24–28 days).

Figure 13 demonstrates further the seasonal variabilities in total days of 3-MCS events and their spatial pattern. The total days in spring were about 1–5 days in most of the Arabian Sea, except for the waters off south India (5–7 days). The total days in summer were about 3–7 days in most of the Arabian Sea but reached up to 7–9 days in the waters off Oman and Yemen and 9–10 days in the waters off Somalia. The total days in autumn and winter shared a similar pattern as that in summer, but had slightly lower values, e.g., approximately 6–7 days in autumn and 7–8 days in winter for the waters off Somalia.

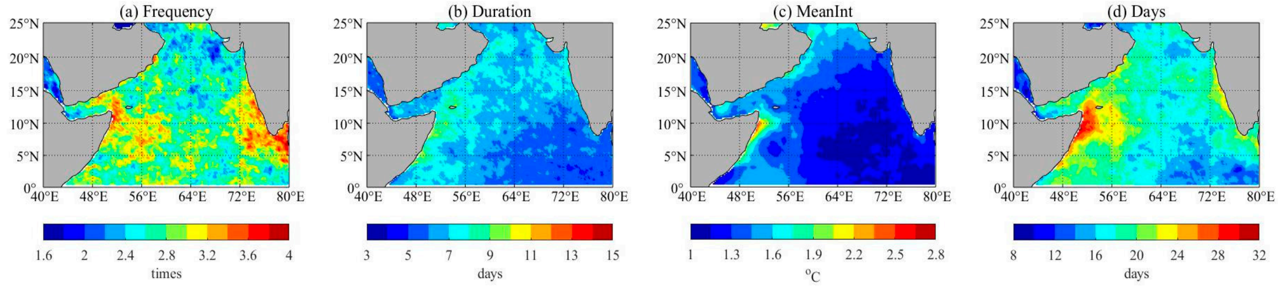

Figure 12. Spatial patterns of annual mean statistical characteristics of 3-MCS events during 1994–2023.

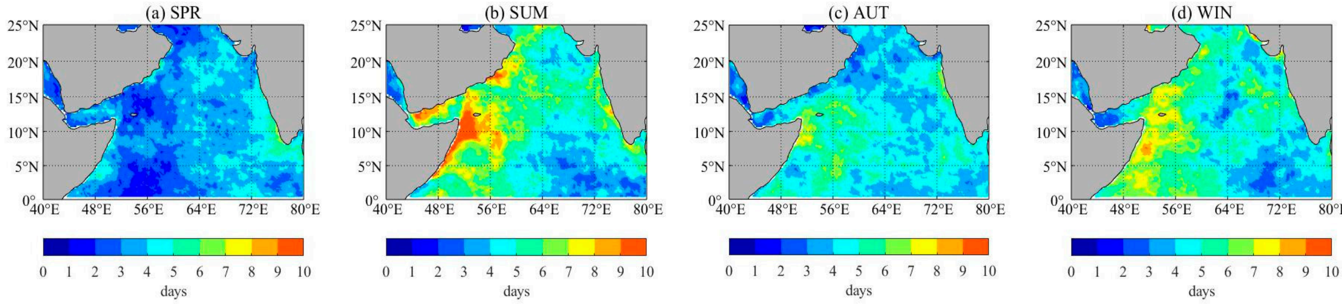

Figure 13. Seasonal variabilities in total days of 3-MCS events during 1994–2023.

Figure 14 demonstrates annual trends of four statistical indicators for 3-MCS events during 1994–2023. Decreasing trends in the frequency of 3-MCS events were found in almost the whole of the Arabian Sea, especially −3.6 to −2 times/decade in the southeastern Arabian Sea and −2.8 to −2 times/decade in the waters off north India. However, these decreasing trends were not statistically significant. The increasing trends in frequency appeared only in the waters off Oman and Somalia and passed the statistical significance test. The mean duration of 3-MCS events showed a statistically significant trend (−3 to 3 days/decade) in most of the Arabian Sea. The mean intensity of 3-MCS events changed slightly in the whole Arabian Sea, except in offshore Somalia (approximately 0.8 °C/decade). For the total days of 3-MCS events, all decreasing trends (−12 to −24 days/decade) in most of the whole Arabian Sea were not statistically significant, while increasing trends (8–12 days/decade) in the water off Oman and Somalia were statistically significant.

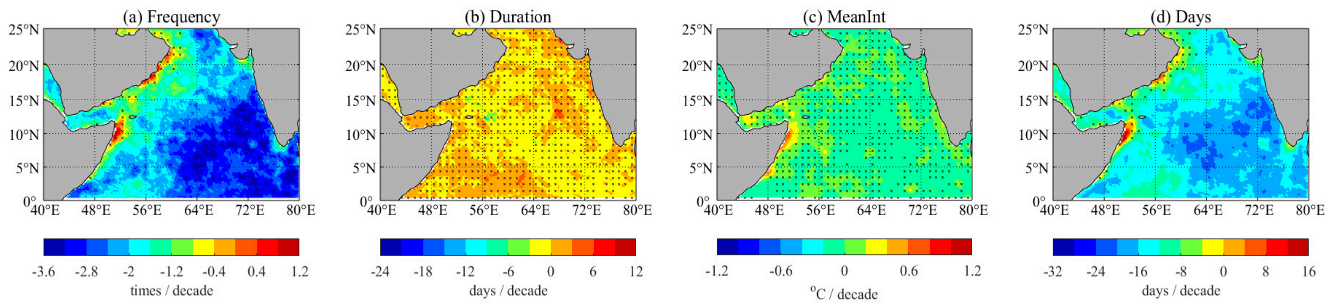

Figure 14. Annual trends of four statistical indices for 3-MCS events during 1994–2023, where the dots denote statistical significance at the $p < 0.05$ level.

The probability of Category I–IV of 3-MCS events during 1994–2023 is shown in Figure 15. Category I and II events occurred throughout the Arabian Sea and the probability of Category I events was very high (>70%), and that of Category II events was about 10–20%. Category III events always sparsely occurred and category IV events sporadically occurred.

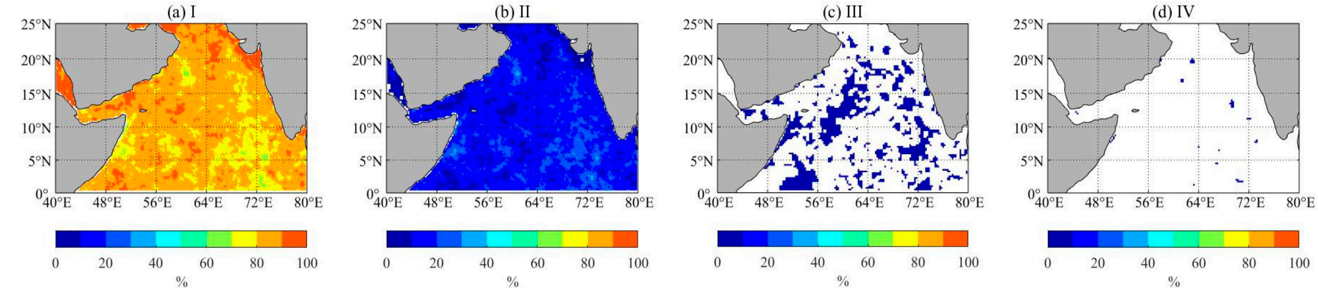

Figure 15. Probability of different categories of 3-MCS events during 1994–2023 (blank areas indicate that no 5-MCS events occurred).

In order to investigate seasonal differences, we analyzed the probability of different categories of 3-MCS events in four seasons (Figure 16). The spatial variation of Category I events was not significant in each season. The western and northern Arabian Sea tended to have more 3-MCS events in summer than the other three seasons, and the southwestern Arabian Sea tended to have more 3-MCS events in summer and winter than those in spring and autumn. Compared with Category I events, the spatial variation of Category II events in each season was significantly large. Category II events tended to occur in the northeast Arabian Sea (spring), west Arabian Sea (summer), offshore Oman (autumn), and southeast Arabian Sea (winter). Category III events were relatively sporadic and had a high probability in autumn and winter.

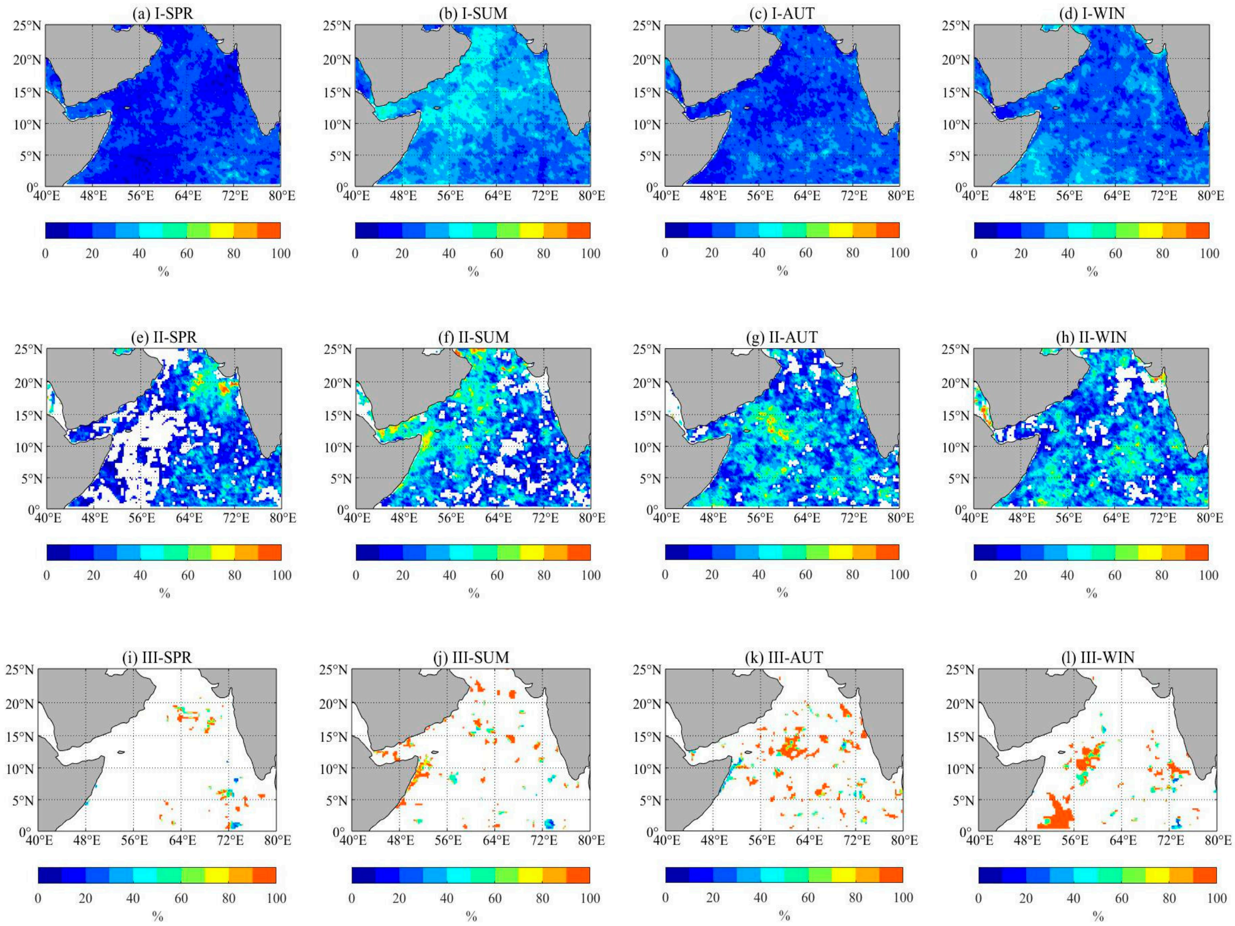

Figure 16. Probability of different categories of 3-MCS events in spring, summer, autumn, and winter of 1994–2023.

4.4. Analysis of 1-MCS Events

Figure 17 demonstrates the spatial pattern of the annual mean statistical characteristics of 1-MCS events during 1994–2023. The annual frequency of 1-MCS events appeared low in the north and high in the south. In detail, 1-MCS events occurred approximately 5 times/year in the north Arabian Sea, 7–8 times/year in the southwestern Arabian Sea, and 8–9 times/year in the waters at the southern end of the Indian Peninsula. The annual mean duration was approximately 2–5 days, especially in offshore Oman (4–5 days), offshore North India (4–5 days), and offshore Somalia (4–6 days). The annual mean intensity was about 1–1.6 °C in most of the Arabian Sea and was especially high (1.6–2.5 °C) in offshore Somalia. The annual number of total days of 1-MCS events was about 20–28 days in the whole Arabian Sea, except for offshore Somalia (30–36 days) and offshore south India (26–30 days).

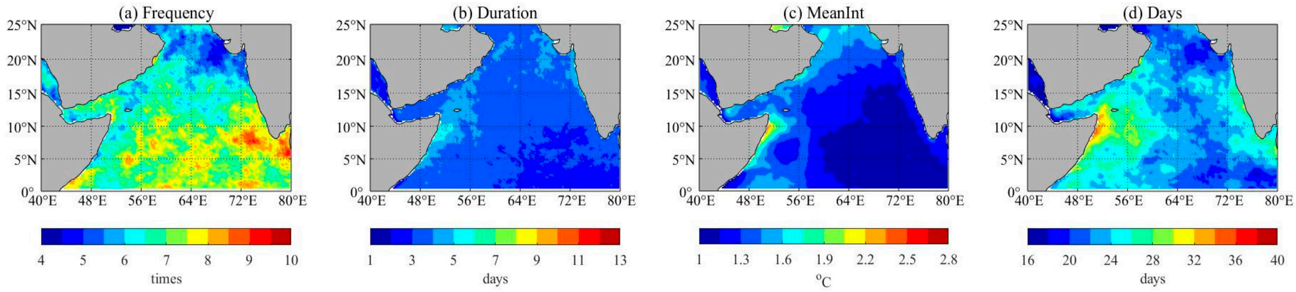

Figure 17. Spatial patterns of annual mean statistical characteristics of 1-MCS events during 1994–2023.

The seasonal differences in the total days of 1-MCS events are shown in Figure 18. The total days in summer and winter were significantly higher than those in spring and autumn. The total days of 1-MCS events in spring were about 3–7 days and demonstrated a spatial pattern of even distribution compared with other seasons. It is worth noting that the total days in offshore Somalia were significantly high (9–10 days) in summer and relatively high (7–9 days) in winter and autumn.

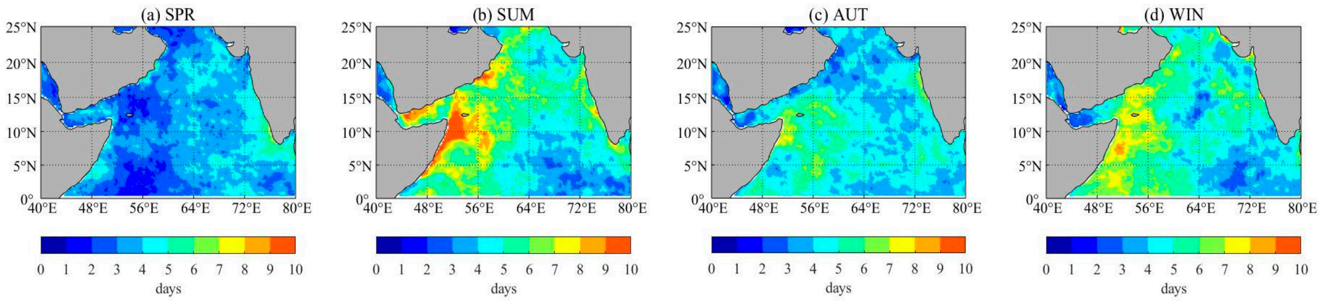

Figure 18. Seasonal variabilities in total days of 1-MCS events during 1994–2023.

Figure 19 demonstrates the annual trends of 1-MCS events in terms of frequency, mean duration, mean intensity, and total days. The frequency of 1-MCS events was found to have a decreasing trend with statistical insignificance in almost the whole Arabian Sea, especially −8 to −6 times/decade in the southeastern Arabian Sea. However, the frequency in offshore Oman and offshore Somalia was found to have a slightly increasing trend (0–1 time/decade), which passed the statistical significance test. The mean duration of 1-MCS events was found to have a statistically significant trend (−3 to 3 times/decade), specifically with a consistently increasing trend in the southwestern Arabian Sea. Similar to the mean duration, the mean intensity also showed a trend of −0.2 to 0.2 °C/decade, which was statistically significant in most of the Arabian Sea, but had a higher trend (0.2–0.8 °C/decade) in offshore Somalia, and was not statistically significant. The spatial pattern of total days was similar to that of frequency, only the increasing trends (8–12 days/decade) in offshore Somali and offshore Oman were statistically significant.

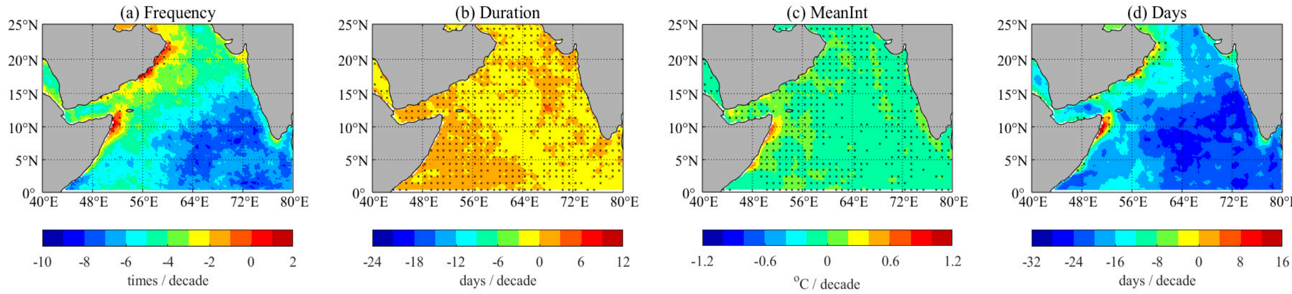

Figure 19. Annual trends of four statistical indices for 1-MCS events during 1994–2023, where the dots denote statistical significance at the $p < 0.05$ level.

The probability of Categories I–IV of 5-MCS events occurring in the Arabian Sea during 1994–2023 is shown in Figure 20. Both Category I and II MCS events occurred in the whole Arabian Sea, and the probability of Category I (50–90%) was much higher than that of Category II (10–50%). Category III MCS events only occurred in approximately 36% of the Arabian Sea and had a probability of <20%, and Category IV rarely occurred.

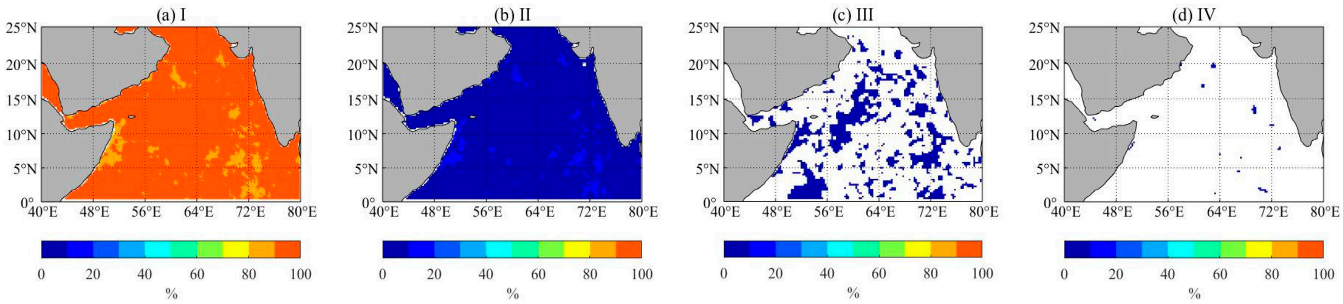

Figure 20. Probability of different categories of 1-MCS events during 1994–2023 (blank areas indicate that no 5-MCS events occurred).

The seasonal distribution of Category I–III events is shown in Figure 21. The northern Arabian Sea had 30–50% of Category I events occurring in summer and the southern Arabian Sea had 30–40% of Category I events occurring in winter. Spatial variabilities in occurring Category II events were more pronounced than those in Category I events. The main locations and seasons where Category II occurred at a probability of >70% were the northeastern Arabian Sea (spring), western Arabian Sea (summer), and offshore Oman (Autumn). Category III events always occurred sparsely, and occurred more in sea areas in autumn and winter than in spring and summer.

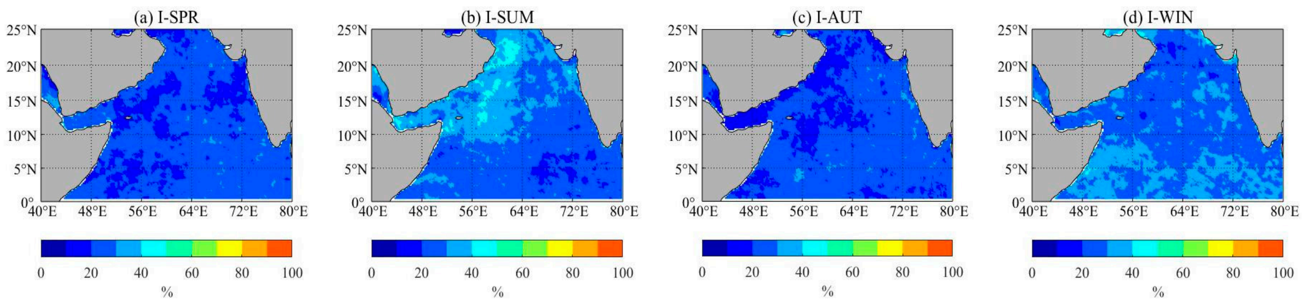

Figure 21. *Cont.*

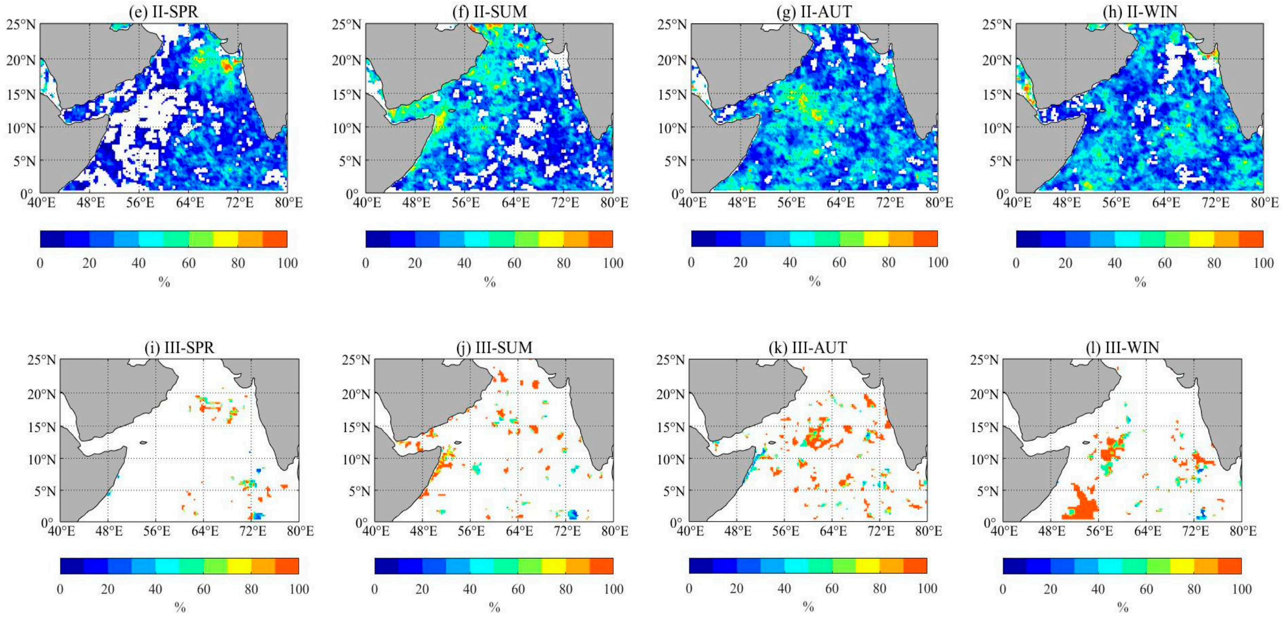

Figure 21. Probability of different categories of 1-MCS events in spring, summer, autumn, and winter of 1994–2023.

4.5. Similar Spatio-Temporal Modes in MCS Evolution

Figure 22 demonstrates the temporal evolution features of MCS events in the Arabian Sea during the past 30 years (1994–2023). The frequency of 1-MCS events had a more significant decreasing trend than that of 3-MCS, 5-MCS, or 7-MCS events. This means that ocean warming mainly led to the significant disappearance of short-period MCS events. The annual frequency of 3-MCS, 5-MCS, or 7-MCS events had similar oscillation modes, especially after 2010. The mean duration of 1-MCS, 3-MCS, 5-MCS, and 7-MCS shared similar oscillation modes, but had no significant trend during the past thirty years. The average intensity of MCS events had similar oscillation modes at different scales, but the internal difference among MCS events significantly increased, specifically, a larger magnitude of fluctuation appeared in 7-MCS events since 2015. The total days of MCS events showed similar decreasing trends and fluctuation features at all scales (1-MCS, 3-MCS, 5-MCS, 7-MCS), and their internal difference was very limited.

In order to further explore similarities and differences in spatial modes of MCS evolution (Figure 23), we considered eight typical areas in the Arabian Sea: offshore Somalia, offshore Yemen, offshore Oman, offshore North India, offshore South India, South–East Arabian Sea, offshore Mumbai (India), and offshore Cape Comorin (the southernmost part of India).

In terms of frequency, MCS events showed decreasing trends in almost all of the typical sea areas. 5-MCS events and 7-MCS events had similar evolution trends in all eight typical sea areas, and were very different from 1-MCS events and 3-MCS events. It is worth noting that only the waters off Somalia demonstrated positive trends in 3-MCS, 5-MCS, and 7-MCS events. The largest decreasing trends always appeared in the southeastern Arabian Sea (SEAS).

In terms of mean duration, the offshores of Somalia, North India, South India, and Mumbai showed an increasing trend, specifically 1-MCS and 3-MCS events had small magnitudes in increasing trend than those in 5-MCS events and 7-MCS events. The offshores of Yemen, Oman, Cape Comorin, and the southeastern Arabian Sea showed a decreasing trend, specifically, the largest decreasing trend appeared in offshore Oman. It is worth noting that the mean duration of MCS events in the offshores of Oman and Mumbai demonstrated opposite trends.

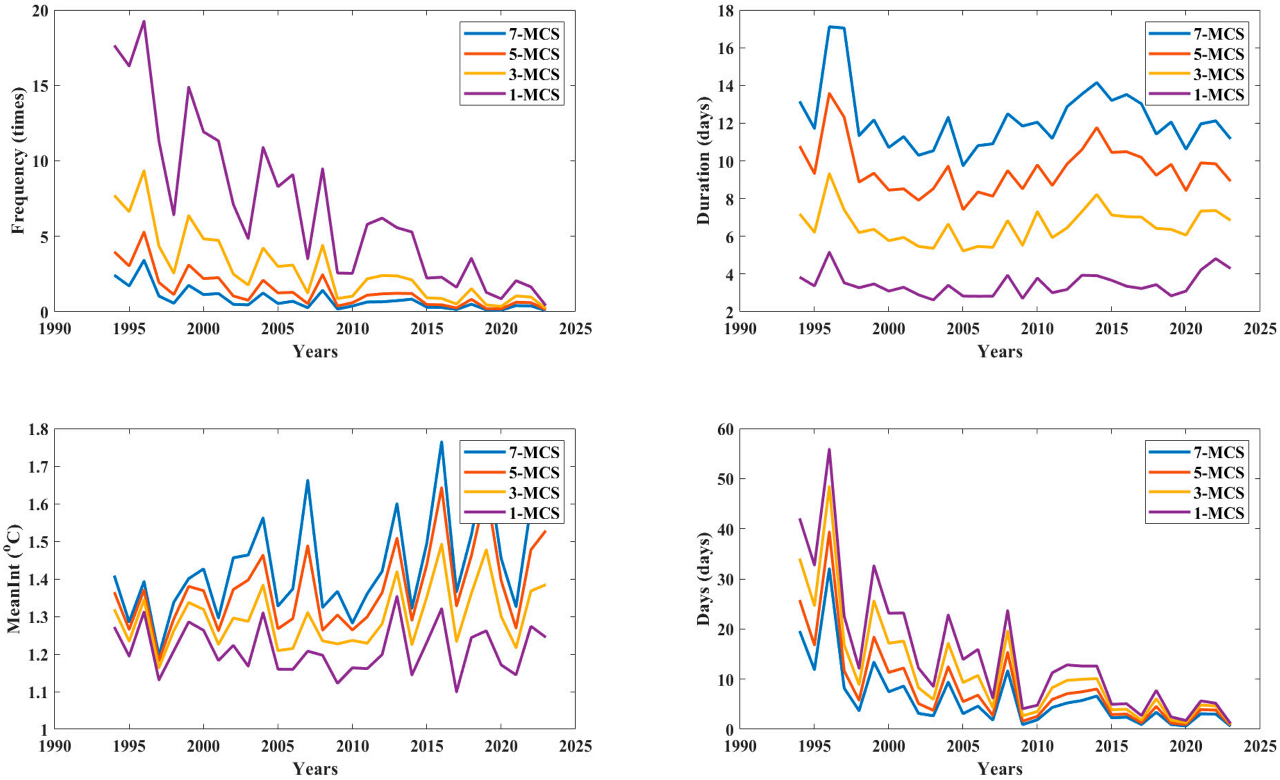

Figure 22. Temporal evolution of MCS events under different scales in the Arabian Sea during 1994–2023.

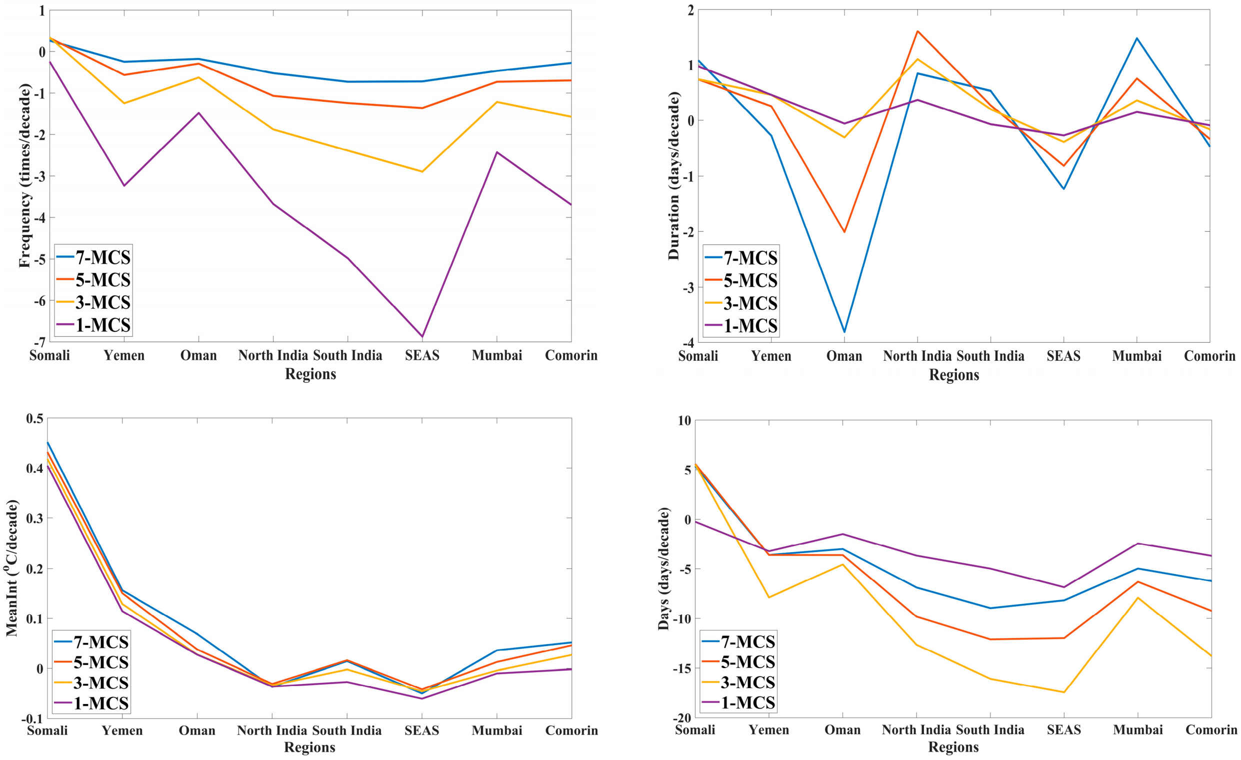

Figure 23. Annual trends of frequency, mean duration, mean intensity, and total days of MCS events in eight typical sea areas in during the last 30 years (1994–2023).

In terms of mean intensity, the difference in MCS events at all scales was demonstrated to be very small in all of the eight typical sea areas. The offshore of Somalia was shown to have the largest increasing trends in mean intensity of the MCS events under all four scales. The offshores of Yemen and Oman were also shown to be similar, but with smaller increasing trends. Moreover, the shorter the MCS duration, the smaller the increasing trend in mean intensity. However, the southeastern Arabian Sea demonstrated a significantly decreasing trend in MCS events, and the shorter the MCS duration, the greater the decreasing trend in mean intensity. For offshore Cape Comorin, the mean intensity of the longer duration of MCS events had slightly increased trends, and that of the shorter duration of MCS events had sightly deceased trends.

In terms of total days, all the typical sea areas showed a decreasing trend except for offshore Somalia. Moreover, the 3-MCS, 5-MCS, and 7-MCS events in offshore Somalia had almost the same increasing trends, and the 1-MCS events demonstrated almost no change. Among all scales, except for offshore Somalia, 3-MCS events demonstrated the largest decreasing trends and 1-MCS events demonstrated the smallest decreasing trends.

4.6. Teleconnection Mechanisms

4.6.1. Linked with South Asian Summer Monsoon

The South Asian Summer Monsoon (SASM) is a prominent monsoon system characterized by prevailing westerly winds in the lower troposphere, and is considered one of the most spectacular monsoon systems in the world. The onset of the South Asian Summer Monsoon (SASM) is marked by a rapid reversal of prevailing winds and a sudden increase in precipitation in South Asia, which typically occurs from late May to early June. The South Asian Summer Monsoon Index (SASMI) proposed by Li and Zeng [32–34] is an annual index to measure the interannual variability of the monsoons. It is defined as the intensity of the area-averaged seasonality (June–September) of the wind field at 850 hPa within the South Asian domain (5°–22.5° N, 35°–97.5° E). It can be downloaded from http://lijianping.cn/dct/page/65576 (assessed on 1 July 2024).

The correlation between the annual frequency of MCS events in the Arabian Sea and the South Asian Summer Monsoon (SASM) Index is shown in Figure 24. The spatial distribution of correlation degree between the SASM index and four types of MCS events was similar. Except for the waters off Somalia, Yemen, and Oman, the South Asia Summer Monsoon had positive impacts on MCS events and had larger degrees of impact on short-period MCS events than long-period MCS events. The correlation coefficients could reach 0.4–0.6 in most of the southern Arabian Sea and offshore of South India and can pass the statistical significance test at the level of 0.05. Compared with these, the SASM had negatively correlated with MCS events occurring in offshore Somalia during the past thirty years. Since its correlation coefficient with 7-MCS events could reach −0.6 and that with 1-MCS events was only −0.2, this means that long-period MCS events were easily affected by SASM.

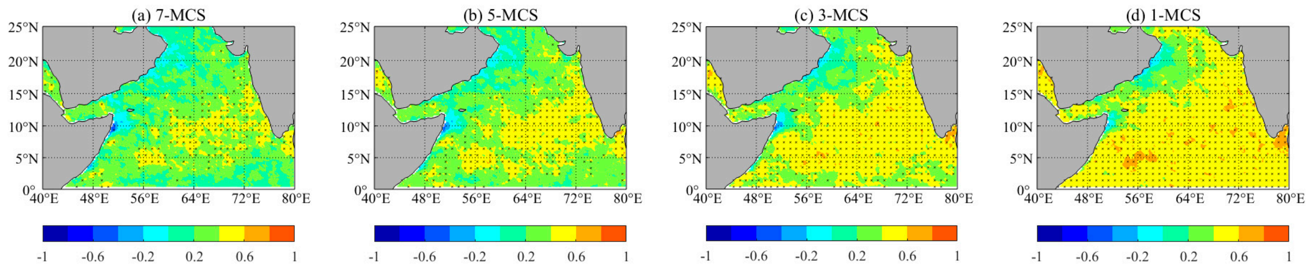

Figure 24. Correlation of annual frequency of MCS events and the South Asian Summer Monsoon Index, where the dotted area denotes statistical significance at $p < 0.05$ level.

The correlation between the mean duration of MCS events and the SASM index is shown in Figure 25. Generally, the spatial distribution of correlation degree was negative in the west and positive in the east. The largest negative correlation (−0.6 to −0.5) appeared in offshore Somalia and the largest positive correlation (0.4–0.8) appeared in the offshore of south India. The difference in correlation coefficients for 1-MCS, 3-MCS, 5-MCS, and 7-MCS events was slight, indicating that SASM had almost consistent impacts on the mean duration of both long-period and short-period MCS events. However, the SASM had weaker impacts on mean duration than the frequency of MCS events at different scales.

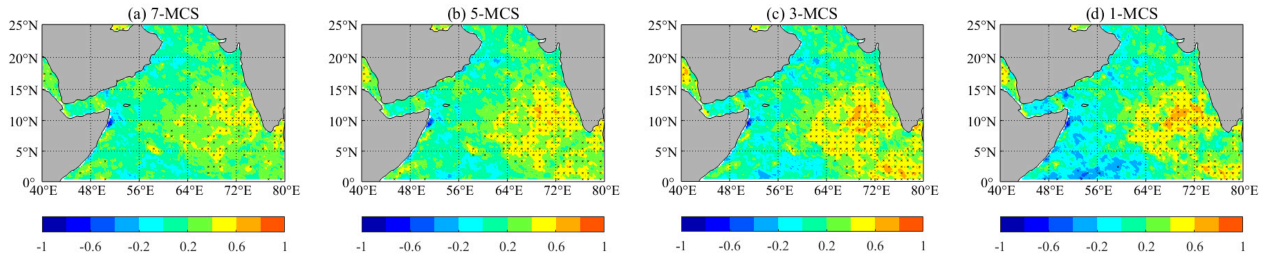

Figure 25. Correlation of mean duration of MCS events and the South Asian Summer Monsoon Index, where the dotted area denotes statistical significance at $p < 0.05$ level.

The correlation between the mean intensity of MCS events and the SASM index is shown in Figure 26. The SASM was shown to be consistently negatively correlated with the mean intensity of MCS events throughout the whole Arabian Sea, with the largest negative correlation coefficient appearing in the southeastern Arabian Sea. Similar to mean duration, the difference in correlation coefficients for 1-MCS, 3-MCS, 5-MCS, and 7-MCS events was also slight, indicating that SASM had almost consistent impacts on the mean intensity of both long-period and short-period MCS events.

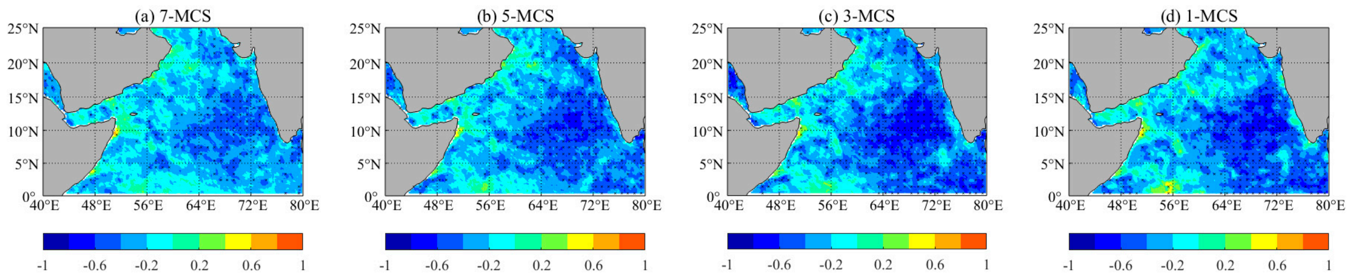

Figure 26. Correlation of mean intensity of MCS events and the SASM Index, where the dotted area denotes statistical significance at $p < 0.05$ level.

The correlation between the total days of MCS events and the SASM index is shown in Figure 27. Generally, the spatial distribution of the correlation degree between total days and SASM had a similar mode as that between frequency and SASM. The statistical significance test revealed that SASM had stronger and broader impacts on short-period MCS events than long-period MCS events.

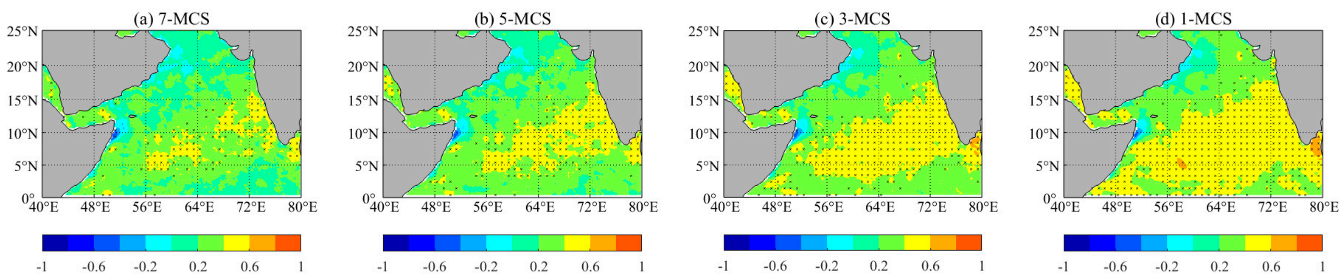

Figure 27. Correlation of total days of MCS events with SASM Index, where the dotted area denotes statistical significance at $p < 0.05$ level.

4.6.2. Linked with El Niño

The El Niño and the Southern Oscillation (ENSO) is the dominant mode of interannual climate variability, affecting not only the Pacific Ocean but also the global climate [35,36], so here we investigated the link between El Niño and MCS events in the Arabian Sea. Here, we considered four Niño indices: the Niño1+2 Index captures SST anomalies in the box 0°–10° S, 90° W–80° W; the Niño 3 index captures SST anomalies in the box 5° N–5° S, 150° W–90° W; the Niño 3.4 Index captures SST anomalies in the box 5° N–5° S, 170° W–120° W; and the Niño 4 index captures SST anomalies in the box 5° N–5° S, 160° E–150° W.

The frequency of MCS events in the northern Arabian Sea was positively correlated with all Niño indices (Figure 28), and the correlation degree with the Niño1+2 index was slightly high and that with the Niño4 index was slightly lower. In the central and southern Arabian Sea, a negative correlation with the Niño indices appeared, with a significantly high negative correlation in offshore Somalia and the Central Arabian Sea (−0.6 to −0.4). Moreover, the correlation degree with the Niño1+2 index was slightly high, and that with the Niño4 index was slightly lower. Moreover, the negative correlation degree with the Niño4 index was stronger than that with Niño1+2, Niño3, or Niño 3.4.

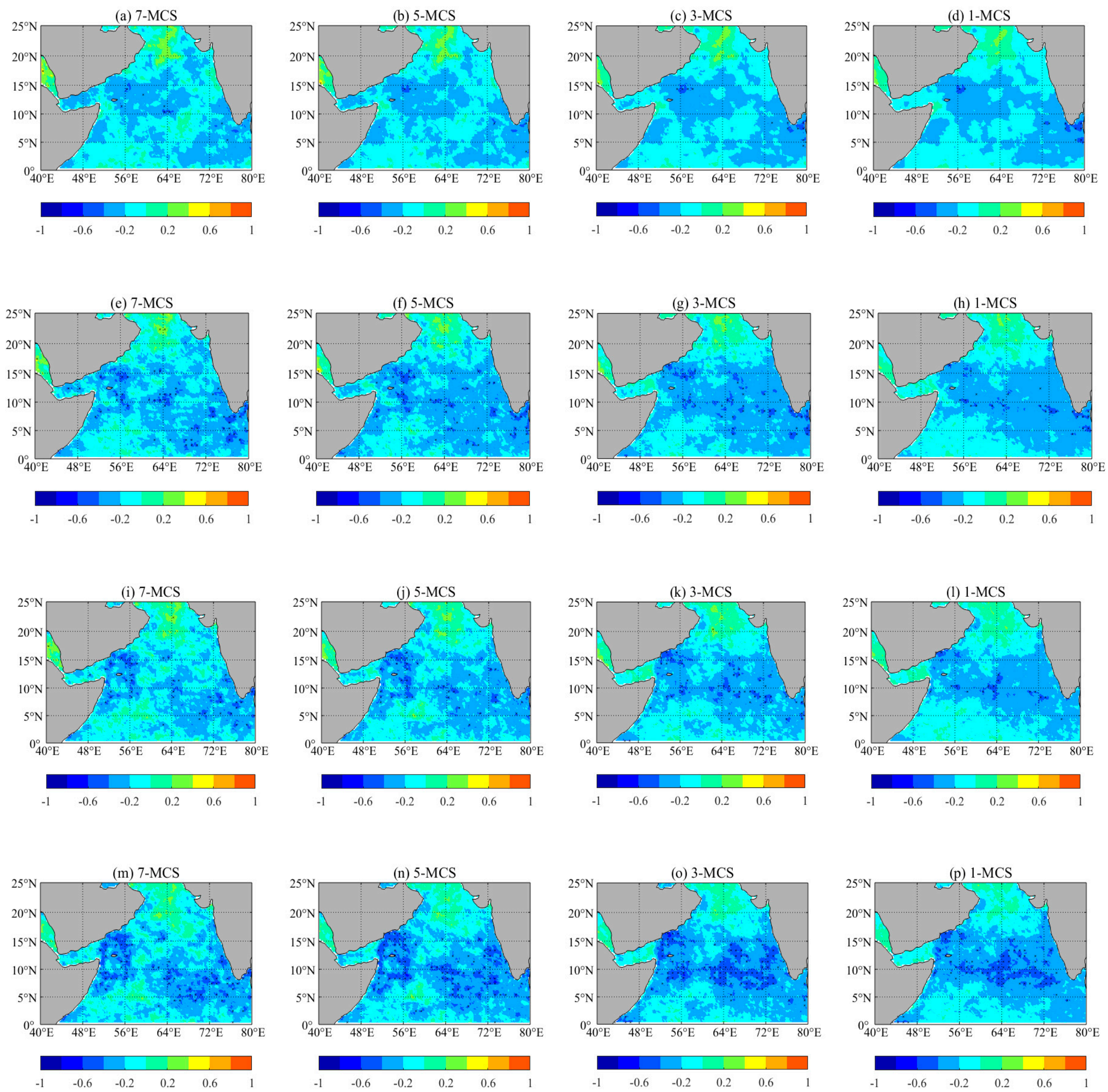

Figure 28. Correlation between frequency of MCS events and different Niño indices: (**a**–**d**) Niño1+2 index, (**e**–**h**) Niño3 index, (**i**–**l**) Niño3.4 index, and (**m**–**p**) Niño4 index (dotted area indicates statistically significant level at $p < 0.05$).

The correlation of mean duration of MCS events and Niño indices was positive in both the northern and southwest Arabian Sea, and was negative in offshore Somalia and the southeast Arabian Sea (Figure 29). These correlation degrees passed the statistical significance test only in sporadic regions of the Arabian Sea. The correlation difference among the different-scale MCS events (i.e., 1-MCS, 3-MCS, 5-MCS, 7-MCS) was small. Similar to the frequency of MCS events, the negative correlation of mean duration and the Niño4 index was strongest in the southeastern Arabian Sea compared with Niño1+2, Niño3, or Niño 3.4.

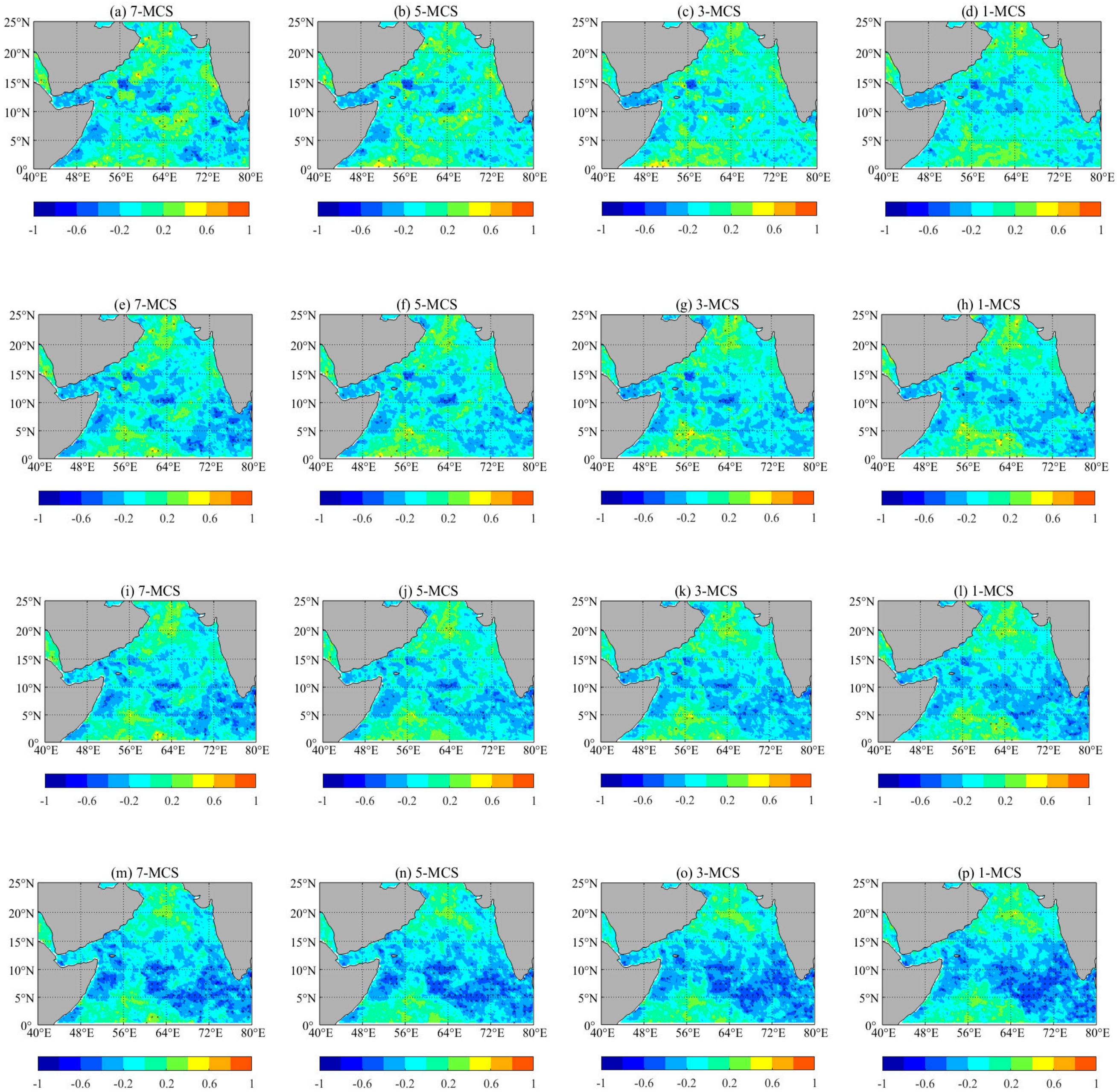

Figure 29. Correlation between mean duration of MCS events and different Niño indices: (**a**–**d**) Niño1+2 index, (**e**–**h**) Niño3 index, (**i**–**l**) Niño3.4 index, and (**m**–**p**) Niño4 index (dotted area indicates statistically significant level at $p < 0.05$).

The mean intensity of MCS events was positively correlated (0–0.6) with various Niño indices almost throughout the whole Arabian Sea, and it was negatively correlated (−0.4 to 0) only in the northern Arabian Sea (Figure 30). Moreover, the difference in correlation degrees among different types of MCS events was small. It is worth noting that the correlation between mean intensity and the Niño4 index passed the statistical significance test in many regions of the central and southern Arabian Sea.

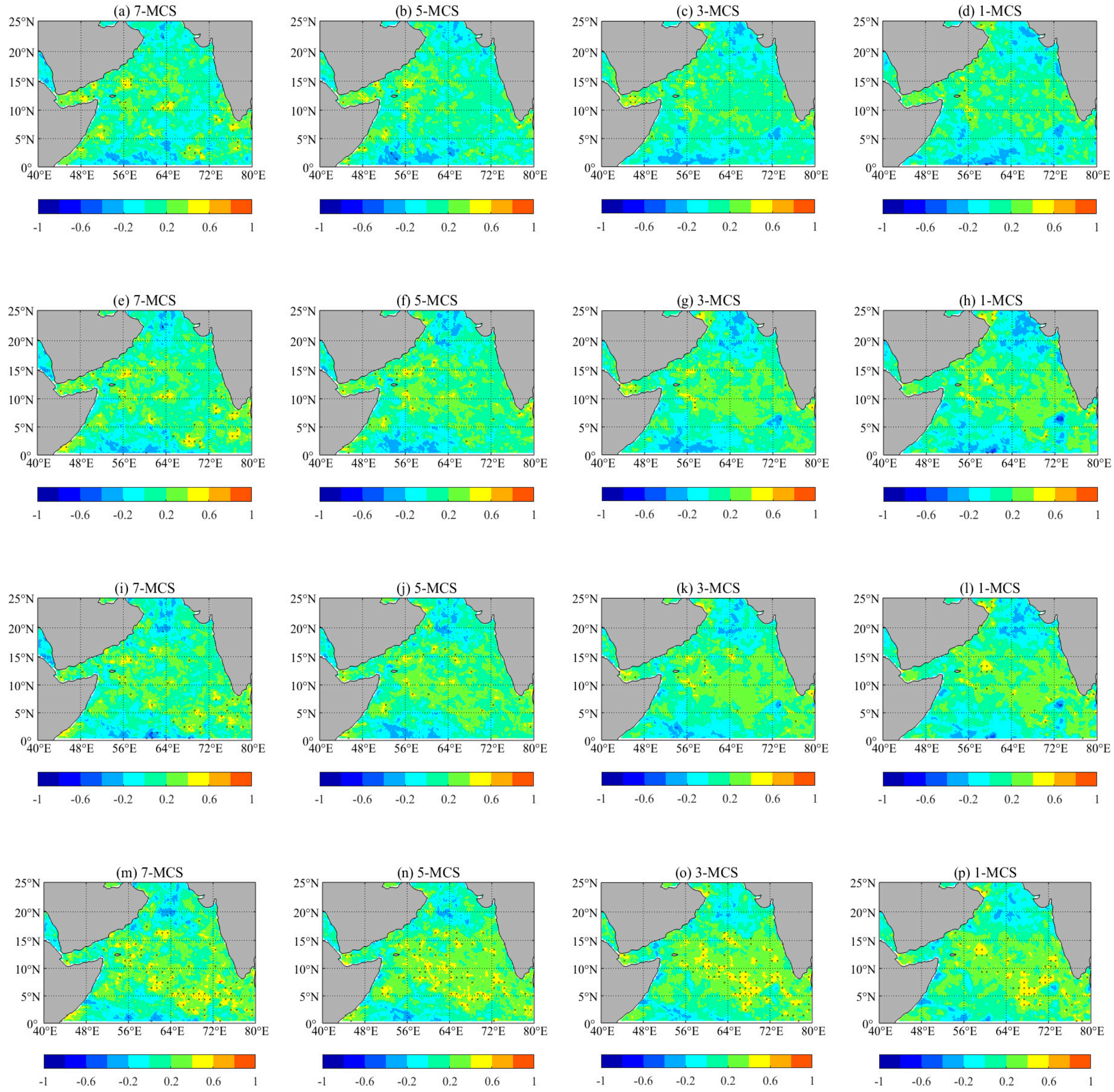

Figure 30. Correlation between mean intensity and different Niño indices: (**a**–**d**) Niño1+2 index, (**e**–**h**) Niño3 index, (**i**–**l**) Niño3.4 index, and (**m**–**p**) Niño4 index (dotted area indicates statistically significant level at $p < 0.05$).

For the total days, their correlations with Niño indices were positive in the northern Arabian Sea (0–0.4) and negative in the central and southern Arabian Sea (−0.6 to 0) (Figure 31). The spatial distribution of the correlation degrees between total days and the Niño indices was similar to that between frequency and the Niño indices. Moreover, the negative correlation of total days and the Niño4 index was strongest in the southeastern Arabian Sea and offshore Somalia when compared with Niño1+2, Niño3, or Niño 3.4.

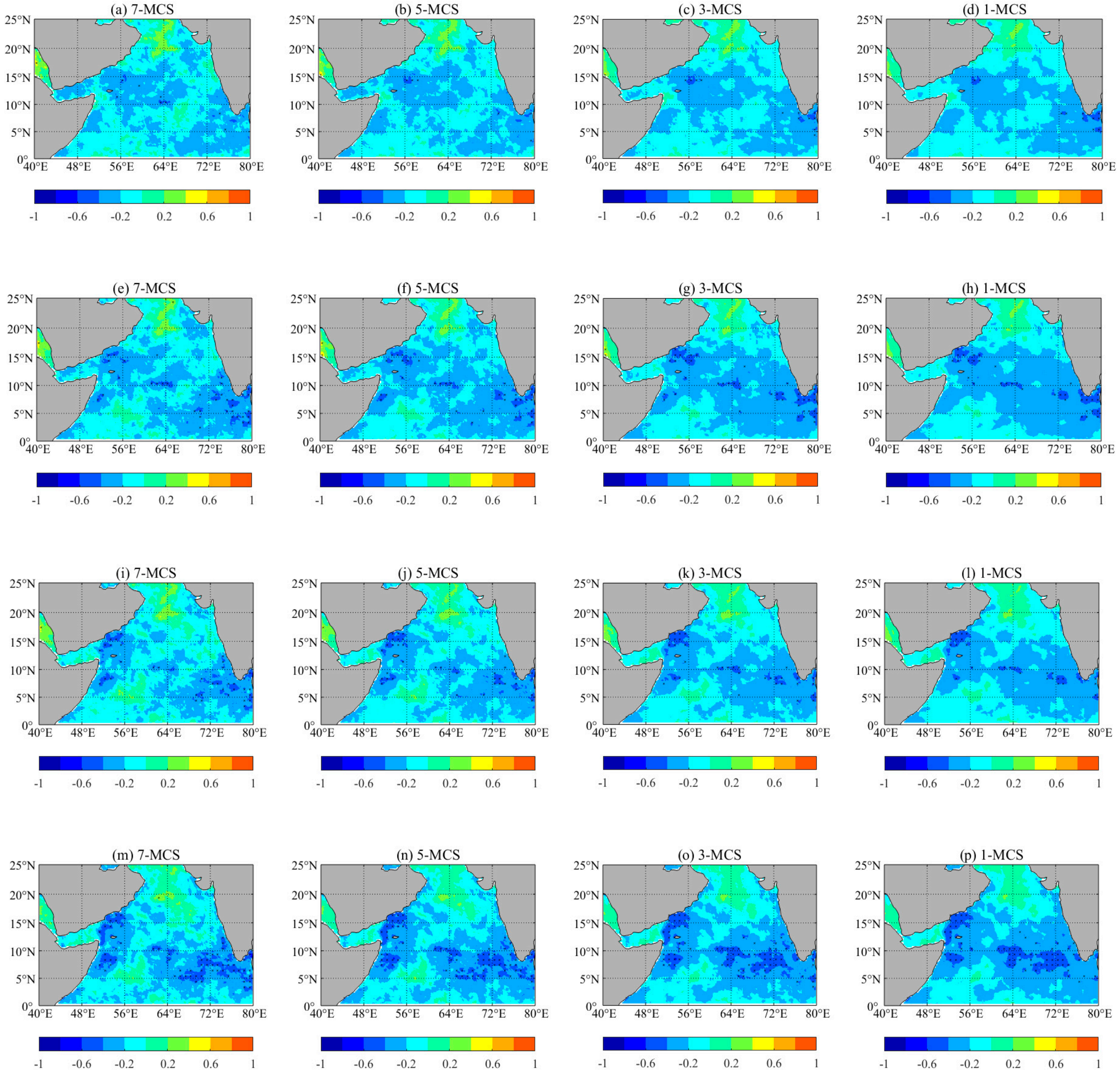

Figure 31. Correlation between total days and different Niño indices: (**a**–**d**) Niño1+2 index, (**e**–**h**) Niño3 index, (**i**–**l**) Niño3.4 index, and (**m**–**p**) Niño4 index (dotted area indicates statistically significant level at $p < 0.05$).

5. Conclusions

Our study focused on spatial patterns and evolution features of MCS events in the Arabian Sea during the past three decades. We considered four types of MCS events (7-MCS, 5-MCS, 3-MCS, 1-MCS) and four severity categories (I, II, III, IV) and gave a detailed analysis of four statistical indices (frequency, mean duration, mean intensity, total days) for different MCS type with various categories.

In the whole Arabian Sea, four types of MCS events (7-MCS, 5-MCS, 3-MCS, 1-MCS) shared similar spatial patterns in terms of frequency, mean duration, mean intensity, and total days. The MCS events in offshore Somalia had the highest occurring frequency, longest duration, largest intensity, and maximal total days, demonstrating significant differences from those in other regions of the Arabian Sea. The Somali current passing through offshore Somalia is a cold current with upwelling during summers and a warm current during winters, while other currents in the Arabian Sea are all warm currents. The cold–warm changes of Somali current make larger fluctuations in sea surface temperatures in offshore Somalia, enhancing the occurrence probability of MCS events, especially during the summers.

Mean duration and mean intensity were found to have statistically significant trends in most of the Arabian Sea, and frequency and total days were found to have statistically significant trends in limited waters off Somalia and Oman. Since 3-MCS and 1-MCS occurred much more frequently than 5-MCS and 7-MCS during 1994–2023, we showed that significantly large numbers of MCS events had only a duration of 1–3 days, and the waters at the southern end of the Indian Peninsula had significantly more short-duration MCS events. Moreover, the frequency of 1-MCS events had a more significant decreasing trend than that of 3-MCS, 5-MCS, or 7-MCS events. This means that ocean warming mainly led to the significant disappearance of short-period MCS events. It is worth noting that the mean duration of MCS events in the offshore of Oman and Mumbai demonstrated opposite trends and the difference in mean intensity of MCS events at all scales was shown to be very small.

Among four severe categories, approximately 90% of MCS events in the Arabian Sea during 1994–2023 belonged to Categories I and II. The spatial variation of Category I events was not significant inside each season, but that of Category II events was significantly large. Category II events tended to occur in the northeast Arabian Sea (spring), west Arabian Sea (summer), offshore Oman (autumn), and southeast Arabian Sea (winter). Category III events always occurred sparsely and occurred more in sea areas in autumn and winter than in spring and summer. The Category IV events occurred sporadically.

The evolution of MCS events in the Arabian Sea was found to be strongly linked with the South Asian Summer Monsoon (SASM). The correlation coefficients between frequency/mean duration/total days and SASM indices reached 0.4–0.6 in most of the southern Arabian Sea and offshore of South India and passed the statistical significance test at the level of 0.05, while the correlation between mean intensity and SASM indices was negative. The evolution of MCS events in the Arabian Sea was found to be slightly linked with ENSO. It is positively correlated in the northern Arabian Sea and negatively correlated in the central and southern Arabian Sea.

Author Contributions: Q.W. and Z.Z. are co-first authors. Conceptualization, Z.Z.; methodology, Z.Z.; software, Q.W.; validation, Q.W.; formal analysis, Z.Z., Q.W. and M.J.C.C.; investigation, Q.W.; data curation, Q.W.; writing—original draft preparation, Q.W. and Z.Z.; writing—review and editing, Z.Z. and M.J.C.C.; visualization, Q.W. All authors have read and agreed to the published version of the manuscript.

Funding: The corresponding author was supported by the European Commission Horizon 2020 Framework Program No. 861584 and the Taishan Distinguished Professor Fund No. 20190910.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to privacy reasons.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Global Monitoring Laboratory Earth System Research Laboratories: Trends in Atmospheric Carbon Dioxide (CO_2). Available online: https://www.esrl.noaa.gov/gmd/ccgg/trends/monthly.html (accessed on 6 August 2024).
2. Rhein, M.; Rintoul, S.R.; Aoki, S.; Campos, E.; Chambers, D.; Feely, R.A.; Gulev, S. Observations: Ocean. In *Climate Change 2013: The Physical Science Basis*; Cambridge University Press: Cambridge, UK, 2013; pp. 255–316.
3. Intergovernmental Panel on Climate Change (IPCC). *The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2022; pp. 3–36.

4. IPCC. 2023. Summary for policymakers. In *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Core Writing Team, Lee, H., Romero, J., Eds.; IPCC: Geneva, Switzerland, 2023; pp. 1–34.
5. Venegas, R.M.; Acevedo, J.; Treml, E.A. Three Decades of Ocean Warming Impacts on Marine Ecosystems: A Review and Perspective. *Deep. Sea Res. Part II Top. Stud. Oceanogr.* **2023**, *212*, 105318. [CrossRef]
6. World Meteorological Organization (WMO). *State of the Climate in Asia 2023 (WMO-No. 1350)*; WMO: Geneva, Switzerland, 2023; pp. 10–13. Available online: https://library.wmo.int/idurl/4/68890 (accessed on 1 January 2024).
7. Roxy, M.K.; Ritika, K.; Terray, P.; Murtugudde, R.; Ashok, K.; Goswami, B.N. Drying of Indian subcontinent by rapid Indian Ocean warming and a weakening land-sea thermal gradient. *Nat. Commun.* **2015**, *6*, 7423. [CrossRef] [PubMed]
8. Rao, S.A.; Dhakate, A.R.; Saha, S.K.; Mahapatra, S.; Chaudhari, H.S.; Pokhrel, S.; Sahu, S.K. Why is Indian Ocean warming consistently? *Clim. Chang.* **2012**, *110*, 709–719. [CrossRef]
9. Swapna, P.; Krishnan, R.; Wallace, J.M. Indian Ocean and monsoon coupled interactions in a warming environment. *Clim. Dyn* **2014**, *42*, 2439–2454. [CrossRef]
10. Roxy, M.K.; Ritika, K.; Terray, P.; Masson, S. The Curious Case of Indian Ocean Warming. *J. Clim.* **2014**, *27*, 8501–8509. [CrossRef]
11. DiNezio, P.N.; Puy, M.; Thirumalai, K.; Jin, F.-F.; Tierney, J.E. Emergence of an equatorial mode of climate variability in the Indian Ocean. *Sci. Adv.* **2020**, *6*, eaay7684. [CrossRef]
12. Du, Y.; Xie, S.P.; Huang, G.; Hu, K. Role of air–sea interaction in the long persistence of El Niño–induced north Indian Ocean warming. *J. Clim.* **2009**, *22*, 2023–2038. [CrossRef]
13. Hobday, A.J.; Alexander, L.V.; Perkins, S.E.; Smale, D.A.; Straub, S.C.; Oliver, E.C.J.; Benthuysen, J.A.; Burrows, M.T.; Donat, M.G.; Feng, M.; et al. A hierarchical approach to defining marine heatwaves. *Prog. Oceanogr.* **2016**, *141*, 227–238. [CrossRef]
14. Oliver, E.C.J.; Donat, M.G.; Burrows, M.T.; Moore, P.J.; Smale, D.A.; Alexander, L.V.; Benthuysen, J.A.; Feng, M.; Gupta, A.S.; Hobday, A.J.; et al. Longer and more frequent marine heatwaves over the past century. *Nat. Commun.* **2018**, *9*, 1324. [CrossRef]
15. Smale, D.A.; Wernberg, T.; Oliver, E.C.J.; Thomsen, M.; Harvey, B.P.; Straub, S.C.; Burrows, M.T.; Alexander, L.V.; Benthuysen, J.A.; Donat, M.G.; et al. Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nat. Clim. Chang.* **2019**, *9*, 306–312. [CrossRef]
16. Oliver, E.C.; Benthuysen, J.A.; Darmaraki, S.; Donat, M.G.; Hobday, A.J.; Holbrook, N.J.; Schlegel, R.W.; Gupta, A.S. Marine Heatwaves. *Annu. Rev. Mar. Sci.* **2021**, *13*, 313–342. [CrossRef]
17. Ibrahim, O.; Mohamed, B.; Nagy, H. Spatial Variability and Trends of Marine Heat Waves in the Eastern Mediterranean Sea over 39 Years. *J. Mar. Sci. Eng.* **2021**, *9*, 643. [CrossRef]
18. Dinesh, A.S.; Kumar, P.; Mishra, A.K.; Pandey, L.K.; Tewari, M.; Cabos, W.; Sein, D.V. Analyzing future marine cold spells in the tropical Indian Ocean: Insights from a regional Earth system model. *Q. J. R. Meteorol. Soc.* **2024**, *150*, 1668–1685. [CrossRef]
19. Li, Y.; Ren, G.; Wang, Q.; Mu, L. Changes in marine hot and cold extremes in the China Seas during 1982–2020. *Weather. Clim. Extrem.* **2023**, *19*, 100553. [CrossRef]
20. Yao, Y.; Wang, C. Marine Heatwaves and Cold-Spells in Global Coral Reef Zones. *Prog. Oceanogr.* **2022**, *209*, 102920. [CrossRef]
21. CMFRI: Marine Fisheries Profile India. 2007. Available online: http://www.cmfri.org.in/data-publications-/5/2007 (accessed on 6 August 2024).
22. Shankar, D.; Remya, R.; Anil, A.C.; Vijith, V. Role of physical processes in determining the nature of fisheries in the eastern Arabian Sea. *Prog. Oceanogr.* **2018**, *172*, 124–158. [CrossRef]
23. Levitus, S.; Antonov, J.I.; Boyer, T.P.; Baranova, O.K.; Garcia, H.E.; Locarnini, R.A.; Mishonov, A.V.; Reagan, J.R.; Seidov, D.; Yarosh, E.S.; et al. World ocean heat content and thermosteric sea level change (0–2000 m), 1955–2010. *Geophys. Res. Lett.* **2012**, *39*, L10603. [CrossRef]
24. Crisp, D.J. The Effects of the Severe Winter of 1962-63 on Marine Life in Britain. *J. Anim. Ecol.* **1964**, *33*, 165. [CrossRef]
25. Chang, Y.; Lee, M.-A.; Lee, K.-T.; Shao, K.-T. Adaptation of fisheries and mariculture management to extreme oceanic environmental changes and climate variability in Taiwan. *Mar. Policy* **2013**, *38*, 476–482. [CrossRef]
26. Crabbe MJames, C. Adapting to extreme environments: Can coral reefs adapt to climate change? *Emerg. Top. Life Sci.* **2019**, *3*, 183–195.
27. Zapata, F.A.; Jaramillo-González, J.; Navas-Camacho, R. Extensive bleaching of the coral porites lobata at malpelo island, colombia, during a cold water episode in 2009. *Boletín De Investig. Mar. Y Costeras-INVEMAR* **2011**, *40*, 185–193.
28. Huang, B.; Liu, C.; Banzon, V.; Freeman, E.; Graham, G.; Hankins, B.; Smith, T.; Zhang, H.-M. Improvements of the Daily Optimum Interpolation Sea Surface Temperature (DOISST) Version 2.1. *Am. Meteorol. Soc.* **2021**, *34*, 2923–2939. [CrossRef]
29. Schlegel, R.W.; Darmaraki, S.; Benthuysen, J.A.; Filbee-Dexter, K.; Oliver, E.C. Marine cold-spells. *Prog. Oceanogr.* **2021**, *198*, 102684. [CrossRef]
30. Zhao, Z.; Marin, M. A MATLAB toolbox to detect and analyze marine heatwaves. *J. Open Source Softw.* **2019**, *4*, 1124. [CrossRef]
31. Hobday, A.J.; Oliver EC, J.; Gupta, A.S.; Benthuysen, J.A.; Burrows, M.T.; Donat, M.G.; Holbrook, N.J.; Moore, P.J.; Thomsen, M.S.; Wernberg, T.; et al. Categorizing and naming marine heatwaves. *Oceanography* **2018**, *31*, 162–173. [CrossRef]
32. Li, J.P.; Zeng, Q.C. A new monsoon index, its interannual variability and relation with monsoon precipitation. *Clim. Environ. Res.* **2005**, *10*, 351–365.
33. Li, J.P.; Zeng, Q.C. A new monsoon index and the geographical distribution of the global monsoons. *Adv. Atmos. Sci.* **2003**, *20*, 299–302.

34. Li, J.P.; Zeng, Q.C. A unified monsoon index. *Geophys. Res. Lett.* **2002**, *29*, 1274. [CrossRef]
35. Zhang, L.; Du, Y.; Tozuka, T.; Kido, S. Revisiting ENSO impacts on the Indian Ocean SST based on a combined linear regression method. *Acta Oceanol. Sin.* **2021**, *40*, 47–57. [CrossRef]
36. Cai, W.; Ng, B.; Wang, G.; Santoso, A.; Wu, L.; Yang, K. Increased ENSO sea surface temperature variability under four IPCC emission scenarios. *Nat. Clim. Chang.* **2022**, *12*, 228–231. [CrossRef]