A Case Study of the 2012 Marine Heat Wave in the Gulf of Maine (Northwest Atlantic)

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1. Introduction

1.1 Brief overview:

Ecosystems around the world have responded to anthropogenic climate change, with major implications for ecological goods and services. Links between a changing climate, shifts in species distributions, and the structure of communities and ecosystems have been documented convincingly for many taxa across many regions (Rosenzweig et al. 2008). However, in conjunction with a distinct long-term warming signal (an increase in mean temperature at a location), the frequency and intensity of extreme temperature events are also increasing (Perkins et al. 2012) because of anthropogenic climate change. Storms, droughts, floods, and heatwaves are prolonged periods where temperatures are substantially hotter than normal and they can have catastrophic effects on terrestrial ecosystems (Jentsch et al. 2007), with significant socio-economic ramifications.

Extreme climatic events are important in determining ecosystem structure; however, most of our current understanding stems from the study of terrestrial ecosystems. Investigation of marine ecosystems is important, as they play a central role culturally, socially, and economically in the lives of most people (Richardson and Poloczanska 2008). Marine ecosystems, like their terrestrial counterparts, are strongly influenced by extreme climatic events, including **heatwaves** (Garrabou et al. 2009), cold snaps (Firth et al. 2011), storms (De'ath et al. 2012) and floods (Gillanders and Kingsford 2002), which are driven by complex physical processes interconnected in the climate system and interacting across a hierarchy of spatial and temporal scales (Feng et al. 2013).

1.2 Defining Marine heatwaves (from Hobday et. al 2016):

Marine heatwaves (MHWs) are defined as discrete, prolonged, anomalously warm water events occurring in a particular location, relative to a baseline climatology (Garrabou et al., 2009; Feng et al., 2013; Mills et al., 2013). These events can occur during any time of the year, not just warmer months, as their impacts can vary by season and species (Lotze et al., 2001). The baseline climatology is typically calculated over a 30-year period and incorporates an 11-day moving window to account for seasonal variability. A high percentile threshold (e.g., 90%) is used to define an MHW, rather than an absolute anomaly, to account for regional variability and avoid assumptions about anomaly distributions (Zhang et al., 2005).

A MHW must persist for at least five days to be classified as "***prolonged***". Durations shorter than this tend to over-represent MHWs in tropical regions, while longer durations may under-represent events globally. The threshold of five days achieves a balance for global consistency under current climatic conditions. An MHW event is "***discrete***," with well-defined start and end points. Short gaps (≤2 days) between prolonged warm periods are treated as part of a single MHW event, while longer gaps lead to distinct events. For instance, five warm days followed by two cool days and then six warm days would constitute a single 13-day MHW event, but five warm days followed by four cool days and six warm days would be treated as two separate events.

1.3 Importance of studying MHWs

MHWs, which can be caused by a combination of atmospheric and oceanographic processes, have a strong influence on marine ecosystem structure and function. They have a profound impact on benthic ecosystems and especially cool-water habitat-forming species (Wernberg et al. 2013). They may increase in frequency and magnitude because of anthropogenic climate change (IPCC 2012), and they are important events that can cause rapid changes in biodiversity patterns and ecosystem structure and functioning. Apart from the physical drivers of short-term temperature variability and extremes, there is a pressing need to examine the characteristics of MHWs and their biological impacts within a coherent and comparable framework.

1.4 **Objectives of report:**

For my report, I choose to analyze MHWs in the Gulf of Maine. I selected this location as it would provide a good understanding of the effects on the marine ecosystem and biodiversity. The area is a temperate ecosystem in the high latitudes, and it is one of the fastest warming water bodies.

2. Study area context

Over the last decade, sea surface temperatures in the Gulf of Maine increased faster than 99% of the global ocean. The warming was related to a northward shift in the Gulf Stream and to changes in the Atlantic Multidecadal and Pacific Decadal Oscillations. Several studies have documented fish populations changing in response to long-term warming in this region. One instance of this the reduced recruitment and increased mortality in the region's Atlantic cod (*Gadus morhua*) stock (Pershing et. al 2015).

From 1982-2013, daily satellite-derived sea surface temperature in the Gulf of Maine rose at a rate of 0.03°C yr−1. This rate is higher than the global mean rate of 0.01°C yr−1 and led to gradual shifts in the distribution and abundance of fish populations (Pinsky et. al 2013).

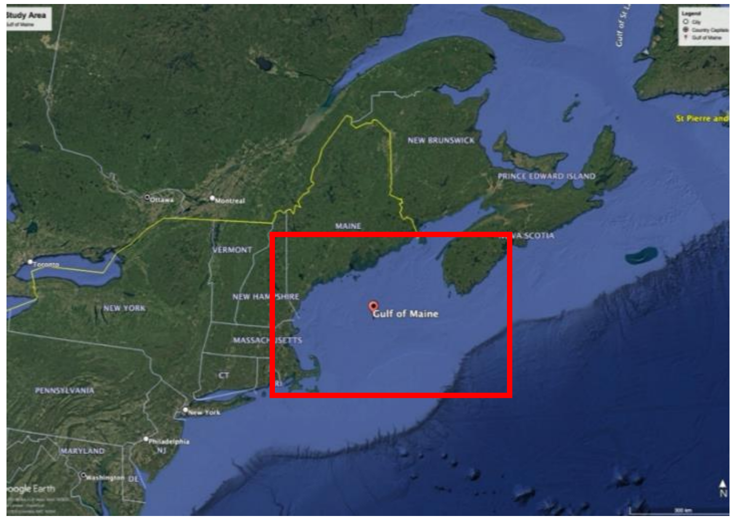

Fig.1: Map of Study area (Yellow line: USA-Canada Border)

Beginning in 2004, the warming rate in the Gulf of Maine increased more than seven-fold to 0.23°C yr−1. This period began with relatively cold conditions in 2004 and concluded with the two warmest years in the time series. The peak temperature in 2012 was part of a large "ocean heat wave" in the northwest Atlantic that persisted for nearly 18 months (Mills et. al 2013). This peak in 2012 is my focus in this report.

2.1 Data & methodology:

I try to investigate MHW events using Sea Surface Temperature (SST) data, focusing on their spatial and temporal characteristics over the selected study periods and regions. The primary objectives include identifying MHW events, analyzing their intensity, frequency, and duration, and exploring long-term trends in these metrics.

2.2 Data sources:

I downloaded high-resolution (L4) SST data set from the CEMEMS website. These datasets provide detailed information on sea surface temperature, latitude, longitude, and time. The datasets span multiple decades (1990–2022). For my report, I choose to highlight the MHW events and combed literature to back-up the visuals obtained by utilising the data with the help of jupyer notebooks.

- Variable: SST measured in Kelvin and converted to Celsius for analysis.
- Spatial Coverage: Gulf of Maine (NW Atlantic).
- Temporal Coverage: Decadal timeframes (1990–2022).

2.3 Data Processing and Preprocessing:

The raw SST data is subjected to the following preprocessing steps to ensure consistency and reliability:

- **Loading Data**: SST data is extracted the files using robust libraries, ensuring compatibility with multi-dimensional datasets. The primary variables include SST, latitude, longitude, and time.
- **Handling Missing Data**: Missing values in SST, latitude, and longitude arrays are replaced with NaN to avoid computational errors and ensure uniformity in data processing.
- **Data Subsetting**:
  - **Spatial Selection**: Specific locations are selected using longitude and latitude indices, corresponding to areas of interest.
  - **Temporal Selection**: SST time series for the selected locations are extracted for the study period.
- **Conversion**: SST data, initially in Kelvin, is converted to Celsius by subtracting 273.15.

2.4 Marine Heatwave Detection:

MHWs are identified using a standardized methodology based on climatology and thresholds. The relevant terminology is defined below:

- **Climatology and Thresholds**: A baseline climatology is established from historical SST data, representing the normal temperature range for the region. MHWs are defined as periods when SST exceeds the 90th percentile of this climatology for a minimum duration, typically five consecutive days (Hobday et al., 2016).
- **Calculation of MHW Metrics**: Once detected, MHW events are characterized using several key metrics to understand their intensity and impact (Schlegel et al., 2019):
  - **Mean Intensity:** The average temperature anomaly during MHW events, indicating the overall deviation from climatology.

- **Maximum Intensity:** The peak temperature anomaly during the events, highlighting the most extreme conditions.
- **Cumulative Intensity:** The total accumulated anomaly over the duration of the events, which provides an integrated measure of thermal stress.
- **Frequency:** The number of MHW events occurring within a specific timeframe, helping to track their recurrence.
- **Duration:** The average length of MHW events, reflecting their persistence and potential ecological impact.

- **Trend Analysis**: Long-term trends in MHW metrics are derived to understand changes in frequency, intensity, and duration over the study period.

2.5 Visualization:

Visualization was achieved by plotting time series and heat maps in jupyter using julia.

3. Results

3.1 Spatial trends:

MHW Frequency (Mean MHW Freq.): The mean frequency of MHW events shows spatial heterogeneity, with areas of higher frequency (up to 2 events on average) located predominantly in the central parts of the study region (Fig. 2a).

MHW Duration (Mean MHW Dur.): The duration of MHW events is consistently longer in the southern and central parts of the study area (Fig. 2b), with average durations exceeding 14 days. This suggests that once initiated, MHW events in these areas tend to persist longer, possibly due to reduced cooling mechanisms or stronger ocean heat retention.

MHW Mean Intensity (Mean MHW MeanInt.): The mean intensity of MHW events indicates that anomalies exceeding 1.5°C are prevalent throughout the region (Fig. 2c). The spatial homogeneity of high mean intensities reflects the region's overall sensitivity to warming conditions.

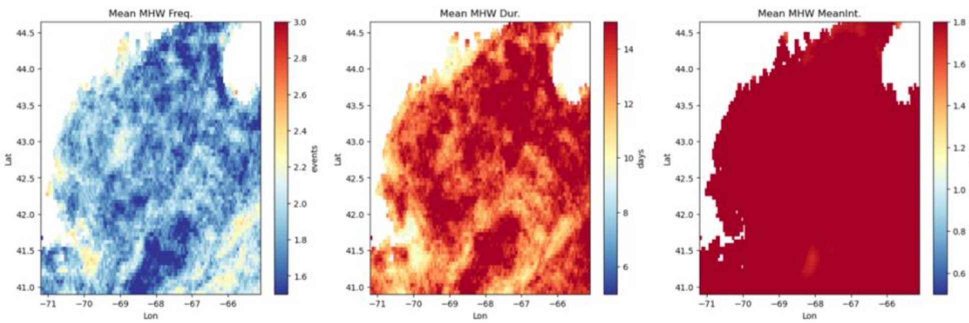

Fig.2 (a-c): Mean MHW freq., duration and Meanint.

MHW Maximum Intensity (Mean MHW MaxInt.): Maximum intensity plots reveal hotspots where peak temperature anomalies reach up to 5°C (Fig. 3a). These regions are likely subject to extreme episodic heat events, which may have implications for marine ecosystems and biodiversity.

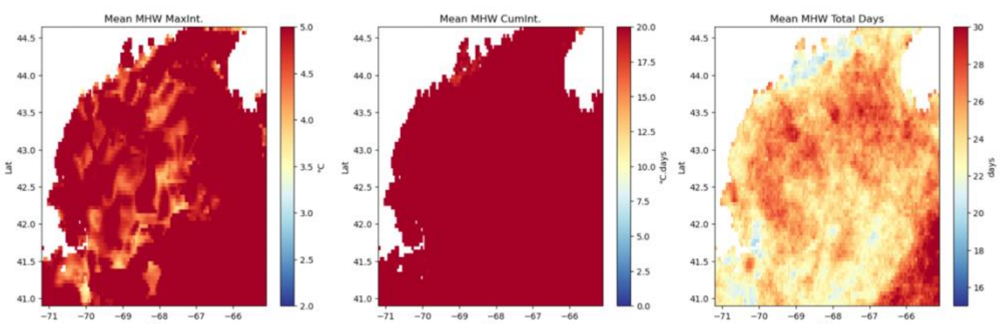

Fig.3 (a-c): Mean MHW freq., duration and Meanint.

MHW Cumulative Intensity (Mean MHW CumInt.): The cumulative intensity map highlights areas where the overall heat stress is greatest, with total anomalies exceeding 15°C days (Fig. 3b). This metric integrates frequency and intensity, providing a measure of the total thermal stress experienced by the marine environment over time. We can observe extremely high values throughout (>17.5 °C/days).

MHW Total Days (Mean MHW Total Days): Spatial patterns show that the total number of MHW days is highest in the southern and southeastern regions of the study area, exceeding 30 days on average (Fig. 3c). This indicates prolonged exposure to anomalously warm conditions, which can have long-term ecological impacts.

MHW Rates of Onset and Decline (Mean MHW ROnset and RDecline): The rate of onset (ROnset) and decline (RDecline) of MHW events exhibit contrasting spatial patterns. Regions with faster onset rates (up to 0.3°C/day) are observed in the central areas, indicating rapid warming at the beginning of MHW events (Fig. 4a & 4b). Decline rates are slower, reflecting delayed cooling after MHW events.

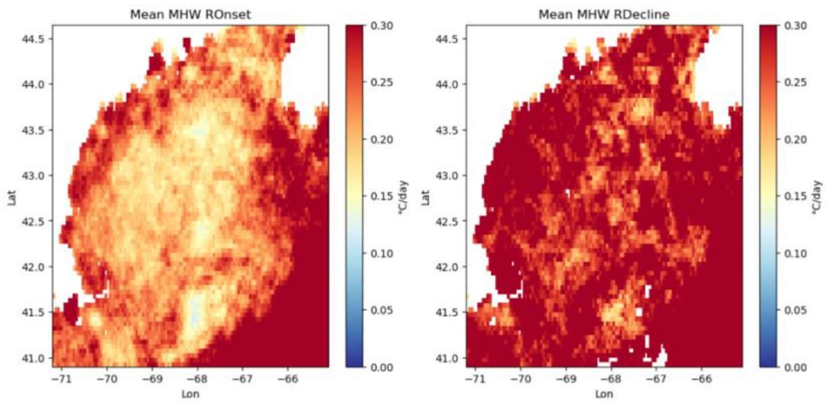

Fig.4 (a & b): Mean MHW freq., duration and Meanint.

3.2 ***Temporal trends:***

The temporal trends observed in the plots (Fig. 5 a-h) provide insights into the variability and evolution of marine heatwave (MHW) metrics over the study period. They can be summarised as follows:

Frequency (Freq.): The number of MHW events shows periodic fluctuations, with distinct peaks in the early 2000s and post-2010 (Fig. 5a). These spikes suggest increased MHW activity during certain years. The frequency of these events in the 1990s is less as opposed to late 2000s.

Duration (Dur.): MHWs exhibit variability in duration, with longer events occurring more frequently after 2010. Notable peaks in duration highlight the occurrence of exceptionally prolonged events in specific years, indicating a potential trend toward more persistent MHWs in the later years of the dataset (Fig. 5b). A significant peak can be observed in 2012 which will be discussed later.

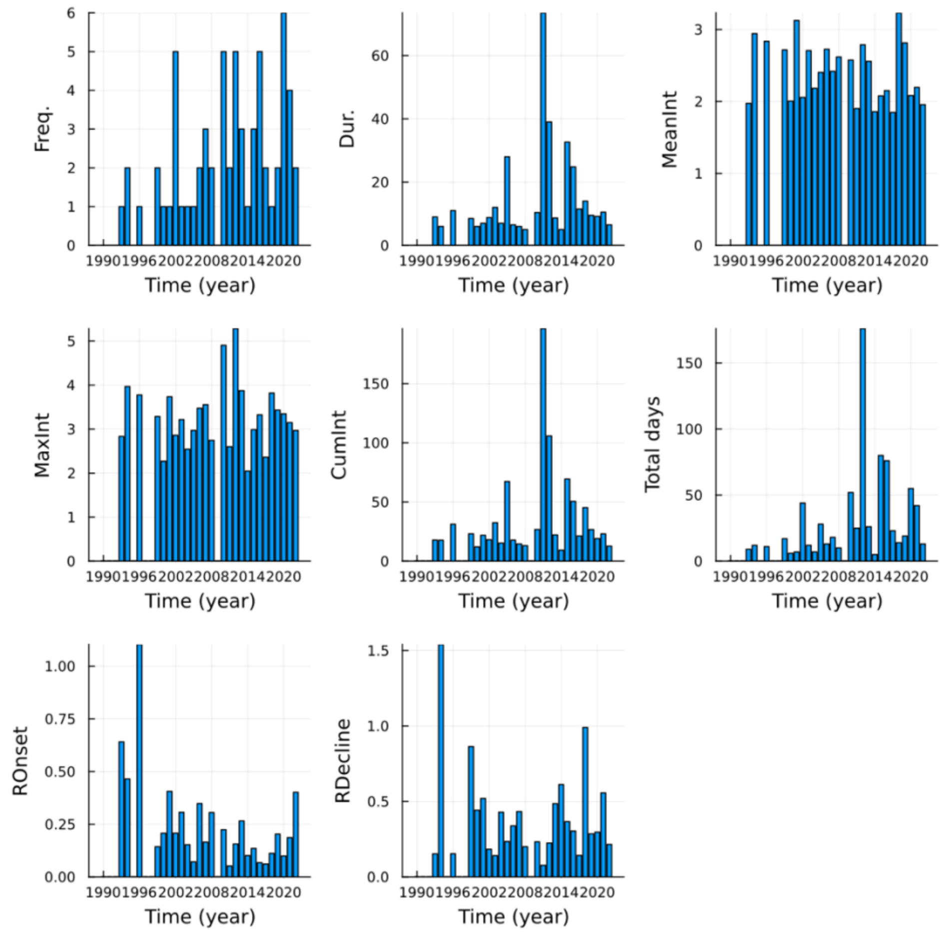

Fig.5 (a-h): Plots displaying the temporal variations across the different parameters of MHWs.

Mean Intensity (MeanInt.): The mean intensity remains relatively steady across most years, with subtle increases during periods of heightened MHW activity. This stability suggests that while the frequency and duration of MHWs may fluctuate, their average severity remains more consistent (Fig. 5c).

Maximum Intensity (MaxInt.): The maximum intensity of MHWs exhibits distinct peaks, particularly in years corresponding to increased duration and frequency. This indicates that extreme temperature anomalies occur sporadically, aligning with years of intensified MHW activity (Fig. 5d).

Cumulative Intensity (CumInt.): The cumulative intensity, reflecting the total thermal impact of MHWs over their duration, shows significant variability. Peaks in this metric align with years of prolonged and intense events, particularly post-2010 (Fig. 5e).

Total Days: The total number of days affected by MHWs follows a similar pattern to duration and cumulative intensity, with extended periods of MHW conditions becoming more prominent in the latter part of the timeline (Fig. 5f).

Rate of Onset and Decline (ROnset and RDecline): The rates of onset and decline exhibit sporadic peaks but remain relatively stable overall. These rates suggest no significant trend toward faster or slower development and decay of MHWs over time (Fig. 5g & 5h).

3.3 Overall Temporal Trend:

The temporal trends indicate a pattern of heightened MHW activity in certain periods, particularly in the later decades. This includes more frequent, prolonged, and intense events. The observed trends may suggest underlying shifts in oceanic and climatic conditions.

3.4 Categories of MHWs:

They represent the intensity levels of heatwave events, typically classified based on the deviation of sea surface temperature (SST) from the climatological threshold (Hobday et. al 2018). They are:

- Category 1 (Moderate): SSTs exceed the climatological 90th percentile but remain within a moderate range of anomaly.
- Category 2 (Strong): SSTs exceed the 2x threshold, indicating a stronger deviation from normal conditions.
- Category 3 (Severe): SSTs exceed the 3x threshold, signifying severe and persistent heatwave conditions.
- Category 4 (Extreme): SSTs exceed the 4x threshold, indicating an extreme and rare marine heatwave event with significant ecological and environmental impacts.

In Fig. 6, the spikes indicate the duration and category of the MHW events over time, with the 2012 event reaching a Category 3 level, highlighting its severity compared to others in the record. This will be the focus of our discussion.

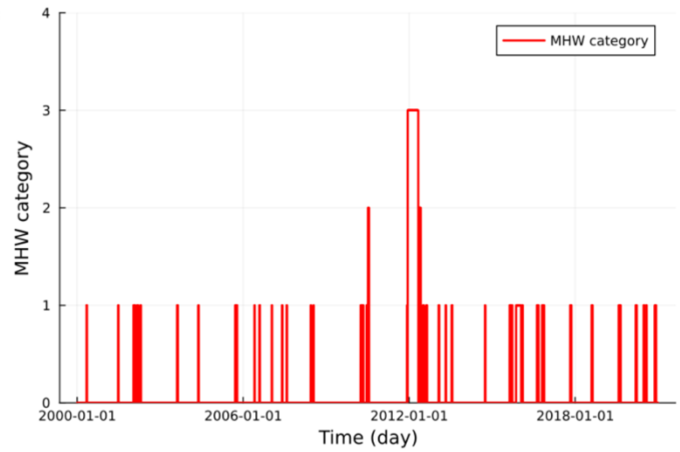

Fig.6: Plot displaying the categorical variation across different MHW events in the Gulf of Maine. The scale ranges from 0-4.

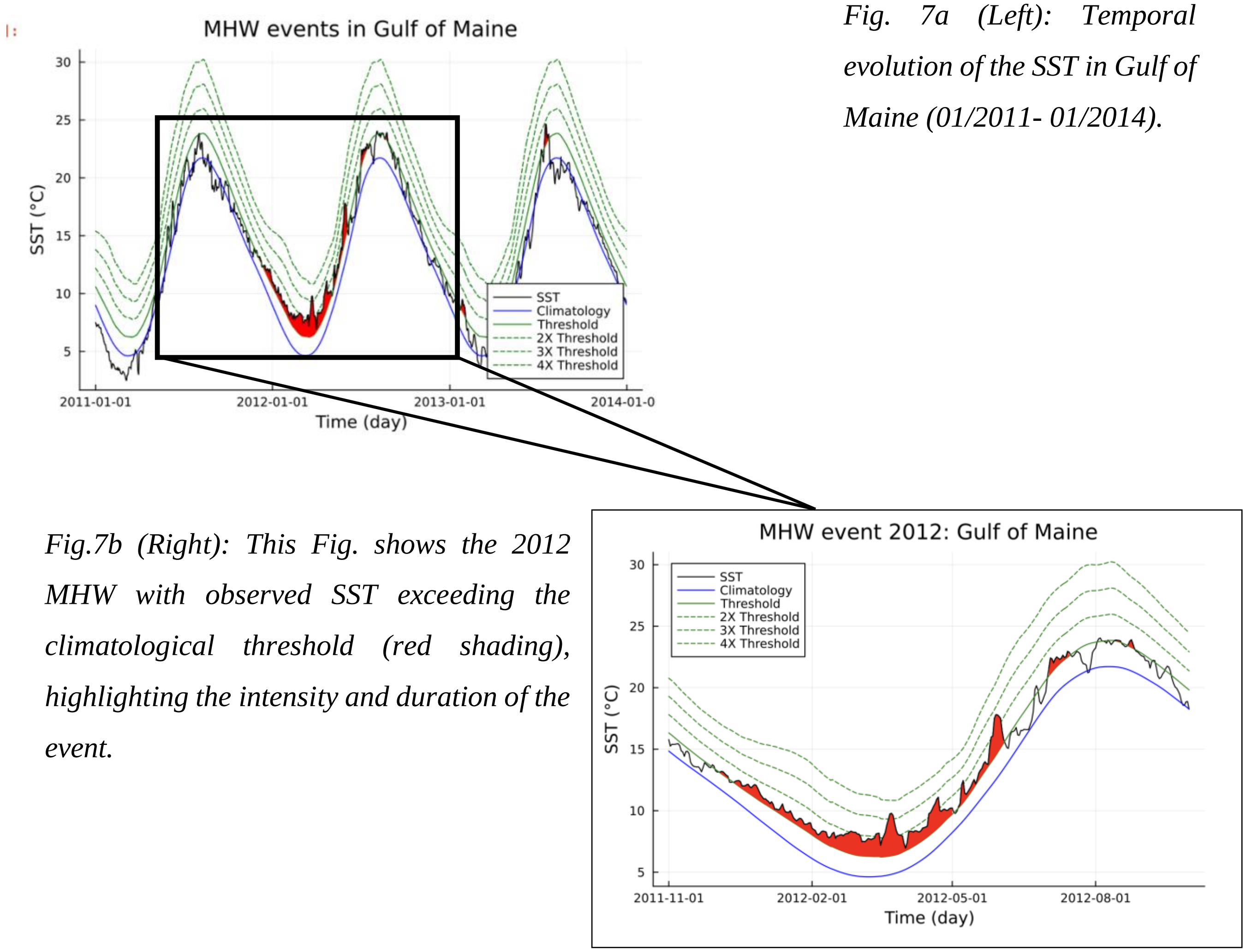

Fig. 7a (Left): Temporal evolution of the SST in Gulf of Maine (01/2011- 01/2014).

Fig.7b (Right): This Fig. shows the 2012 MHW with observed SST exceeding the climatological threshold (red shading), highlighting the intensity and duration of the event.

The plot (Fig. 7b) depicts the 2012 MHW in the Gulf of Maine, where sea surface temperatures (SST) exceeded the climatological threshold for an extended duration from December 2011 to August 2012. The event peaked above the 3x threshold during spring and early summer in 2012, with the SST anomaly reaching its maximum intensity around May 2012.

4. Discussion

The 2012 MHW in the Northwest Atlantic, particularly in our study area, Gulf of Maine, represents a significant climatic event with far-reaching ecological and economic implications. This heatwave was characterized by its intensity, persistence, and regional impacts, standing out as one of the most extreme ocean warming events recorded over the last three decades. The event's onset and persistence were driven by atmospheric blocking patterns, which transported warm air masses into the region during late winter and summer months. Sea surface temperatures (SSTs) in the Gulf of Maine experienced an annual anomaly of +2°C above the 1982–2011 climatology. This warming rate, accelerated after 2004 to 0.26°C/year, reached levels comparable to the end-of-century projections under climate change scenarios (Mills et. al 2013). There were several periods in late winter and in summer of persistent atmospheric blocking that brought warm air into the region and contributed to ocean warming (Mills et. al 2013).

The 2012 MHW in NW Atlantic consisted of distinct episodes, including a 56-day event from April 10 to June 4, with a maximum intensity (i_{max}) of 4.89°C above the threshold, and a prolonged 187-day event from July 31, 2012, to February 2, 2013. As per research conducted by Mills et al. (2013), the corresponding i_{mean} and i_{cum} for this 56 day event was 2.59°C and 145 °C days, respectively. The two episodes were separated by a short cooling period, emphasizing the variability within the anomalous warming. The cumulative intensity (i_{cum}) of the 187-day event was a record 443°C days, highlighting the extreme duration and energy of the heatwave.

The elevated temperatures triggered abrupt ecological responses, including shifts in the distribution and behavior of marine species. For instance, warm-water species expanded northward into the Gulf of Maine, while the earlier-than-normal inshore migration of lobsters disrupted traditional fishing cycles. These changes caused record landings of lobsters but paradoxically led to an economic crisis due to market oversupply and price collapses (Mills et al. 2013). The 2012 heatwave provides critical insights into how marine ecosystems may respond to climate-driven extreme events. Persistent warming trends and extreme anomalies like this one highlight the need for adaptable management frameworks. Fisheries in regions like the Gulf of Maine require anticipatory models to predict species responses, as well as policies that address the economic vulnerabilities exposed by sudden ecological changes.

By analyzing the 2012 event in detail, including its drivers and consequences, researchers and policymakers can better understand and prepare for future climate-related disruptions in marine environments. To effectively analyze these trends, it is crucial to employ remote sensing and satellite oceanography to monitor, interpret, and analyze the data.

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