Compounding effects of hurricanes and marine heat waves in the Gulf of America

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Abstract

Exposure to extreme events is a primary concern for coastal regions where growing populations and stressed ecosystems are increasingly vulnerable. This study assesses the compounding effects of hurricanes and marine heatwaves (MHWs) in the Gulf of America. Using data from 1982 to 2024, we quantify MHWs through metrics of intensity, frequency, duration, and spatial extent, and examine their interaction with hurricane activity. Our results show that hurricanes have become more frequent and their active season has lengthened. Concurrently, MHW events have become significantly longer and more frequent during the summer months compared to spring or late winter. The convergence of these trends demonstrates a rising compound effect in the Gulf of America. These results underscore the need for further research into multi-hazard interactions to better inform regional disaster prevention.

1. Introduction

The Gulf of America is a semi-enclosed basin critical to the economy and ecology of the United States and Mexico, supporting vital energy infrastructure, fisheries, and unique marine ecosystems [1]. However, this region faces numerous natural hazards, with tropical cyclones (Hurricanes) and Marine Heat Waves (MHWs) posing two of the most significant and rapidly evolving threats. Hurricanes are intense, low-pressure systems characterized by high winds, torrential rainfall, and destructive storm surges, representing acute, short-duration hazards. In contrast, MHWs are prolonged periods of anomalously high sea surface temperatures (SST) that can persist for weeks or months, representing chronic thermal stress on the marine environment [2].

Hurricanes have been infamous for causing catastrophic damage, both in human and economic terms. Storm surge, high winds, and heavy rainfall culminate in widespread destruction, with each hurricane making landfall causing an average of $22.8B in damage from destroyed infrastructure, business interruptions, and rising insurance premiums [3]. The Gulf of America is especially at risk, with the majority of the 52 deadliest hurricanes in the United States making landfall there [4].

Long-term trends indicate that damage associated with hurricanes in the Gulf of America will intensify. Hurricane flood hazards will increase as the effects of sea level rise and hurricanes compound, causing more intense hurricane-induced flooding in over 40% of Gulf countries [5]. Moreover, other associated risks are likely to increase across the next 50 years as well. For example, hurricane landfall rates and wind speeds are expected to intensify due to climate change, leading to increased vulnerability in Gulf regions such as Florida, George, South Carolina, and North Carolina [6]. Overall, these factors will culminate in more extreme hurricane events in the future. To make matters worse, the growing populations and regional wealth in the

Gulf of America will only increase the propensity for hurricane-related damage, with two storms in 2017 alone costing the region over 125 billion dollars.

On the other hand, MHWs arguably pose a risk just as salient as hurricanes on the Gulf of America. MHWs cause coral bleaching by exerting significant thermal stress on coral reefs, which leads to mass die-offs, threatening ocean biodiversity [7]. Moreover, MHWs cost local economies billions of dollars through destroying fisheries, eroding essential ecosystems, and driving mass mortality of iconic species [8].

MHWs in the Gulf of America have also become increasingly threatening, with rising frequencies, duration, and intensities from 1983 to 2021. This trend can be attributed to increased variability in atmospheric circulation, such as trade winds, which push warm, low-latitude seawater into the Gulf of America, causing a denser concentration of warm water in the Gulf. Furthermore, warm-core mesoscale eddies, such as anticyclonic eddies, are characterized by high SSTs and shallower mixed layers than the surrounding water, which increases the likelihood of MHW formation [7].

However, despite the extensive focus on individual hazards and their long-term trends, a critical gap remains: the vast majority of existing studies treat hurricanes and MHWs as isolated, independent threats. To effectively inform disaster planning and mitigation policies, it's imperative to quantify the characteristics of the disasters, along with their compounding effects. This gap in the literature overlooks the potential for compounding impacts, posing roadblocks to disaster planning in the Gulf of America, which jeopardizes the livelihood of millions. For instance, extremely high sea surface temperatures during an MHW can provide the necessary thermodynamic fuel for passing tropical cyclones, contributing to explosive intensification. Conversely, an ecosystem already weakened by the chronic thermal stress of an MHW may lack the resilience required to recover from the acute physical disturbance and sediment runoff caused by a hurricane. Thus, this paper directly addresses this vulnerability by investigating the compounding effect between MHW events and hurricanes. Specifically, we identify and characterize the spatial patterns and temporal variations of the concurrent events.

2. Data and Methods

2.1 Hurricanes

The hurricane track data is from the National Hurricane Center's (NHC) revised Atlantic Hurricane Database, HURDAT2. The database provides the most available information for hurricanes dating back to 1851, including name, identifier number, and the position of the center of the storm over the course of the hurricane. The position estimation is utilized to track the storm paths.

The raw dataset is processed using the 'hurdat2parser' package. We defined a hurricane as having entered the Gulf of America if it, at any point, crossed the US Gulf Coast and subsequently made landfall. Along the path of each hurricane that enters the Gulf, we assume that the surrounding areas within a 300-kilometer radius will be significantly affected by the hurricane at a given time. If another event (i.e., MHW in this paper) takes place within this area and during the same period, it will be taken as a compounding event along with hurricanes.

2.2 Ocean temperatures

SST data were from NOAA's Optimum Interpolation Sea Surface Temperature (OISST) dataset. It provides daily sea surface temperatures at 0.25 degrees for the entire globe. Using Hobday et al.'s definition, this paper defines MHWs as SST events with temperatures exceeding a seasonally evolving threshold for 5 or more days. This methodology accounts for seasonal variations in ocean temperature, which allows for contextual identification of MHW events across different seasons. Among the numerous metrics in the dataset, we used duration, max intensity, and cumulative intensity data to analyze MHWs.

3. Results

3.1 Hurricanes

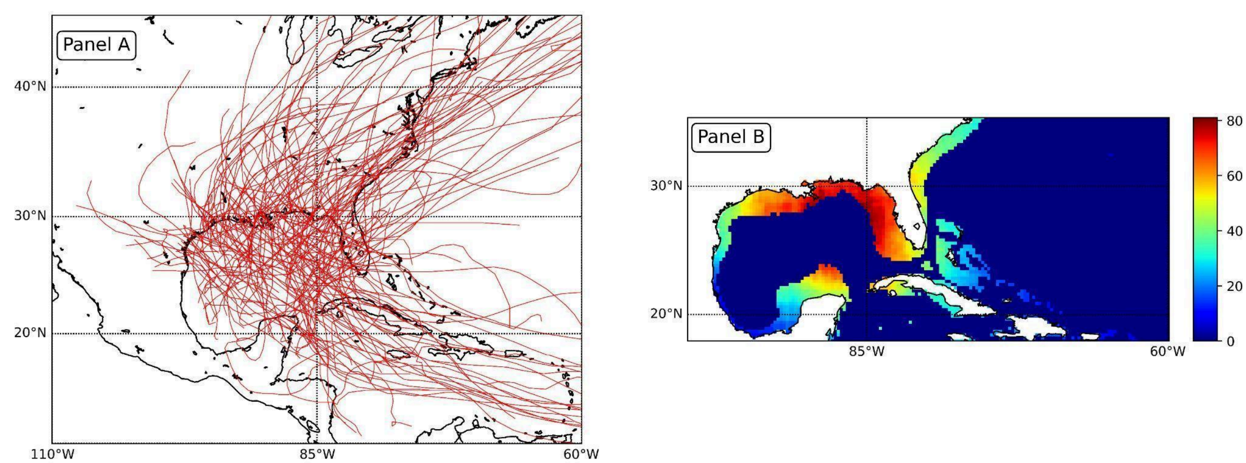

Figure 1. Spatial characteristics of the hurricanes. We selected hurricanes of all categories that made landfall on the Gulf coast between May and December from 1982 to 2024. That identifies 130 hurricanes with tracks shown in panel A. The storms generally have a trajectory entering the Gulf from the Southeast. Our target is to see how hurricanes affect shallow waters (Water depth < 100 meters). To qualify the hurricane frequencies for each location in shallow waters, we analyzed grid by grid. For each grid point, we counted the number of hurricanes whose track fell within 300 kilometers of that location. Panel B denotes the number of hurricanes that affected

each grid point. Hurricanes are especially dense in the Eastern and Northern parts of the Gulf, which will be an object of study in this paper. The hurricane frequency for a grid point ranges from zero to more than seventy.

3.2 Heat waves in ocean temperature

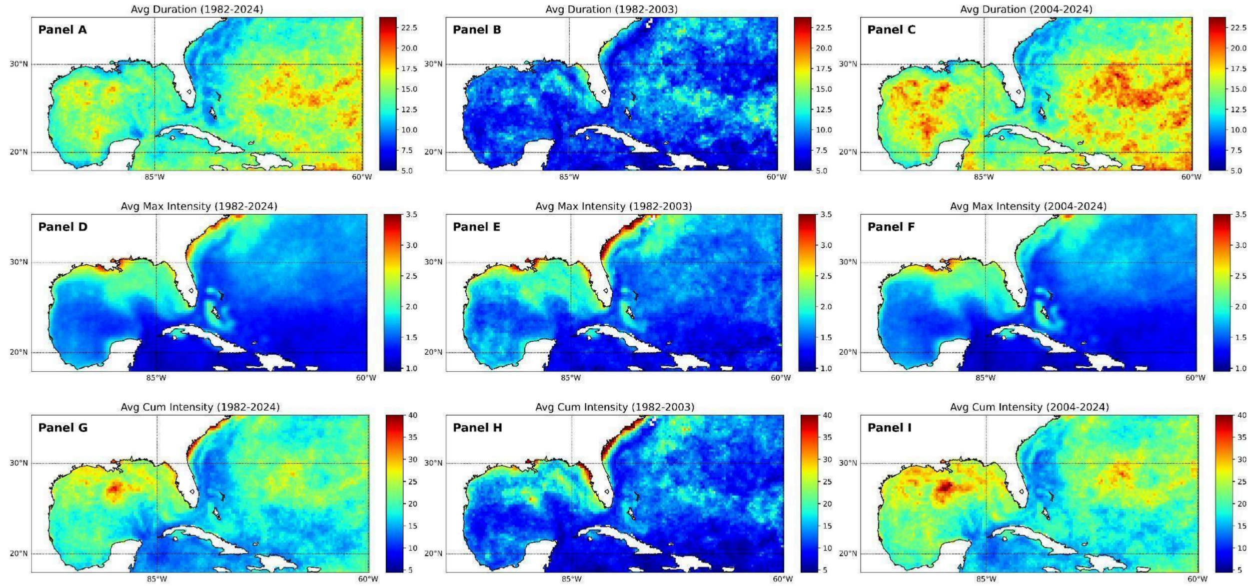

Figure 2. The three figures in the left column describe the properties of MHWs in terms of mean duration, max intensity, and cumulative intensity. In these figures, cumulative intensity is the integral of the intensity over the duration of an individual MHW; max intensity describes the maximum singular value for intensity for a MHW; duration denotes the length of a given MHW in days. The middle and right columns denote the same parameters over 1982-2003 (Period 1) and 2004-2024 (Period 2), respectively.

The properties of the MHWs are shown in Figure 2. The mean duration of MHWs over the past 40 years shows that MHWs in the central Gulf of America can reach a duration of around 20 days (Fig. 2A). The duration is much shorter near coastal regions, with means closer to 10 days. When splitting into two periods, its average duration in period 1 (1982-2003) is generally short, with mean values close to 7-8 days across the Gulf of America (Fig. 2B). MHW duration in period 2 (2004-2024) shows a dramatic increase with especially longer durations in the Western parts of the Gulf of America, along with some parts of the Atlantic Ocean (Fig. 2C). This suggests that the duration of MHW has increased from 1 week to 3 weeks in the last two decades.

The max intensity of MHW is stronger near the coast, reaching more than 3°C. The intensity decreases offshore to values about 2°C (Fig. 2D). Data for Periods 1 and 2 show a similar spatial pattern, with elevated max intensities also appearing along the coast (Fig. 2E, 2F). Notably, the max intensity in period 1 is stronger than that in period 2, especially in coastal areas. The intensities are comparable in the offshore regions in the two periods.

The average cumulative intensities of MHWs over the past 40 years are enhanced in the Northern Central part of the Gulf of America, reaching values of around 30, and become less pronounced towards the outer edge of the Gulf, dropping to a magnitude of around 10 (Fig. 2G). In Period 1, cumulative intensity is much weaker towards the southeastern Gulf region, with values reaching 5. It displays sporadic hotspots in the Central Northern part of the Gulf with values up to 40 (Fig. 2H). As a comparison, data for period 2 shows significant increases with elevated intensity across most of the Gulf. But the cumulative intensities along the coast become much weaker in period 2 (Fig. 2I). Given that the cumulative intensities can be taken as the integral of duration and intensity, their changes from period 1 and period 2 are contributed by either duration or intensity. In short, the coast region is characterized by intensity changes but the offshore region is dominated by duration changes.

3.3 Compounding between MHW and hurricanes

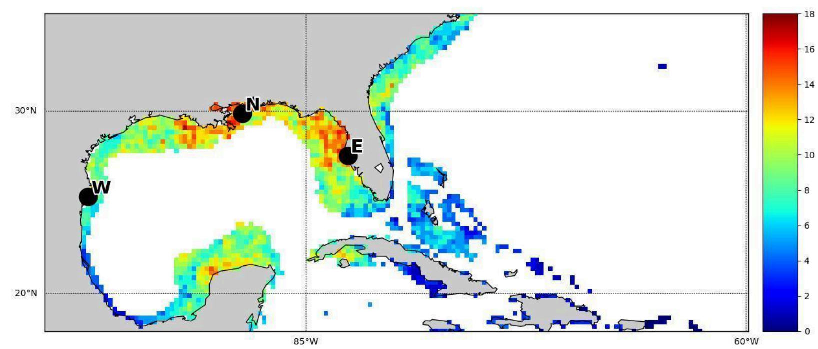

Figure 3. The number of hurricanes and MHWs overlapping at each location, with overlap defined as a hurricane passing a given location within 10 days of an MHW's start date at that location. The three black dots denote three representative locations in the Western, Northern, and Eastern parts of the Gulf that experience the most overlap between MHWs and hurricanes in their respective regions.

The compounding effect of two types of disaster events is quantified by counting the overlap between hurricanes and MHWs. As shown in Figure 3, there are fewer overlapping events in the Southwest and eastmost parts of the Gulf of America, with overlapping numbers ranging from around 2 to 4. The locations with the most overlapping are the Northern and Eastern coasts of the Gulf, with frequencies as high as 18 overlapping events. Other areas in the Gulf, such as the Northwest, Northeast, and Southern portions, experience more moderate frequencies, with overlap ranging from around 6 to 14 events.

To elucidate the factors accounting for the compounding disaster events, the temporal characteristics of hurricanes and MHW are analyzed at the three representative locations.

3.3.1 Yearly Distribution of Hurricanes

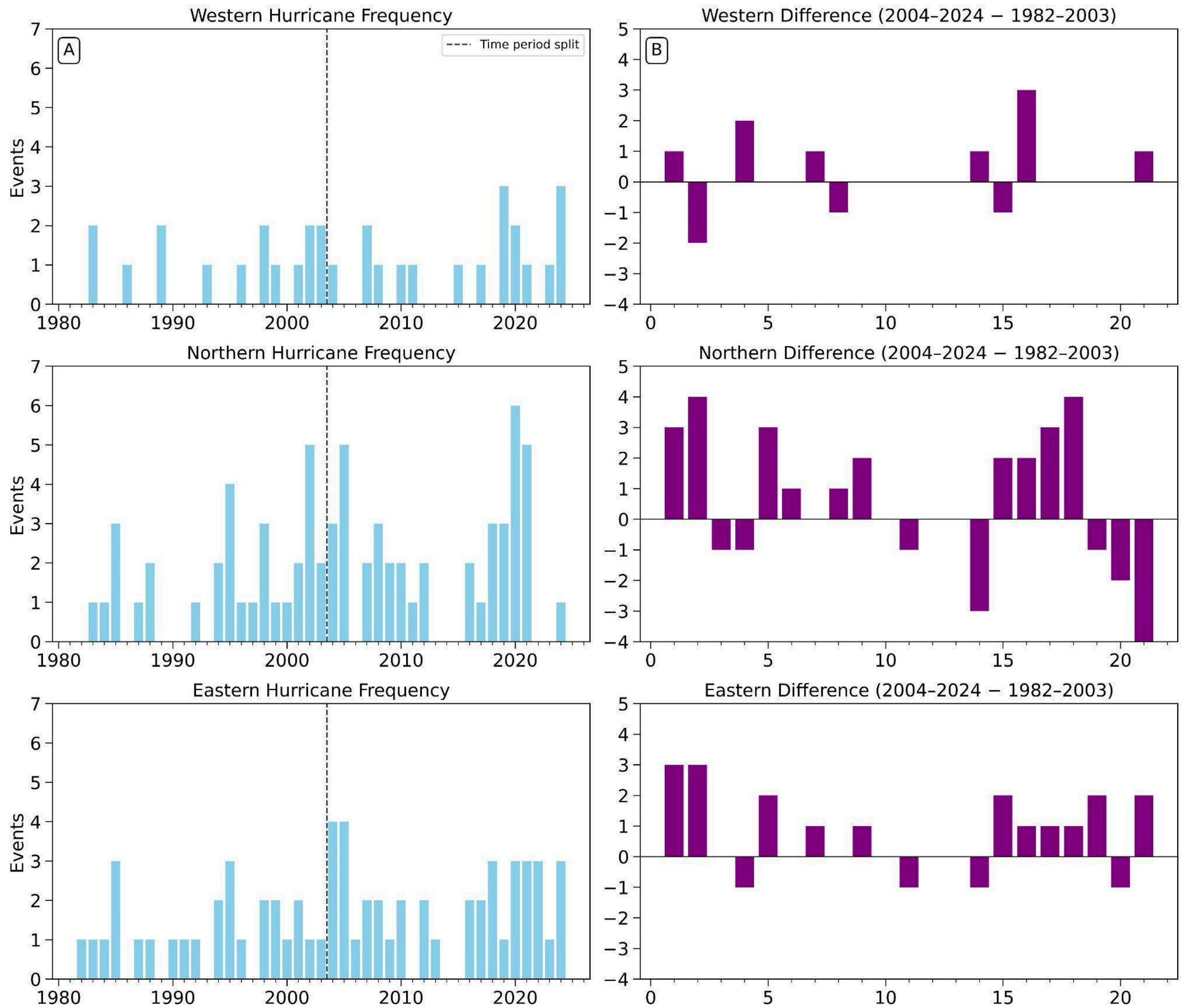

Figure 4. The left column shows the hurricane frequency at the Western (A), Northern (B), and Eastern location (C), with each given a distinct value for each year in our range. The coordinates of the three representative locations are marked in Figure 3. The right column denotes the difference in the number of events between our two time periods, which reveals trends in hurricane frequency over the past few decades.

To examine the temporal changes in hurricane frequency, we analyzed the yearly distribution of hurricanes at three representative locations, representing the western, northern, and eastern parts of the Gulf. In the early 1980s, hurricane frequencies in the Gulf generally ranged from 0 to 2 per year. Starting around the early 2000s and mid-2010s, frequencies began to ramp up, creating two distinct peaks of 3-6 hurricanes per year (Fig. 4). Overall, we observe a general trend of hurricane counts increasing significantly as we compare recent years to earlier ones. The Western region has experienced the least change, remaining relatively inactive, albeit with certain years seeing spikes of up to 3 hurricanes. On the other hand, the Eastern region represents the strongest upward trend and has been dramatically more active in recent decades. Likewise, the Northern region also exhibits similar increases, with strong clustering towards the beginning of the 2020s.

To illustrate the trend of increasing hurricane frequencies, we demonstrate the difference between the two time periods, with positive values indicating an increase in hurricane frequency. The Western region exhibits the least increase in hurricane frequency, with just 1 more hurricane for most years, while the Eastern region denotes a slightly more significant influx with 1-2 more hurricanes for most years. The Northern region is most significant, with the biggest disparity being 4 more hurricanes. Therefore, in the Northern and Eastern Gulf, hurricanes have become more frequent in the past 2 decades.

3.3.2 Monthly Distribution of Hurricanes

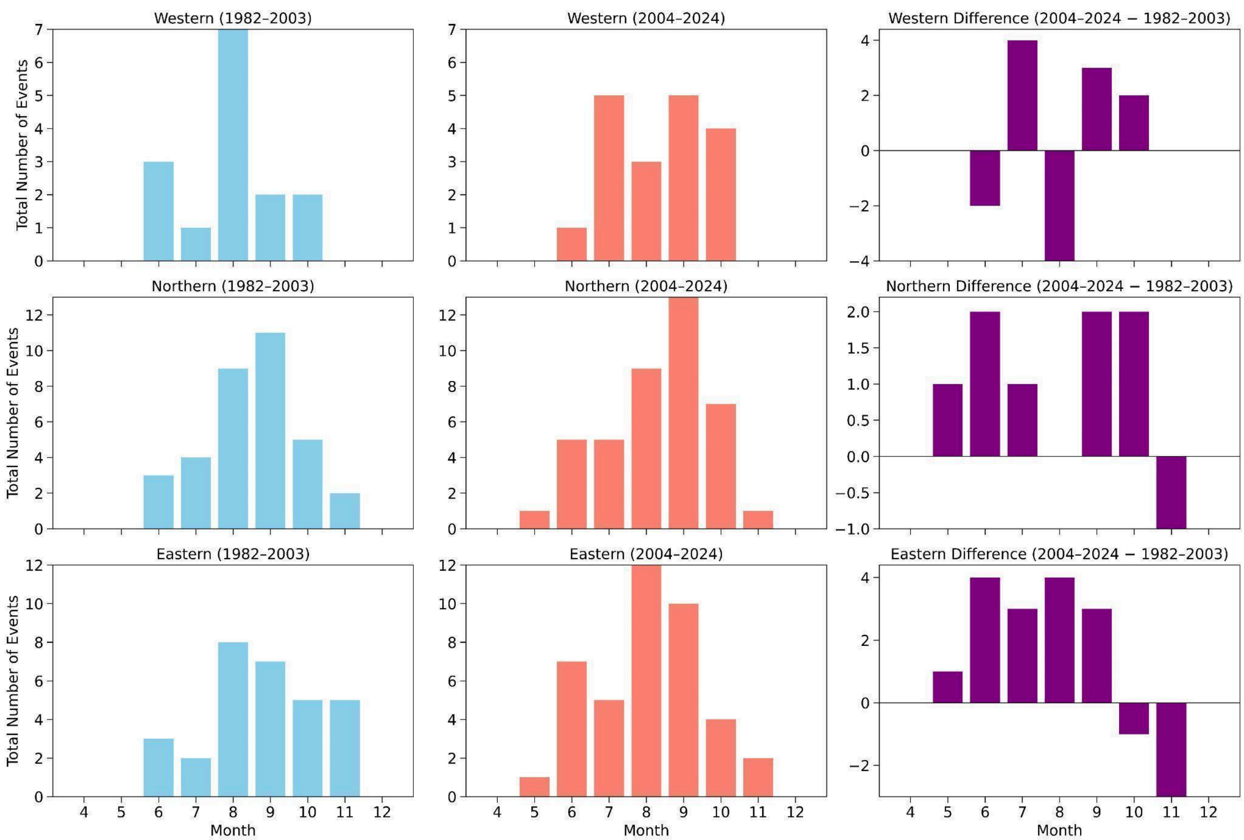

Figure 5. Each row denotes the average monthly hurricane frequency in the Western, Northern, and Eastern Gulf. The graphs in the first column show aggregated monthly data over our first time period (1982-2003), and the second column shows monthly aggregations over the second time period (2004-2024). The third row denotes the difference in monthly frequency between the two time periods, tracking long-term monthly trends in hurricane frequency.

Given that hurricanes only occur in certain months, we analyzed the average monthly distribution of hurricane frequency at the three representative locations. We find August and September to be peak months for hurricanes, with no hurricanes occurring before June or in December (Figure 5). Similar to the yearly distribution, we also compared the monthly distributions in two periods (1982-2003 and 2004-2024). In the first period, hurricane frequency peaked in August and September (7 events in the West, 11 in the North, and 8 in the East) while there were no hurricanes before June or after November of each year. In the second period, the most hurricanes happened in July and September (5 events). In the Northern Gulf, the peak month remained August (13 events in period two) across the two time periods. Similarly, in the Eastern Gulf, the peak month remained August, with frequency increasing from 8 to 12 events across the two periods. Therefore, a comparison of the two periods shows that in the West, hurricane frequencies increased only in July, September, and October. However, in the Northern and Eastern Gulf, hurricanes became more frequent almost every month from May to October (Figure 5).

3.3.3 Monthly Distribution of MHW Duration

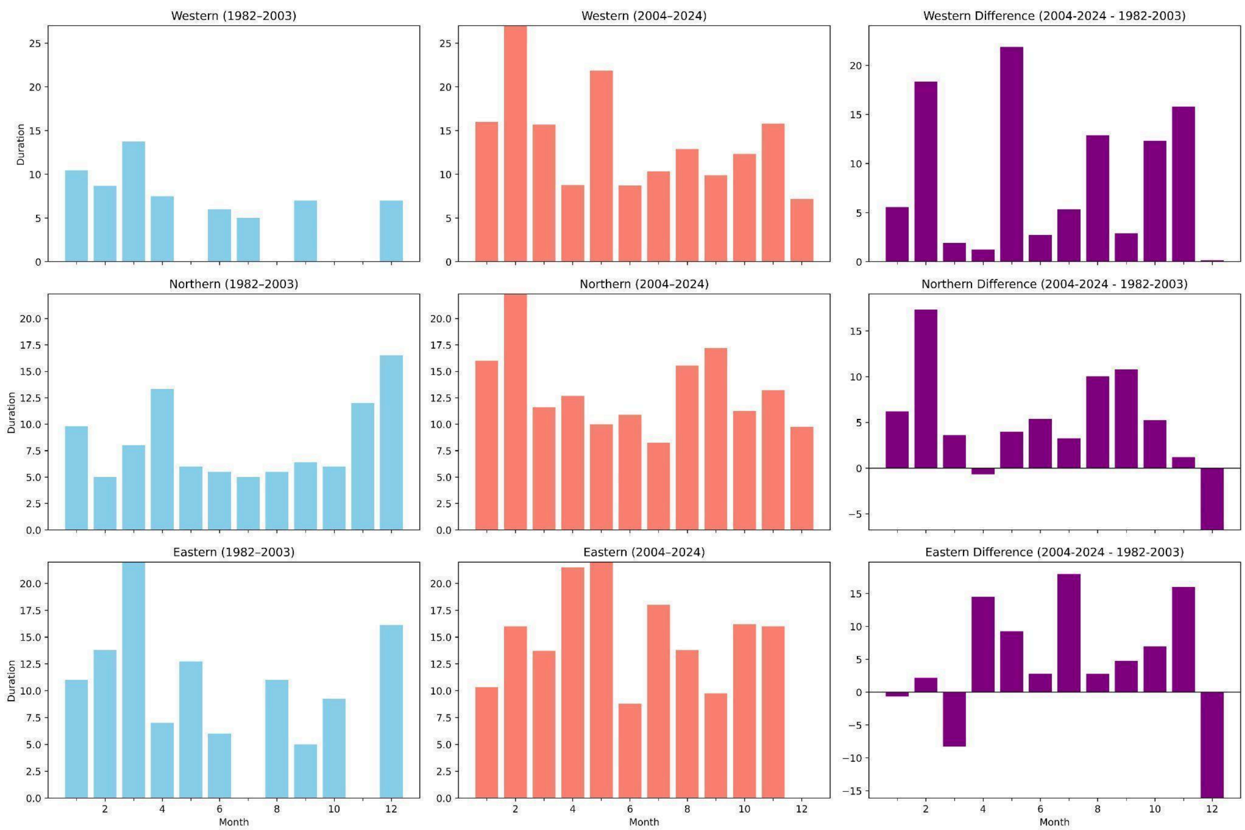

Figure 6. Each row shows the monthly average distribution of MHW duration (unit: days) in three representative regions in the Gulf over the first time period (1982-2003), the second time period (2004-2024), and the difference between the two time periods.

In the first time period, the longest MHW durations were seen in the Spring and Winter, with the shortest values in the Summer. The Northern Gulf saw the longest average MHW duration of ~14 days in March. The longest average duration in the North was around 16 days in December, and 22.5 days in March in the East. Over the second time period, the longest MHW durations also occurred in the late Winter and Spring. Both the Western and Northern periods saw a peak in February, each around 27 and 22.5 days long, respectively. In the Eastern Gulf, the peak took place in May, with an average duration of 22.5 days. However, comparing the two periods, the

MHW duration increased almost every month, aside from a few occasional outliers. Therefore, the longer MHWs in the recent two decades have occurred across the entirety of the Gulf.

3.3.4 Yearly distribution of MHW Duration

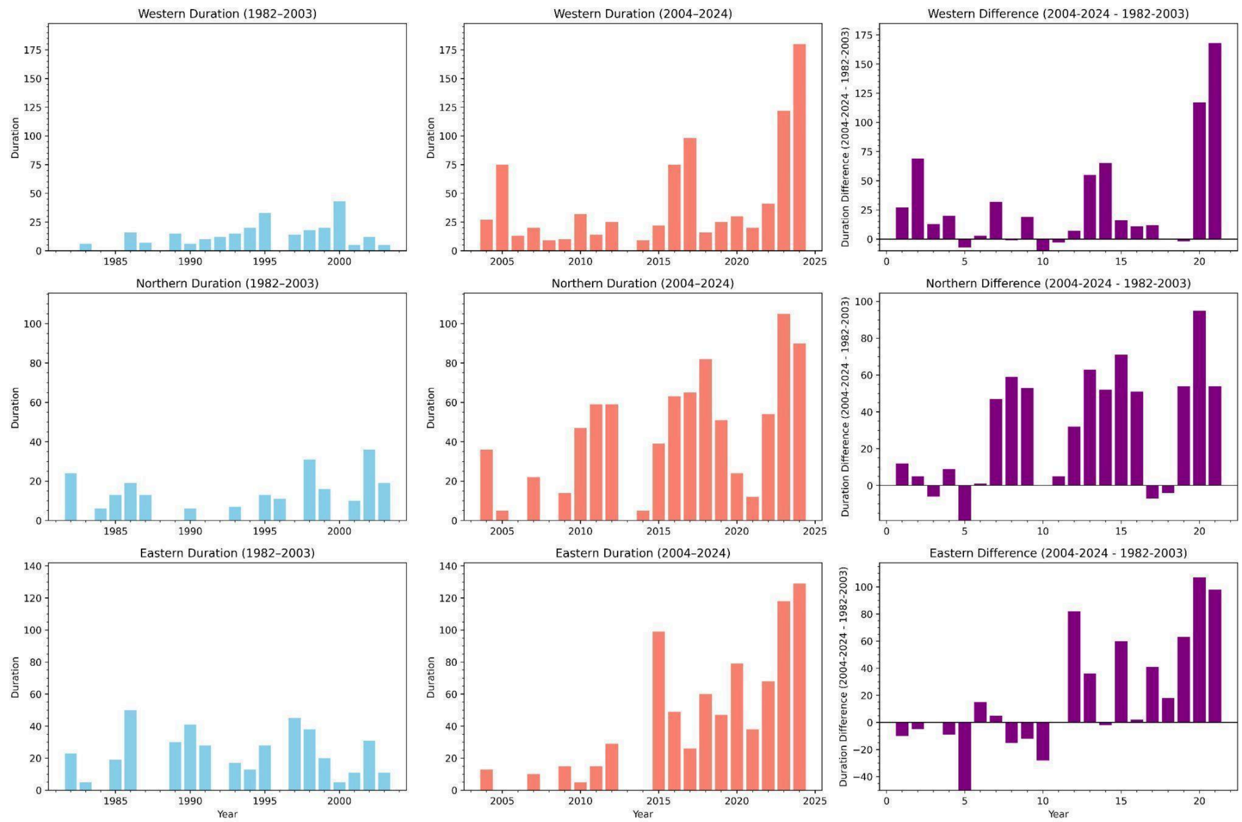

Figure 7. Each row shows the yearly distribution of average MHW duration (unit: days) in a given region. Each of the three columns denotes the first time period (1982-2003), the second time period (2004-2024), and the difference between the two time periods, respectively.

In the first time period, data for duration were sporadic, indicating a shorter duration of MHWs. There was a moderately increasing trend for MHW duration as time went on in the Western and Northern Gulf. For the Eastern Gulf, there wasn't a noticeable trend. In the second time period, all three regions saw significant proliferation in MHW duration. Towards the beginning of the second time period, the regions saw durations of 10-75 days, compared to the 110-180-day events that were common towards the end of the time period. Using a comparison between the two time periods, we see significant increases in MHW duration in the Western and Northern Gulf, with only a few minor anomalies. In the Eastern Gulf, the increase in MHW is most obvious in the latter half of the graph, with MHW duration spiking up to 100 days longer. Therefore, the duration of MHWs has become longer, most significantly in the Western and Northern Gulf, with an even stronger increase in the Eastern region over the last 10 years.

3.3.5 Monthly distribution of Hurricane, MHW, and their overlapping frequency

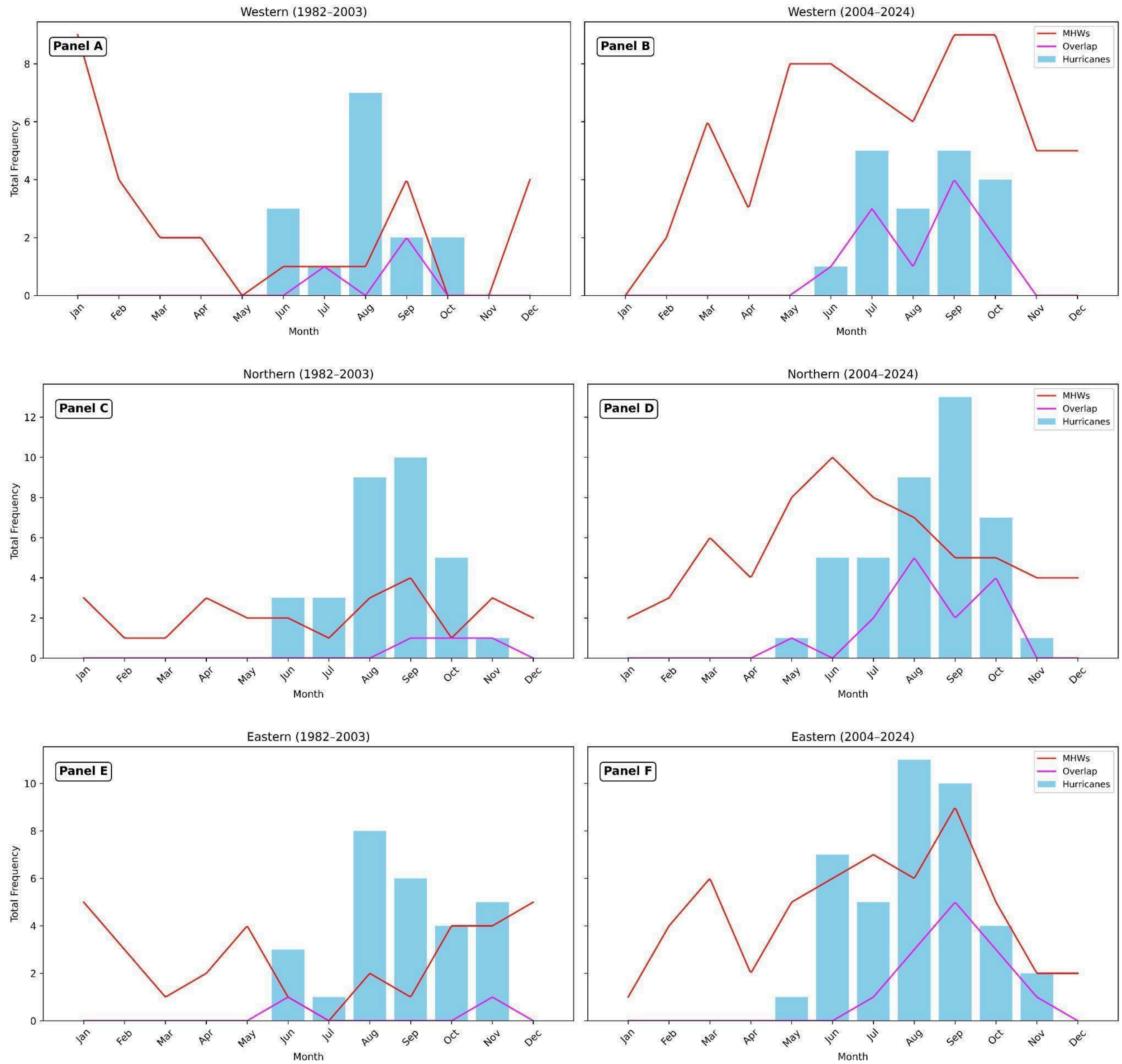

Figure 8. Each row denotes the total monthly frequency of MHWs (red line), hurricanes (blue bar), and their overlap (purple line), for each region. The panels in the first column demonstrate data from period 1 (1982-2003), while the second column contains data from period 2 (2004-2024).

While the above sections have demonstrated that hurricane frequency is enhanced from period 1 to period 2 during the summer and fall seasons, the monthly distribution of MHW events should also be elaborated on. In the Western and Eastern Gulf, the MHWs display more events in the Spring and late Winter with a maximum of 6-8 events in the 20-year period in period 1. However, MHWs only take place occasionally in the summer months, with a total of 0-2 events for July and August in period 1. In period 2, however, MHWs become more common in the summer months, reaching 9 events in September and October, but less often in the Spring and late Winter months. For the Northern Gulf, the MHW frequencies are uniformly distributed in each month for period 1, with a total of MHW events ranging from 1 to 4 over the entire period

1. In period 2, MHWs become more frequent in the early summer months, such as May, June, and July, reaching up to 8-10 MHWs in period 2. Thus, the number of MHWs in both the Eastern, Western, and Northern Gulf is dramatically amplified during the summer and fall seasons, which are also the active hurricane seasons.

The overlap between MHWs and hurricanes results from the enhanced frequency of both types of events in summer and fall. In the Western Gulf, overlap doubled from 2 events in period 1 to 4 events in period 2, revealing a stronger correlation between the two phenomena over the past decades. Similar to the Western and Northern regions, the Eastern Gulf goes from only 0-1 overlapping events in June and November, to 1-5 overlapping events from July to November, confirming our trend of strengthening overlap over time. In the North, overlap also becomes stronger across the periods. The overlapping events rise from 0-1 in period 1 to 2-5 in July to October in period 2.

4. Summary and Conclusion

This study quantifies the spatial and temporal properties of hurricane and MHW events in the Gulf of America by analyzing hurricane tracks, frequency, and ocean temperature during 1982-2024. Through our analysis, we found a higher hurricane and MHW frequency, along with temporal shifts in MHW seasonality across the past few decades.

We identify all the hurricane tracks that passed the Gulf, observing a general trend of hurricanes entering from the Southeast, near the Caribbean, and leaving the Gulf towards the Northeast. Using this data, we also found areas especially prone to hurricanes, namely the Northeastern Gulf of America. The hurricane frequency generally shows an increasing trend from 1982 to 2024. To further our temporal analysis, we then split the relevant time period into two periods (1982-2003 and 2004-2024) to better observe changes in hurricane patterns over time.

We analyzed MHW data by gathering ocean temperature data from NOAA in the Gulf of America. An MHW is defined as a discrete, prolonged anomalously warm water event. By using temporal and intensity data, we mapped the duration, maximum intensity, and cumulative intensity of all MHW events in the Gulf of America. We find an increase in MHW duration across the two periods, along with a tendency for MHW duration to decrease towards the coastline, while max intensity and cumulative intensity increase in magnitude towards the coast.

In addition, by graphing hurricane and MHW frequency, along with their duration, we observe a strong compounding effect, which means both events take place at the same location simultaneously. Such a strong connection between the two types of events indicates that their impacts can be amplified and lead to a catastrophic disaster. The spatial distribution patterns of MHW and hurricane compounding demonstrate three MHW hotspots in the Western, Northern, and Eastern Gulf, respectively. The characteristics of hurricane and MHW events in the three areas are further investigated in detail.

For all three regions, in the first period, hurricanes typically occurred at a frequency of 1-3 events per year, compared to the typical 3-4 events per year observed in the second period. We also observed in period 1 that hurricanes were especially common in August and September. However, in period 2, hurricane frequency became more spread out, with a more even distribution of hurricanes from July to October.

On the other hand, MHW durations in three regions have become significantly longer, increasing by up to 160 days, with the most significant temporal change in duration occurring in the Eastern Gulf. We also grouped relevant metrics by month to explore the shift in seasonality. In period 1, MHWs are more common in the Spring and late Winter, while period 2 exhibits a higher tendency for MHWs to rise in the Summer.

Our results show that hurricane frequency has increased over the past few decades, while also becoming more spread out across the summer months. Similarly, MHWs have also become significantly longer and more common, while also tending to occur in the summer months. This is the most important underlying factor leading to more compounding effects between hurricanes and MHWs in the Gulf of America.

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