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MARINE HEAT WAVES IN A LOW-LYING COUNTRY: OCCURRENCE, COMPUTATION AND IMPACT

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Abstract:

Over the past several decades, there has been an extreme increase in high temperatures across the global ocean, termed Marine Heatwaves (MHW). MHWs have devastating impacts on human life and ecological systems, affecting biodiversity, fisheries, and aquaculture. Due to extreme heat, mass extinctions of various species and marine habitats such as seagrass and coral reefs are occurring. It is crucial to investigate how the dynamics and trends of MHWs might change using available data from models and satellites to better mitigate future predicaments. This study presents a detailed analysis of MHWs, including an examination from 2001 to June 2024 in a low-lying country like Bangladesh. A step-by-step procedure is shown to calculate MHWs using a computer program (MATLAB). This study also shows a recent increasing trend in MHW, predicting an increased amount of land loss for low-lying countries.

Keywords: Marine heatwaves (MHW), sea surface temperature (sst), 90th percentile limit, sea level rise, land loss.

1. Introduction

1.1 Marine heatwaves

A formal definition of Marine Heat Wave (MHW) is established by Hobday et al. (2018) as anomalous high-temperature extreme events indicated by Sea Surface Temperature (SST) for a minimum of 5 days above seasonally varying 90th percentile based on climatological 30-year data. The minimum 5-day duration is selected to achieve balance from the impact of the MHW to ocean environment consideration and its number of occurrences. The climatological period of 30 years is defined to include long-time scales of ocean phenomenon variability (e.g. ENSO). The 90th percentile limit is used to adapt the definition to the corresponding average temperature profile in a different region. This implies that MHW can also occur in winter and is plausible to be applied in many biology studies. Finally, its formal definition is not limited by its driver and impact as these variables can be varied.

1.2 Marine heatwaves category

Categorization of MHW is developed from the previous definition and parameter of MHW by Hobday et. al. (2016) MHW can be classified into 4 categories based on the temperature excess from the local climatology which is (I) Moderate, (II) Strong, (III), Severe, and (IV) Extreme. This category is extended using the previous parameter of intensity which is the Sea Surface Temperature Anomaly (SSTA) which is based on the climatology mean of a particular region. MHW is classified in Category I when its SST value crosses the threshold of the 90th percentile, Category II threshold value, is 2x90th percentile, and so forth until Category IV at the 4x90th percentile (Hobday et al., 2016). This category is limited to 30year duration because of the prevalent data availability and most importantly, different projected climate conditions change after 30 years because of ocean decadal oscillation or global warming trend.

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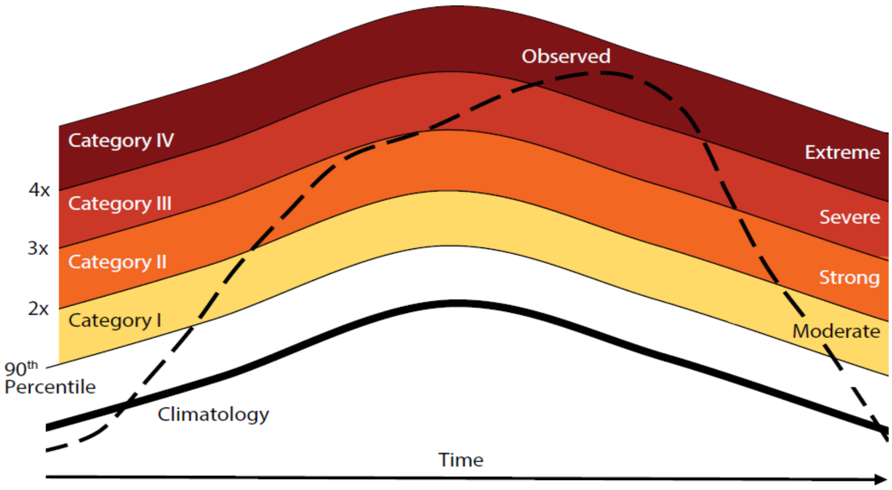


Fig. **1.** Categories of MHW events (Hobday, 2016)

1.3 Marine heatwaves occurrences

Over the last decades, a significant number of prominent MHWs have been reported which changes the whole marine ecosystem across the planet. Among these, significant MHW events occurred in the northwest Atlantic in 2012, the northeast Pacific Ocean from 2013 to 2016., the Tasman Sea in 2015 to 2016, and water around tropical Australia in 2015 to 2016. The more complete list of MHW occurrences over the last decade is displayed in Table 1

Generally, the magnitude, frequency and time duration of all the MHW events do not have a homogenous distribution across the ocean., The highest intensity of MHWs (maximum SST) is associated with boundary currents like the Gulf Stream or their extensions except for the upwelling regions of the equatorial Pacific cold tongue. Upwelling is the process where there is a displacement of the water column and is restored by the vertical flow of cold water from the deep. It is notable that western boundary current regions where reports of MHW events are less in number despite the large temperature variability found. Conversely, the number of MHW events is very high in the eastern boundary current region. On average, the longest duration MHW occurs in the eastern equatorial Pacific which is associated with El Nino events. (Holbrook et al., 2019)

Table 1. An example of MHW with its corresponding heatwave metrics throughout the globe (Hobday et al., 2016)

	Event	Peak Date	I_{max}	Duration	$P_{moderate}$	P_{strong}	P_{severe}	$P_{extreme}$	Season	Biological Studies
Category I (Moderate)	Mediterranean Sea 1999	Sep 27, 1999	1.92	8	100	–	–	–	Autumn	Cerrano et al., 2000 Garrabou et al., 2001 Linares et al., 2005 Coma et al., 2009
Category II (Strong)	Mediterranean Sea 2003	Jun 14, 2003	4.38	31	58	42	–	–	Early Summer	Crisci et al., 2011
	Mediterranean Sea 2006	Jul 26, 2006	3.99	33	76	21	–	–	Summer	Kersting et al., 2013 Marba and Duarte, 2010
	Tasman Sea 2015	Dec 19, 2015	2.70	252	59	41	–	–	Spring/Summer	Oliver et al., 2017
	Great Barrier Reef 2016	Mar 11, 2016	2.15	55	55	45	–	–	Summer/Autumn	Hughes et al., 2017
Category III (Severe)	Western Australia 1999	Jul 25, 1999	2.13	132	86	12	2	–	Winter	None available
	Northwest Atlantic 2012	May 20, 2012	4.30	132	76	23	2	–	Winter/Spring	Mills et al., 2013
	Northeast Pacific Blob 2015	Jul 13, 2015	2.56	711	44	43	13	–	Year-round	Cavole et al., 2016 Bond et al., 2015 McCabe et al., 2016
	Santa Barbara 2015	Oct 13, 2015	5.10	93	44	41	13	–	Summer	Reed et al., 2016
Category IV (Extreme)	Western Australia 2011	May 20, 2011	4.89	66	42	33	12	12	Summer	Wernberg et al., 2013

1.4 Drivers of marine heatwaves

Two main reasons are controlling the MHW intensities. The first is due to the solar energy during sunny days. Sunlight passes through the surrounding atmosphere and heats the sea surface which results in an increasing sea surface temperature due to the net surface heat flux. With the absence of strong wind, this warm water sits on top of cool water without mixing and keeps increasing its heat which can influence El Nino/ La Nina events. Moreover, the other key mechanism for marine heatwaves is the displacement of seawater to other directions and cold water is replaced by warm water due to ocean currents. However, climate modes (climate changes and wind changes) can also be regarded as marine heatwaves.

There is clear evidence that the maximum surface temperature anomaly peak occurs in summer when it features shallow mixed layers and weak wind speed. Prominent factors affecting subtropical extreme MHW are persistent atmospheric high-pressure systems and anomalously weak wind speed that corresponds to insolation and reduced ocean heat loss (Oliver et al., 2018). In addition, the Southern Hemisphere experiences more intense and features a severity asymmetry compared to the Northern Hemisphere as explained by Gupta et al. (2020) as follows:

1. The area of the ocean experiencing its most severe or intense MHWs was enhanced during the El-Nino periods and tends to peak during boreal winter.
2. Seasonal asymmetry: Shallower oceanic mixed layer depth from corresponding local summer. Heat flux anomaly from the atmosphere or horizontal ocean advection would generate a larger change in surface temperature in shallow mixed waters. The mixed layer depth correlates with the seasonality in wind strength (weaker winds, suppress vertical mixing, mixed layer shoal)
3. Long-term trends of SSTA in summer and autumn are higher than winter and spring season trends in both hemispheres.

Additionally, (Oliver et al., 2021) shows that the physical drivers of MHW can be explained by the observation of a mixed-layer temperature budget which accounts for the accumulation of surface ocean heat, horizontal currents, and air-sea heat exchange (Gupta et al., 2020).

This study outlines the calculation method for Marine Heat Waves (MHW) in the Bay of Bengal and discusses the potential consequences of their increasing trend for low-lying countries like Bangladesh. The findings suggest that previous predictions of land loss due to global warming, based on earlier data, may underestimate the future impact, as the risk is likely to increase further. For example, some of the reports on the Sea Surface Rise in a low-lying country like Bangladesh are-

a. **World Bank**: By 2050, one-third of agricultural GDP may be lost due to climate variability and extreme events – a devastating figure as the agriculture sector represents around half of employment in the country (World Bank Group, 2022).

b. **IPCC**: Coastal erosion could lead to a loss of 17 percent of land surface and 30 percent of food production by 2050 (IPCC).

c. **climaterealityproject.org:** By 2050, Bangladesh may lose approximately 11% of its land by then, and up to 18 million people may have to migrate because of sea-level rise alone (IPCC, 2021).

The authors suggest that, based on the recent trends in MHWs, the projected land loss could escalate further due to the ongoing rise in global warming.

2. Data Collection

Nowadays, Oceanographic data can be collected using different sensors mounted with autonomous vehicles or marine survey vehicles because the cost of collecting data using ships has been drastically reduced due to different types of design improvements such as the CRP system and ship design procedures shown by Khan et al (2020). To collect data with autonomous vehicles, a fixed platform can also be used as a dock, which can be designed following the method shown by Kundu et al (2018). To analyze the marine heat wave (MHW) consistently, it is very crucial to use the temperature data with daily resolution. Moreover, these data sets should be long enough to characterize the climatology. It is very tough to characterize the subsurface measurements as the subsurface daily temperature data is only available in some locations considering the longer time scale. In this study, the daily mean sea surface temperature has been collected from the Physical Science Laboratory of

USA (NOAA OI SST V2 High-Resolution Dataset) (Table -3) for the Bay of Bengal (Lon: 80º to 100ºE, Lat: 05ºN to 22ºN) region.

Table 2: Summary of ocean temperature data set used

Data Source	Spatial Resolution	Temporal Resolution	Dataset format
NOAA OI SST V2 High Resolution Dataset (Reanalysis data)	0.25degree latitude x 0.25-degree longitude global grid	Daily mean of Sea surface temperature. Available from 1981 to present.	NetCDF

3. Methodology

3.1 Main idea

More quantitative and targeted studies can be extended from previously established qualitative definitions following a hierarchical MHW parameter and its computation as shown in Table 3 (Hobday et al., 2018). The primary metrics provide the most general information which quantifies the previously established qualitative definition such as climatology, threshold, start and end of MHW, and duration intensity. Secondary and tertiary factors can be further estimated for further detailed and addressed studies

Table 3: A systematic and hierarchical for MHW characterization (Hobday et al., 2018)

	Name	Definition		Units
Primary	Climatology	T_m: The climatological mean, calculated over a reference period, to which all values are relative	$T_m(j) = \sum_{y=y_s}^{y_e} \sum_{d=j-5}^{j+5} \frac{T(y,d)}{11(y_e-y_s+1)}$ where j is day of year, y_s and y_e are the start and end of the climatological base period respectively, and T is the daily SST on day d of year y	°C
	Threshold	$T_{\%}$: The seasonally varying temperature value that defines a MHW (e.g. T_{90} is the 90th percentile value based on the baseline periods)	$T_{90}(j) = P_{90}(X)$ where P_{90} is the 90th percentile and $P_{90}(X)$ where $X = \{T(y,d) \mid y_s \leqslant y \leqslant y_e, j-5 \leqslant d \leqslant j+5\}$	°C
	Start and end of MHW	t_s, t_e: dates on which a MHW begins and ends	t_s is the time, t, where $T(t) > T_{90}(j)$ and $T(t-1) < T_{90}(j)$ t_e is the time, t, where $t_e > t_s$ and $T(t) < T_{90}(j)$ and $T(t-1) > T_{90}(j)$ For MHWs, $t_e - t_s \geqslant 5$, and where gap $\leqslant$2 days (see text)	days
	Duration	D: Consecutive period of time that temperature exceeds the threshold	$D = t_e - t_s$	days
	Intensity (max/ mean/variance)	i_{max}: highest temperature anomaly value during the MHW i_{mean}: mean temperature anomaly during the MHW i_{var}: variation in intensity of the MHW over the duration	$i_{max} = \max(T(t) - T_m(j))$ $i_{mean} = \overline{T(t) - T_m(j)}$ $i_{var} = \sigma_{T(t)}$ where $t_s \leqslant t \leqslant t_e, j(t_s) \leqslant j \leqslant j(t_e)$, σ is the standard deviation, and the overbar indicates the time mean	°C
Secondary	Rate measures	r_{onset}: rate of temperature change from the onset of the MHW to the maximum intensity $r_{decline}$: rate of temperature change from the maximum intensity to the end of the MHW	$r_{onset} = \frac{i_{max} - (T(t_s-1) - T_m(j-1))}{t_{max} - (t_s - 1)}$ $r_{decline} = \frac{i_{max} - (T(t_e) - T_m(j))}{t_e - t_{max}}$ where t_{max} is the time of MHW_{imax}	°C/day
	Cumulative measure	i_{cum}: sum of daily intensity anomalies. Note that the integral omits t_e which is below the T_{90} threshold	$i_{cum} = \int_{t_s}^{t_{e-1}} (T(t) - T_m(j))dt$	°C days
	Spatial extent	A: Area of ocean meeting the MHW definition L: Length of coastline for the MHW	A = area over which MHW detected L = length of coast where MHW detected	km^2 km
Tertiary	Preconditioning factors	Factors such as time of year relative to the onset of the MHW, or periods of above mean temperature preceding the MHW may lead to greater impacts	n/a	Various – specific to study system

The parameter in Table 3 can be illustrated to explain MHW from the SST time series example shown in Figure 2. The blue line represents the average temperature (based on the centered 10-day window) which varies due to seasonal change. The dashed line above is the threshold value at the 90th percentile of the blue line. MHW event officially occurs when the instantaneous SST is above this threshold value for at least 5 days. Heat spike can also be seen on the first day of a year, but it does not count as MHW events as it is less than 5 days. In conclusion, primary metrics such as maximum, average, and cumulative intensity can be found in Figure 2 which is indicated by I_{max}, i_{mean}, and i_{cum}, respectively (Hobday et al., 2018).

3.2 Computation

For the analysis of the collected data, a MATLAB program was developed by the authors, which produced graphs of mean SST for each day from 2001 to 2024.

It is already stated that MHW can be determined by considering a threshold value above which 5 consecutive days of extreme temperatures are considered an MHW event. To determine the threshold value, there are two approaches either using the fixed in time or using the value which varies seasonally. In this study, the climatological threshold value is determined in such a way that shows seasonal variation for a longer period. Analyzing the daily sea surface temperature (SST) data for more than 23 years, the climatological mean is calculated. A longer period of SST data analysis (e.g., 23 years), gives a more accurate climatological mean value.

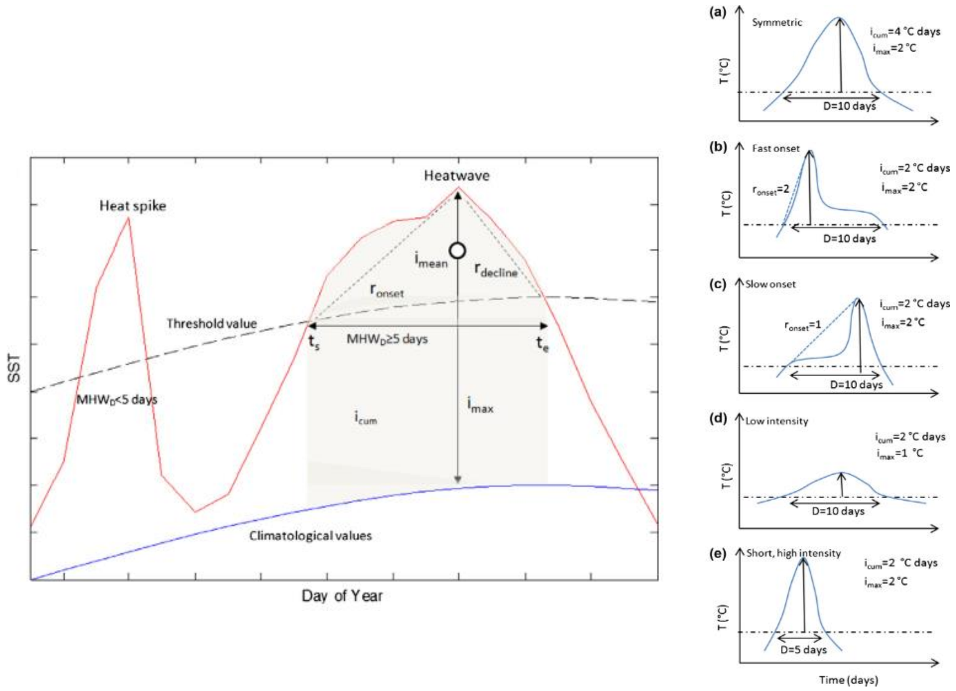


Fig.2: Marine Heatwaves definition in the diagram (Hobday et al., 2018)

Considering the climatological mean, the 90th percentile is considered as the threshold value, and 5 consecutive days' temperature above the threshold value is presented as a single MHW event for a particular year in this study. If the consecutive number of days above the threshold value is less than 5, then it is not considered an MHW event. For example, if the consecutive 6-day temperatures exceed the 90th percentile value, the duration of the MHW is considered as 6 days. On the other hand, if the number of consecutive days' temperatures that exceed the threshold value is less than 5, the duration of the MHW is considered as 0. Following this method, the total number of days of MHW in a particular year is calculated Using MATLAB programming language.

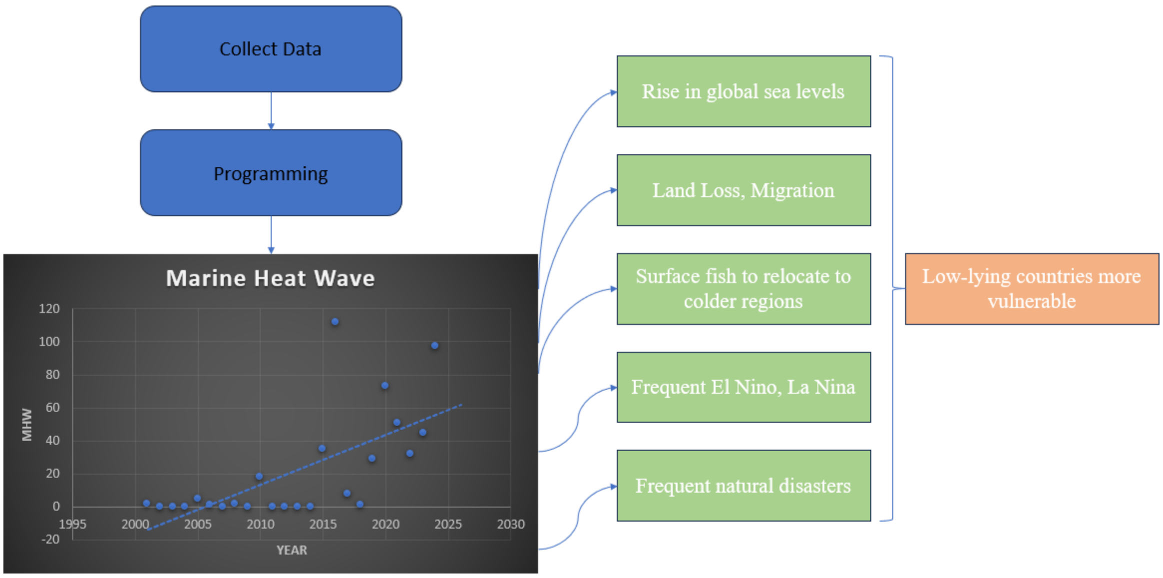


Fig. 3: MHW calculation process and effects.

To quantify the MHW, the average intensity and frequency of the events have been calculated using MATLAB. The temperature anomaly (intensity) for the corresponding date of the particular year, has been characterized by subtracting the daily mean temperature value from the climatological mean value (calculated from the climatology analysis). The greater the anomaly of the temperature, the greater the intensity of MHW.

The computation procedure of MHW and its impact on a low-lying country like Bangladesh is shown in Figure 3.

4. Results and Discussion

Figure 4 shows the daily average temperature in the Bay of Bengal spanning from 2001 to June 2024. The red line and the black line denote the average temperature and its 90th percentile respectively. The seasonal pattern is observed where the value of average temperature is low in winter and high in summer. It is noticeable that during this period, the Bay of Bengal experienced two prominent MHW in 2016 and 2024 compared to the other years, especially during boreal summer.

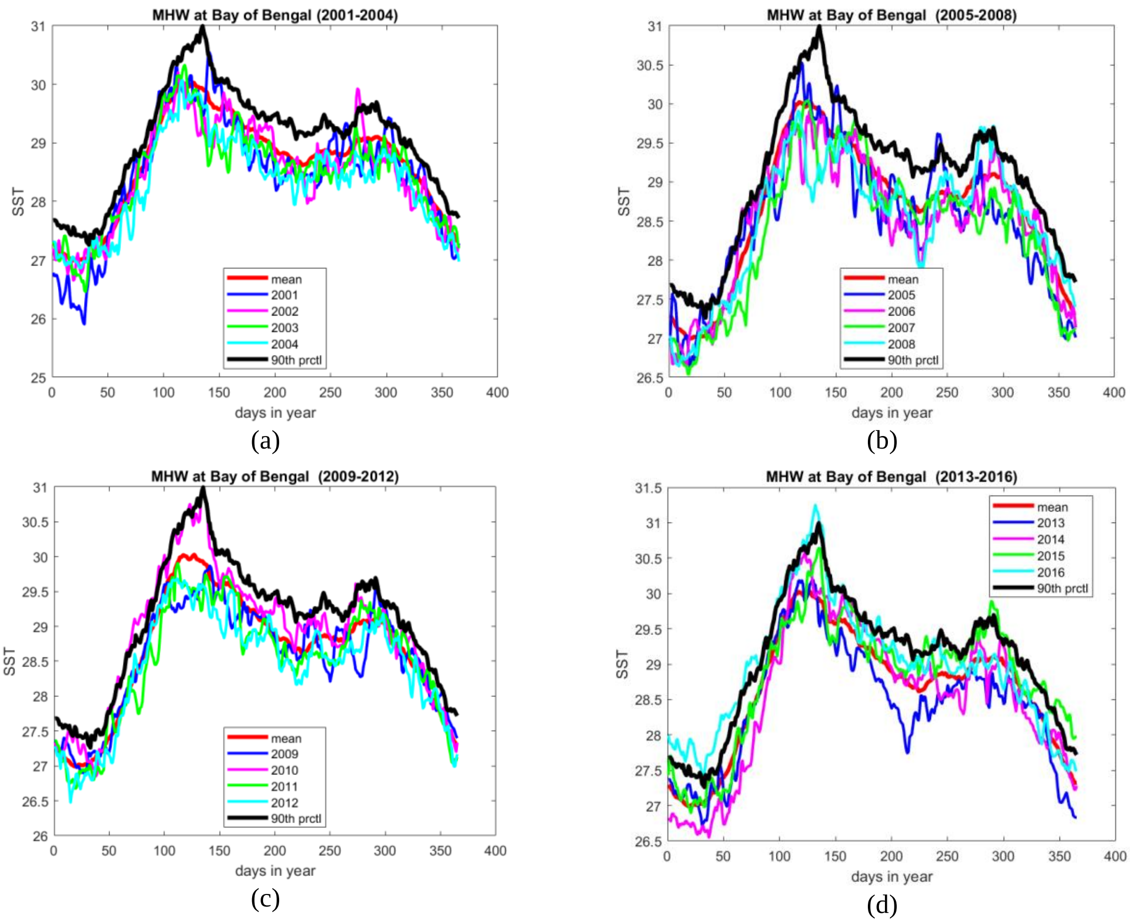
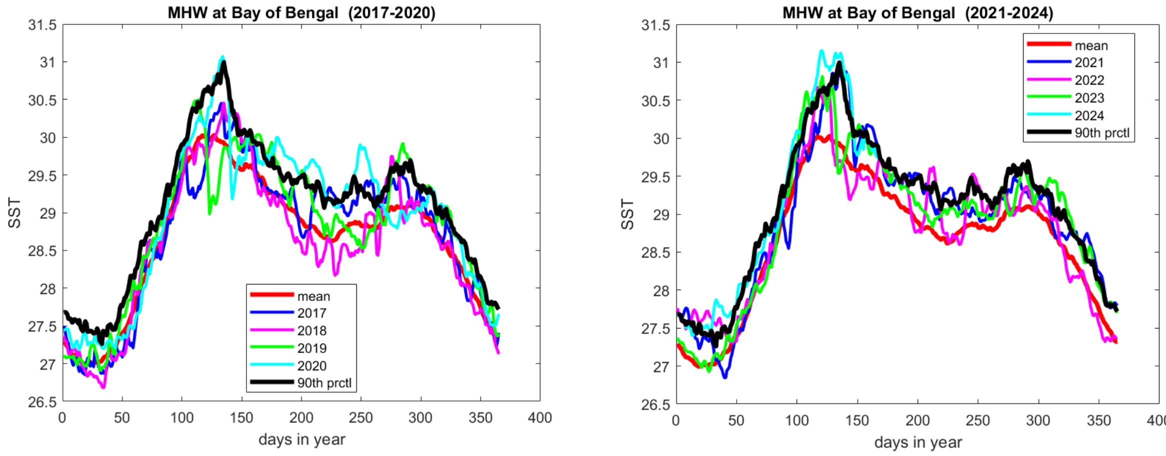


Fig. 4 (i)**:** MHW in the Bay of Bengal from 2001 to 2023 observed above the 90th Percentile (Black) line. (a) and (b): No significant MHW observed from 2001-2008 (c) Small Heatwave observed in 2010 (d) Most Significant MHW of 21st Century occurred in 2016.



(e) (f)

Fig. 4(ii)**:** MHW in the Bay of Bengal from 2001 to 2023 observed above the 90th Percentile (Black) line. (e) Considerable amount of MHW observed in 2020 (f) Decent amount of MHW Observed in Each year of this decade (2021-2024 (until June)) and another most significant MHW occurred in 2024.

To understand the trend of the MHW, the total number of days of MHW has been calculated from 2001 to 2024. These values are incorporated in Figure 5.

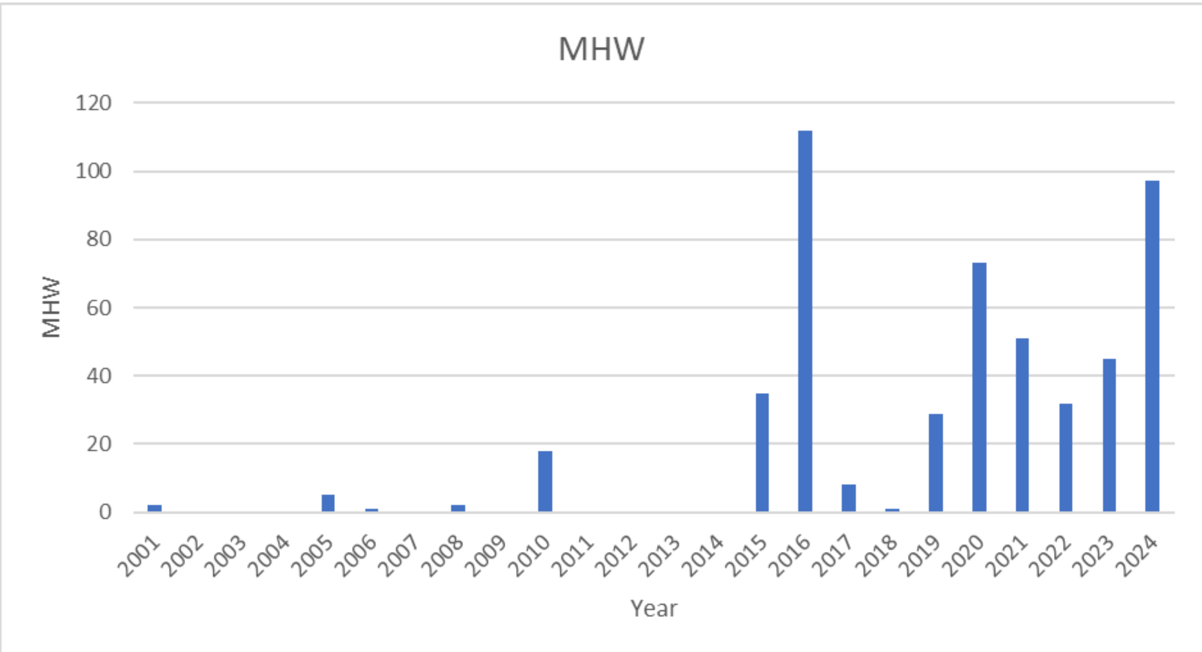


Fig. 5: The total duration of MHW in the Bay of Bengal from 2001 to 2024 (Till June)

It indicates that 2024 is going to be the hottest year in Bangladesh in this decade. The intensity of the two most significant heatwaves in this century (Year: 2016 and 2024) is computed after the subtraction of daily SST from the daily mean temperature of the 21st century, which is shown in Figure 6.

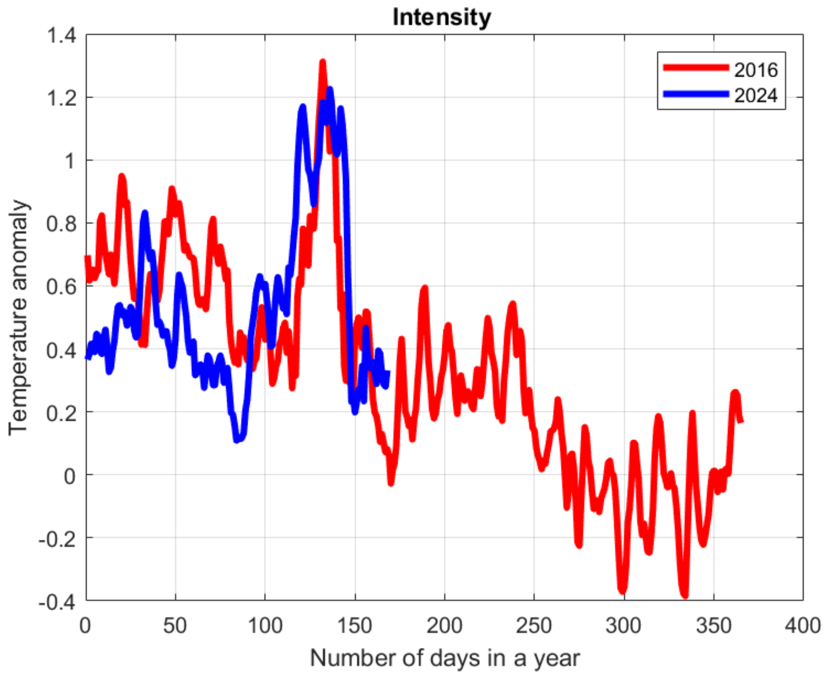


Fig. 6: Comparison of MHW between 2016 and 2024 (Till June)

Based on the above results, it is evident that marine heatwaves (MHWs) have increased at an alarming rate in recent years. The situation worsened notably in 2016 due to periodic warming in the central Pacific region known as El Niño. The heatwave subsided when La Niña arrived later in 2016, bringing storms that stirred and cooled the ocean (Warren Cornwall, 2019). This year has already observed 97 MHWs till June. From this, it can easily be predicted that this year is going to be the worst one. This rise in MHWs indicates a significant increase in global warming. It is predicted that the situation will worsen further, which may result in the following devastating situation:

a. Rise in global sea levels, which can result in loss of land in coastal areas. The recent phenomena of MHW as shown in Figure 5 shows an increasing trend, which indicates the probable loss of land due to global warming may increase more than predicted for low-lying countries like Bangladesh
b. Increasing sea surface temperatures (SST) will force surface fish to relocate to colder regions deep in the sea, decreasing fish production for human consumption. This relocation may also harm marine biodiversity and potentially lead to the death of sensitive species.
c. Increase in El Nino and La Nina will create frequent natural disasters like storms or cyclones.
d. The life of shore habitats and humans living beside the sea will also be severely affected due to the lack of fish and increased temperature.

5. Conclusion

Frequent marine heatwaves (MHW) have become a major concern for low-lying countries like Bangladesh. The frequency and severity of MHWs have increased at an alarming rate. They have a devastating effect on marine species as well as on the human population. Several factors may contribute to the occurrence of MHWs, such as the accumulation of surface ocean heat, horizontal currents, and air-sea heat exchange, primarily driven by global warming. It is high time to take measures against the occurrence of MHWs. Initiatives such as reforestation and reducing greenhouse gas emissions are crucial steps to improve the situation. Otherwise, the world may face a dire situation in the near future. In this work, the linear increasing trend of MHWs is shown and a prediction has been presented that the land loss in the ocean may increase due to the increased trend of MHW in this area. The highest sufferers of this increasing trend of MHW will be the low-lying countries like Bangladesh.

References:

Cornwall, W. (2019): Ocean heat waves like the Pacific's deadly 'Blob' could become the new normal, Science Magazine. https://doi.org/10.1126/science.aaw8401

Gupta, A. S., Thomsen, M., Benthuysen, J. A., Hobday, A. J., Oliver, E., Alexander, L. V., Burrows, M. T., Donat, M. G., Feng, M., Holbrook, N. J., Perkins-Kirkpatrick, S., Moore, P. J., Rodrigues, R. R., Scannell, H. A., Taschetto, A. S., Ummenhofer, C. C., Wernberg, T., and Smale, D. A. (2020): Drivers and impacts of the most extreme marine heatwaves events. Scientific Reports, 10(1), 1–15. https://doi.org/10.1038/s41598-020-75445-3S.

Hobday, A J., Oliver, E. C. J., Gupta, A. S., Benthuysen, J. A., Burrows, M. T., Donat, M. G., Holbrook, N. J., Moore, P. J., Thomsen, M. S., Wernberg, T., and Smale, D. A. (2018): Categorizing and naming marine heatwaves. Oceanography, 31(2), 162–173.

Hobday, Alistair 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., Holbrook, N. J., Moore, P. J., Scannell, H. A., Gupta, A. S., and Wernberg, T. (2016): A hierarchical approach to defining marine heatwaves. Progress in Oceanography, 141, 227–238. https://doi.org/10.1016/j.pocean.2015.12.014

Holbrook, N. J., Scannell, H. A., Gupta, A. S., Benthuysen, J. A., Feng, M., Oliver, E. C. J., Alexander, L. V., Burrows, M. T., Donat, M. G., Hobday, A. J., Moore, P. J., Perkins-Kirkpatrick, S. E., Smale, D. A., Straub, S. C., and Wernberg, T. (2019): A global assessment of marine heatwaves and their drivers. Nature Communications, 10(1), 1–13. https://doi.org/10.1038/s41467-019-10206-z

IPCC (n.d.): Special Report on Climate Change and Land. https://www.ipcc.ch/srccl/ Accessed on 15 June 2024.

Khan, M. R., Islam, A., Abdullah, A. (2020): Time and cost effective ship design process using single parent design approach with considerable dimension difference, 12th International Conference on Marine Technology; Ambon, Indonesia. P. 11-19.

Kundu, R., Khan, M. R., Rahman, S., Saha, G. K. (2018): Design and structural analysis of a pontoon vessel, AIP Conference Proceedings of the 12th International Conference on Mechanical Engineering (ICME 2017). 1980 (1). https://doi.org/10.1063/1.5044285

Oliver, E. C. J., Benthuysen, J. A., Darmaraki, S., Donat, M. G., Hobday, A. J., Holbrook, N. J., Schlegel, R. W., and Gupta, A. S. (2021): Marine Heatwaves. Annual Review of Marine Science, 13, 313–342. https://doi.org/10.1146/annurev-marine-032720-095144

Oliver, E. C. J., Burrows, M. T., Donat, M. G., Gupta, A. S., Alexander, L. V., Perkins-Kirkpatrick, S. E., Benthuysen, J. A., Hobday, A. J., Holbrook, N. J., Moore, P. J., Thomsen, M. S., Wernberg, T., and Smale, D. A. (2019): Projected Marine Heatwaves in the 21st Century and the Potential for Ecological Impact. Frontiers in Marine Science, 6(December), 1–12. https://doi.org/10.3389/fmars.2019.00734

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., Holbrook, N. J., Perkins-Kirkpatrick, S. E., Scannell, H. A., Straub, S. C., and Wernberg, T. (2018): Longer and more frequent marine heatwaves over the past century. Nature Communications, 9(1), 1–12. https://doi.org/10.1038/s41467-018-03732-9

The Climate Reality Project (2021): How the Climate Crisis Is Impacting Bangladesh? https://www.climaterealityproject.org/blog/how-climate-crisis-impacting-bangladesh#:~:text=It has been estimated that of sea level rise alone. Accessed on 15 June 2024.

World Bank Group (2022): Key Highlights: Country Climate and Development Report for Bangladesh. World Bank. https://www.worldbank.org/en/news/feature/2022/10/31/key-highlights-country-climate-and-development-report-for-bangladesh Accessed on 15 June 2024