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ARTICLE

Marine Heatwaves and Cyclone Interactions in the North Indian Ocean: A Tale of Shaheen and Gulab

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ABSTRACT

Tropical cyclones (TCs) are among the most devastating natural hazards, and their development can be significantly influenced by marine heatwaves (MHWs)—periods when sea surface temperatures (SSTs) rise 3–4 °C above average for at least five days. This study investigates the interaction between TCs Gulab and Shaheen and MHW conditions in the North Indian Ocean during September–October 2021. Using data from NOAA-OISST and HYCOM model outputs, along with the Marine Heatwave Tracker, we mapped the timeline of MHWs relative to the formation and intensification of these cyclones. TC Gulab originated in the Bay of Bengal and later redeveloped as TC Shaheen in the Arabian Sea—an uncommon occurrence during the southwest monsoon season. On average, 1–2 cyclones form annually in the Arabian Sea, and about 48.5% dissipate without making landfall. However, TC Shaheen intensified into a Severe Cyclonic Storm (SCS) and made landfall on Oman's coast, where persistent MHWs were observed. The study suggests that elevated SSTs due to MHWs played a significant role in sustaining and intensifying the storm system. These findings highlight the importance of understanding oceanic thermal anomalies in assessing cyclone behavior and potential landfall impacts, especially in the context of a warming climate and increasing frequency of extreme marine heat events.

Keywords: Marine Heatwave; Cyclone; Mixed Layer Depth

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1. Introduction

Tropical cyclones (TCs) are the most devastating natural hazards that affect tropical coastal areas, causing a huge loss of life and economic damage. They are characterized by a strong cyclonic vortex with a warm central core, strong wind, heavy rain at the sidewalls, and a strong surge that makes them more vulnerable to the coastal areas. The SST greater than 26 °C is the primary ingredient for the generation and maintenance of the cyclone. After it, the further intensification or weakening mostly depends on the supply of energy from the upper ocean processes like ocean eddies, MHWs.

Extreme and extended duration of warm ocean water temperatures, also known as marine heat waves (MHWs), has a major impact on marine organisms and ecosystems. Atmospheric and regional oceanic forcing through large-scale teleconnections modulates anomalous warm ocean temperatures, so that the production of MHWs varies in different parts of the world's oceans. They are expected to occur more frequently throughout the year. Turbulent fluxes (energy transfer from ocean to atmosphere), changes in the strength of wind, ocean surface circulation, and local as well as large-scale climate modes with their teleconnections are the most significant drivers for the enhancement and suppression of MHWs. It can extend to a deeper depth of the water column [1]. During a marine heatwave (MHW), several factors contribute to its development and impact on ocean conditions. Firstly, the shallower mixed layer depth leads to increased shortwave radiation, which enhances warming and intensifies upper ocean stratification. This stratification inhibits vertical mixing and heat transport, thereby elevating the upper ocean heat content and bringing warm anomalies from the subsurface to the surface. Over the global ocean, the sea surface temperature (SST) exhibits significant variability both in space and time across a wide spectrum of frequencies. Such variability causes extreme stress to regional marine ecosystems and industries driven by these ecosystems. These extremely warm ocean temperature conditions are called MHWs and are defined as prolonged, unusually warm ocean conditions beyond a predefined threshold [1–6]. The Indian Ocean, the third-largest oceanic division in the world, has been experiencing significant warming over the past few decades [7]. This warming trend has become particularly pronounced in the last ten years, driven by a combination of natural factors and anthropogenic climate change. The effects of this warming are profound, influencing weather patterns, marine ecosystems, and, notably, the frequency and intensity of cyclonic activity. The Arabian Sea, located in the northwestern part of the Indian Ocean, has become a focal point in discussions about the warming of the Indian Ocean. In recent years, this region has experienced a significant rise in sea surface temperatures, making it one of the fastest-warming parts of the Indian Ocean. This warming has had profound effects on the region's climate, particularly in terms of cyclonic activity.

The Bay of Bengal and the Arabian Sea, constituting the two primary arms of the North Indian Ocean, exhibit a bimodal pattern in cyclone activity, with distinct peaks during the pre-monsoon (March–May) and post-monsoon (October–December) seasons. The Bay of Bengal, in particular, is known to experience the most intense and destructive cyclones during these periods, accompanied by significant inter-annual variability in both frequency and intensity [8]. During the pre-monsoon season, elevated relative humidity over oceanic regions is a key driver of cyclogenesis, whereas in the post-monsoon season, reduced low-level vertical wind shear (between 850 hPa and 200 hPa) plays a critical role in cyclone formation. Historically, the Bay of Bengal, situated to the east of the Indian subcontinent, has been more susceptible to cyclonic activity compared to the Arabian Sea. However, recent trends indicate a shift in this pattern. Both basins have recorded a marked increase in cyclogenesis, resulting in severe impacts along the eastern and western coastlines of India [9–14]. Notably, the Arabian Sea has witnessed a significant rise in both the frequency and intensity of cyclones over the past decade. This increase is largely attributed to rising sea surface temperatures, which enhance the oceanic heat content and provide favorable conditions for cyclone development. As a consequence, the Arabian Sea has experienced several high-intensity cyclones in recent years, including Cyclone Vayu (2019) and Cyclone Tauktae (2021).

The Arabian Sea, located between 8°N and 22°N, connects to the Red Sea via the Gulf of Aden and to the Arabian Gulf through the Gulf of Oman. Tropical cyclones in this region typically occur during the pre-monsoon season (April–May) and the post-monsoon season (September–December). However, in recent years, cyclones have also begun forming during the early phase of the southwest monsoon, particularly in June. Cyclones that originate in the Arabian Sea generally move toward the coast of Oman or are redirected toward the western coastline of India. The eastern Arabian Sea exhibits a higher frequency of tropical cyclone genesis compared to its western counterpart. Cyclone tracks in this basin commonly follow a west-northwest direction or curve northward and then eastward due to recurvature effects [15,16]. Most tropical cyclones in the Arabian Sea are formed locally; however, on occasion, cyclones originating in the Bay of Bengal traverse the Indian Peninsula and reintensify upon entering the Arabian Sea. Over the past few decades, the Arabian Sea has been experiencing rapid warming at a rate significantly higher than other tropical ocean basins. This increase in sea surface temperature has contributed to a rise in cyclone frequency and has exacerbated flooding events across the Indian subcontinent [17].

Sea Surface Temperature (SST) plays a critical role in cyclogenesis, as warmer SSTs significantly contribute to the formation, intensification, and propagation of tropical cyclones [17]. Compared to the Bay of Bengal, the Arabian Sea historically records fewer cyclones, with an average of 1–2 events annually, most of which have traditionally been of lower intensity [9]. However, in recent years, there has been a noticeable increase in the intensity of cyclones in the Arabian Sea, with several reaching the status of severe or even super cyclonic storms. This trend has been closely associated with rising SSTs, along with an observed increase in cyclone frequency during the summer monsoon season [18,19]. The formation of high-intensity cyclones in the North Indian Ocean is strongly influenced by SST anomalies and vertical wind shear conditions [10]. Importantly, over the past few decades, the Indian Ocean—particularly the Arabian Sea—has experienced a rate of warming that surpasses that of other tropical ocean basins [20,21], further enhancing the potential for intense cyclonic activity in the region.

In September 2021, a rare weather event occurred when TC Gulab formed in the BoB and followed an unusual path. It crossed over the Indian landmass and re-entered the AS as TC Shaheen. While it is common for remnants of cyclones from the BoB to move across India and intensify into low-pressure systems in the AS, it is rare for them to regain the intensity of a tropical cyclone. One similar event occurred in 2008 when Cyclone Gaja, which developed in the BoB, crossed India and intensified into a depression in the AS. However, in the last 40 years, the India Meteorological Department's (IMD) records show no evidence of a BoB-origin cyclone developing into a tropical cyclone in the AS—until Gulab/Shaheen. This event was unique due to its origin in the BoB during the monsoon season, its journey across India, and its re-emergence in the AS, where it intensified into a severe cyclonic storm before making landfall on the Oman coast [20].

MHWs maximum temperature intensity can reach up to deeper depths (10–50m), particularly in the thermocline; they are not limited to the surface of the ocean. Vertically constant temperature and salinity in the surface turbulent mixed layer restricted the very strong warm temperature anomalies during MHWs. Nevertheless, these warm temperature anomalies have also been observed at hundreds of meters below the ocean's surface. Vertically homogeneous ocean due to turbulence in the surface layer, the well-mixed temperature and salinity strongly suppress the MHWs' extreme warm temperature anomalies [21–25,27]. Large-scale ocean-atmospheric teleconnections forcing regional oceanic and atmospheric changes are the primary drivers of extreme warm temperature anomalies. Such strong temperature anomalies, due to the MHWs, favour the genesis of tropical cyclones and also fuel their rapid intensification [28–33]. During MHW, strong penetration of shortwave radiation into the ocean and shallow mixed layer depth due to the weak winds increased the upper ocean stratification and enhanced the warming. These processes reduce the heat transport and vertical mixing in the ocean. Such vertical structure enhances the upper ocean heat content and also pushes the strong warm temperature anomalies from the subsurface [28]. Recent studies reveal that the basin-wide warming of the Indian

Ocean (IO) and its effects, but the factors causing the warming are still unclear. According to the IPCC [34] report, over the last 100 years, warming has occurred in the western part of the Indian Ocean at a faster rate than in the tropical ocean basins in the world. Vellore et al. [35] noted a 52% increase in severe cyclones in the AS during 1951–2018.

The objective of this study is to assess whether a Marine Heatwave (MHW) influenced the development and intensification of Tropical Cyclone (TC) Gulab in the Bay of Bengal during September, facilitated its sustenance after landfall, and contributed to its subsequent reintensification into TC Shaheen over the Arabian Sea.

2. Materials and Methods

To emphasize the interaction between MHW and cyclone, the following data sets are used:

Sea Surface Temperature: Daily Optimum Interpolation Sea Surface Temperature (OISST) data is utilized, featuring a consistent global grid with a spatial resolution of 0.25° × 0.25°. This dataset integrates long-term climate records derived from various satellite, ship, buoy, and Argo float observations. Missing data within the grid are filled using interpolation techniques to generate a high-resolution spatial map of SST. To address discrepancies arising from different observational platforms and sensor biases, satellite and ship measurements are calibrated against buoy data. The daily OISST version 2 dataset from the National Oceanic and Atmospheric Administration (NOAA) is employed for identifying marine heatwaves and assessing their intensity. Further details are available at https://www.ncei.noaa.gov/products/optimum-interpolation-sst.

Cyclone Data: Gulaab Cyclone: A low-pressure area developed over the east-central Bay of Bengal (BoB) and its surrounding region at 0300 UTC on 24th September. Favorable oceanic and atmospheric conditions led to its intensification into a depression over the east-central and adjoining northeast BoB by 1200 UTC on the same day. The system then moved westward, strengthening further into a deep depression over the northern and adjoining central BoB by 0000 UTC on 25th September 2021. Continuing to move further westwards, it intensified into Gulab over northwest and adjoining west-central BoB in the same evening (1200 UTC) of 25th September, 2021. Subsequently, the system gradually intensified, reaching its peak wind speed of 75–95 km/h around noon (0600 UTC) on 26th September. Continuing its westward trajectory, it made landfall near the coast of North Andhra Pradesh and adjoining South Odisha, approximately at latitude 18.4°N and longitude 84.2°E, between 1400 and 1500 UTC on 26th September (Source: IMD preliminary report).

Shaheen Cyclone: In the morning (0300 UTC) of 29th September 2021, in the southern part of the Gujarat area and the adjoining Gulf of Khambhat, a low-pressure system developed, which is a remnant of the Gulab cyclone in the BoB. This low-pressure system, under the favorable conditions, further developed into a depression the next morning (0000 UTC, 30 September) and concentrated over the northeast AS and adjacent Kutch moved west-northwestwards. At 1800 UTC on 30th September, the depression further intensified into a Deep Depression in the same area. The next morning at 0000 UTC (1st October), reached cyclone stage named as Shaheen over the northeast of the Arabian Sea and further moved in a westward direction. By the evening (1200 UTC, 1 October), Shaheen changes direction from westward to west-northwestward and strengthens into a severe cyclonic storm over the northwest and adjacent northeast AS. Moving west-northwestward until the evening of October 2 (1200 UTC), it turned west-southwestward and crossed the coast of Oman on October 4, 2021. (Source: IMD preliminary report). The trajectories of the Shaheen and Gulab cyclones were obtained from the India Meteorological Department (https://mausam.imd.gov.in/).

Model Simulations: The HYbrid Coordinate Ocean Model (HYCOM) employs a hybrid vertical coordinate system. In the open and stratified ocean, it uses isopycnal coordinates, while in shallow coastal regions, it smoothly transitions to terrain-following coordinates. In mixed-layer or unstratified seas, the model reverts to z-level coordinates. Each coordinate surface is assigned a reference isopycnal, and the model continuously evaluates whether grid points align with their respective reference isopycnals. If misalignment occurs, grid points attempt to shift vertically to the nearest appropriate isopycnal. However, vertical movement is restricted when coordinate surfaces become overcrowded. As a result, in shallow waters, vertical grid points are constrained to fixed depths, though they remain free to move along reference isopycnals in adjacent deeper regions (https://www.hycom.org/).

Within the mixed layer, grid points are arranged vertically so that each layer interface transitions smoothly from isopycnal surfaces to constant-depth levels, with the interface extending into the mixed layer. Consequently, HYCOM functions similarly to a traditional sigma model in very shallow and/or unstratified ocean regions, behaves like a z-level coordinate model in mixed layers or other unstratified zones, and operates as an isopycnic-coordinate model in stratified areas. This hybrid approach allows HYCOM to leverage the advantages of different vertical coordinate systems, thereby optimizing the simulation of both coastal and open ocean circulation dynamics. Furthermore, the current process of driving high-resolution coastal models—which typically use fixed vertical grids—with outputs from basin-scale isopycnic models can be simplified, as HYCOM directly provides the necessary near-shore data at fixed depth intervals.

HYCOM data with a spatial resolution of 0.08° × 0.08° resolution from Asia Pacific Research Data Centre was used to investigate the vertical extent of MHW, MLD, and thermocline depth variations during September to October 2021 (https://apdrc.soest.hawaii.edu/index.php).

Methodology

Following the definition by Hobday et al.[2], a Marine Heatwave (MHW) is identified when the sea surface temperature (SST) remains above the 90th percentile of the climatological baseline for at least five consecutive days, allowing for gaps of up to two days between warming events. Using this criterion and the reference climatology, warming events are detected accordingly. In the present study, the 90th percentile climatology was calculated using an 11-day centered window from the Optimum Interpolation Sea Surface Temperature (OISST) data, spanning the period from 1982 to 2021. The intensity of each MHW event was quantified by subtracting the daily mean climatology from the observed OISST. Key parameters characterizing MHWs include duration, mean intensity, maximum intensity, and variance. The methodology outlined in Hobday et al.[2] was employed to detect and analyze MHWs, with visualization facilitated by Eric Oliver's Python scripts (https://github.com/ecjoliver/marineHeatWaves).

The Mixed Layer Depth (MLD) is estimated using a variable density criterion, calculated based on a density change ($\Delta\sigma$) according to the UNESCO equation of state. In this study, the depth of the 20 °C isotherm is used to define the thermocline depth.

3. Results

During the cyclonic activities of Gulab and Shaheen, a significant presence of a marine heatwave was observed in the North Arabian Sea, which played a crucial role in the intensification of these cyclones. On September 26, 2021, the Marine Heatwave Tracker detected a notable marine heatwave in this region, characterized by elevated sea surface temperatures that created favorable conditions for the intensification of the cyclonic system. This marine heatwave coincided with the timeline when Tropical Cyclone (TC) Gulab, after crossing the Indian landmass, re-entered the Arabian Sea and began its transformation into TC Shaheen.

As the remnants of TC Gulab moved into the North Arabian Sea, the warm waters (28.7 °C–30.5 °C) provided by the MHW contributed significantly to the system's re-intensification. Between September 27 and September 30, 2021 (**Figure 1**), during this critical period, the cyclone rapidly developed from a Category 1 to a Category 3 storm, indicating a severe escalation in intensity. The presence of the MHW likely enhanced the energy available to the storm, fueling its growth and leading to the severe cyclonic conditions observed. This phenomenon underscores the importance of oceanic heat content in the life cycle of tropical cyclones, particularly in the cases of Gulab and Shaheen. The warm SSTs (> 29 °C) associated with the MHW provided the necessary thermal energy for the cyclone to not only survive its transition across land but also to re-strengthen in the AS.

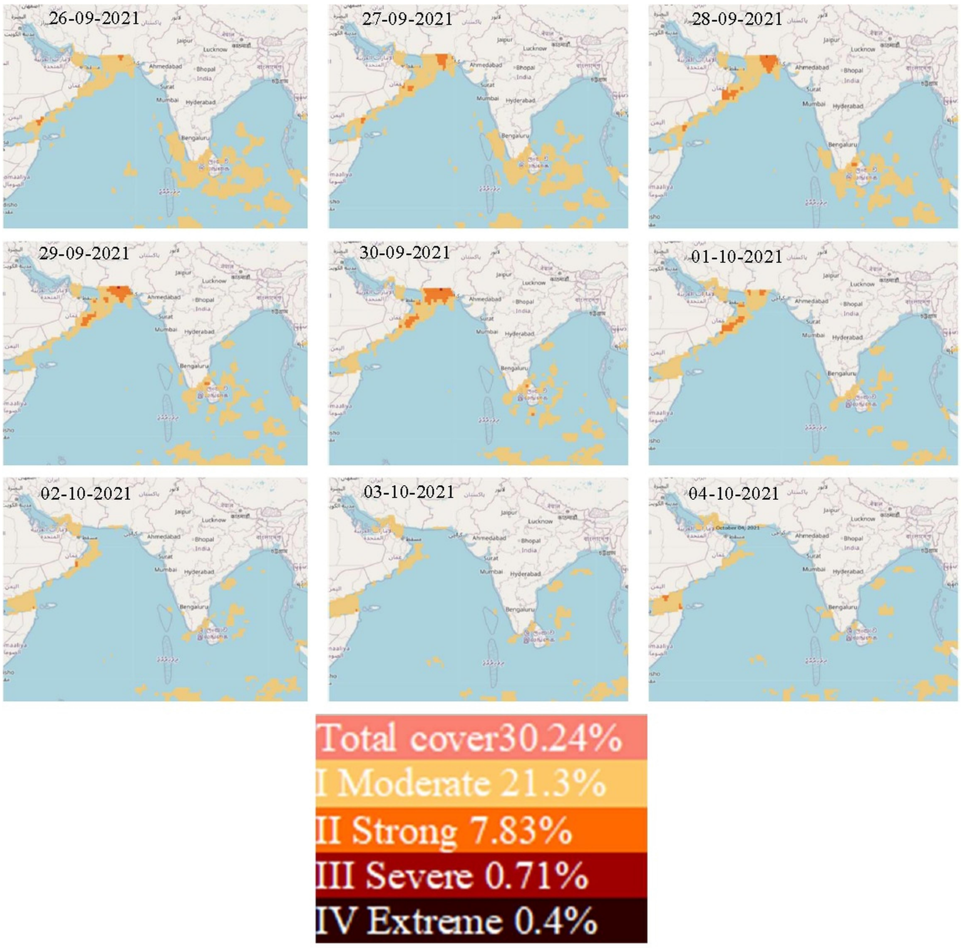

Figure 1. Marine heat wave conditions over the Arabian Sea during the timeline of the Gulab and Shaheen cyclones.

Source: Marine heatwave tracker.

Gulab cyclone formed over the Bay of Bengal between September 24 and September 28, 2021, with SSTs ranging from 29 °C to 31 °C, ideal for cyclone development. These warm SSTs provided the heat and moisture necessary to sustain the storm as it moved westward and made landfall near Kalingapatnam, Andhra Pradesh, on September 26 (**Figure 2**). It had peak sustained wind speeds of approximately 21 m/s (75 km/h), classifying it as a cyclonic storm. These wind speeds were sufficient to cause damage in coastal areas of Andhra Pradesh and Odisha during its landfall. As the cyclone weakened into a deep depression over land, its wind speeds decreased significantly (**Figure 3**). However, after crossing into the Arabian Sea, the remnants of Gulab re-intensified due to favorable conditions, including warm SSTs, and attained wind speeds of 33 m/s (120 km/h) as Cyclone Shaheen, highlighting the dynamic nature of its lifecycle.

During Cyclone Shaheen's path across the Arabian Sea from September 30 to October 4, 2021, the SSTs were notably warm, ranging between 28 °C and 31 °C, creating favorable conditions for the cyclone's intensification (**Figure 4**). These elevated SSTs provided the necessary heat and moisture to fuel the storm as it developed into a severe cyclonic storm, moving westward before making landfall in Oman. The passage of the cyclone likely resulted in localized cooling of SSTs due to ocean mixing, where cooler subsurface waters were brought to the surface, but the warm pre-storm SSTs were instrumental in sustaining its intensity. The cyclone's wind speeds peaked at around 33 m/s, classifying it as a severe cyclonic storm. These warm SSTs supplied the necessary heat and moisture to sustain the storm, which moved westward before making landfall in Oman (**Figure 5**). The passage of the cyclone likely caused localized cooling of SSTs due to ocean mixing, but the combination of elevated SSTs and strong wind speeds was critical to its development and impact.

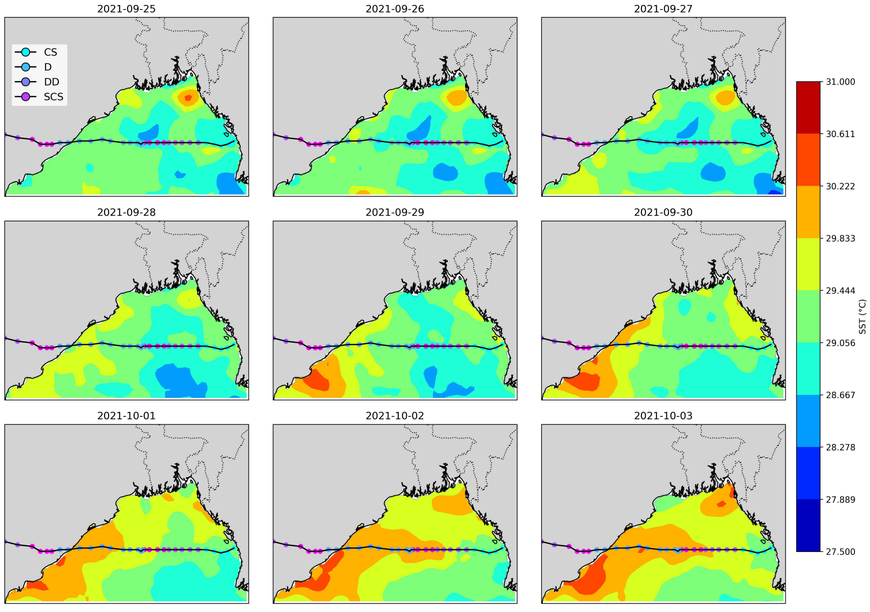

Figure 2. Sea surface temperature changes during Gulab cyclone over Bay of Bengal.

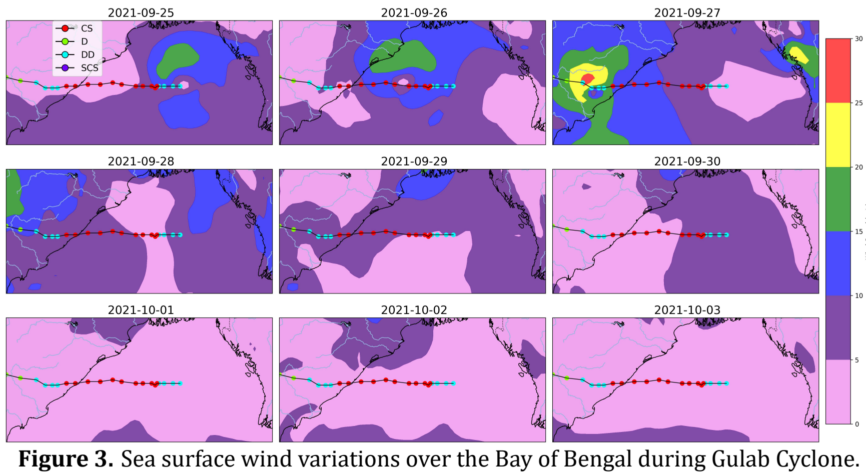

Figure 3. Sea surface wind variations over the Bay of Bengal during Gulab Cyclone.

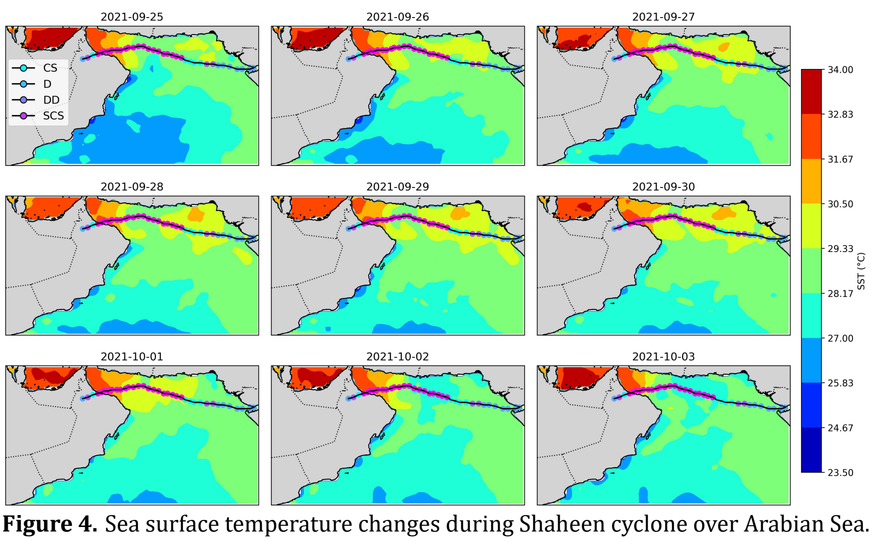

Figure 4. Sea surface temperature changes during Shaheen cyclone over Arabian Sea.

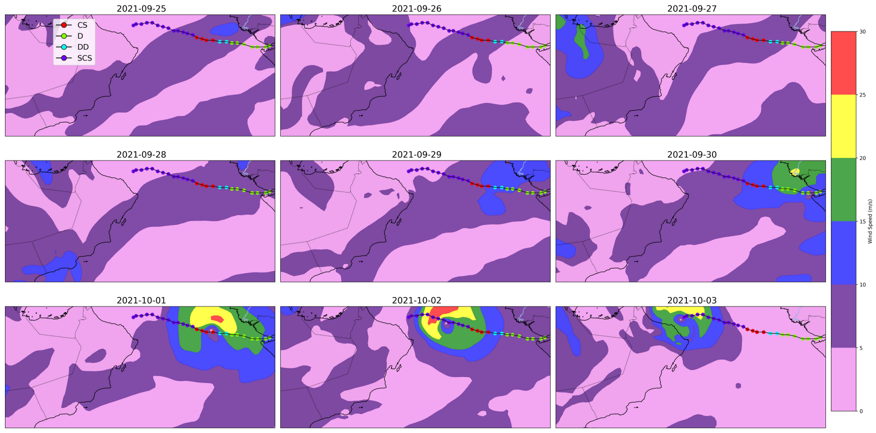

Figure 5. Sea surface wind variations over Arabian Sea during Shaheen Cyclone.

During the MHW event, the thermocline depth was deepened significantly, exceeding 150 meters. This deepening indicates pronounced stratification within the water column, characterized by a stark contrast between warmer surface waters and cooler subsurface layers. The substantial deepening of the thermocline acts as a formidable barrier to vertical mixing between the surface and deeper waters, thereby contributing to the persistence and intensity of the MHW.

Throughout the period from 26th September to 1st October, the region experienced a marine heatwave, with sea surface temperatures peaking at approximately 29 °C. Subsurface temperatures, measured to a depth of 10 meters, were consistently between 28 °C and 29 °C during the MHW.

On 30th September, the MLD showed a marked increase, reaching depths of up to 30 meters. This deepening of the MLD is attributed to the influence of the severe cyclonic storm Shaheen, which generated strong winds that enhanced oceanic mixing (**Figure 6**). Cyclonic winds are known to induce turbulent mixing in the ocean, significantly affecting the depth and dynamics of the mixed layer.

The observed deepening of both the mixed layer and the thermocline during the MHW event underscores the intricate interactions between atmospheric forcing and oceanic response. These modifications in ocean stratification and mixing processes have profound implications for marine ecosystems, biogeochemical cycles, and climate dynamics. The persistence of the MHW, facilitated by these changes, emphasizes the importance of understanding and predicting the impact of extreme atmospheric events on oceanic conditions.

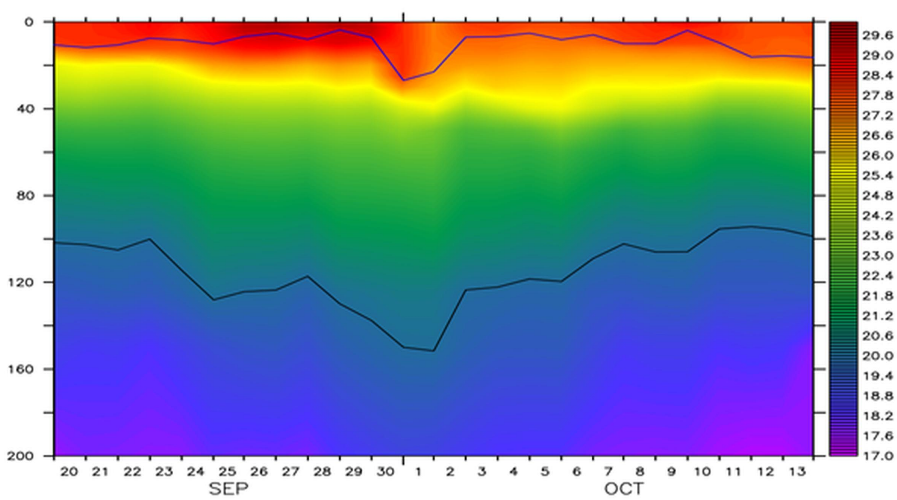

Figure 6. Vertical temperature distribution at 64.2°E, 23.8°N, with the blue line indicating the mixed layer depth (MLD) and the black line indicating the thermocline depth.

4. Discussion

In the present study, we investigate the interaction between MHWs and rare cyclone tracks from the Bay of Bengal to the Arabian Sea during September–October 2021 using multi-satellite data and HYCOM model data. We noticed strong MHWs observed in the northern Arabian Sea three days ahead of the cyclone Shaheen (**Figure 1**). After the first interaction of the MHW with Shaheen SST dropped. This result is in good agreement with Akhila et al.[9], who found the SST changes during cyclone in the Bay of Bengal. The results revealed that the sea surface temperature during different phases of cyclone varies between 26 °C and 30.5 °C in both cyclones (**Figures 2** and **4**). Strong winds and cooling were observed during the Shaheen cyclone period (**Figures 3** and **4**). An anomalous shoaling of MLD and increased solar insolation onto the ocean surface during the MHW event (**Figure 6**). The deepening of the MLD was associated with strong wind-driven mixing due to gale winds of the Shaheen cyclone, resulting in an anomalous cooling in the northern Arabian Sea (**Figures 4–6**). MHWs significantly modify the ocean physics, which includes a rise in SST, a rise in sea level due to thermal expansion, and it also alters the stratification of the ocean. This can reduce the mixing process, strongly impact the nutrient cycle and oxygen levels, and variability in ocean circulation and mixing processes.

Previous studies have established a link between coastal thermal structure and cyclone intensification; however, a more comprehensive understanding of the coastal processes that drive upper ocean heat content to extreme levels during cyclone landfall is needed. The extreme thermal conditions observed during the storm's passage were initially triggered by a mixing event and further amplified by a regional heatwave. Although the storm's downdraft played a significant role in influencing heat at this specific location, the storm-induced mixing impacted the broader continental shelf in two key ways. First, strong vertical mixing redistributed thermal energy within the coastal shelf waters, transporting heat from the surface to deeper layers and displacing the cooler bottom waters. Second, this restructuring of the vertical thermal profile enhanced the ocean's capacity to absorb heat, facilitating a rapid re-warming of the upper ocean.

5. Conclusions

The study was conducted by closely observing the presence and influence of marine heatwaves during the cyclonic activities of Gulab and Shaheen. By tracking the presence of marine heatwaves during the lifecycle of TC Gulab and its subsequent transformation into TC Shaheen, the study aims to establish a direct correlation between these oceanic heat anomalies and the unusual behavior of the cyclones.

MHWs significantly alter the thermal structure of the ocean, creating conditions that can potentially fuel the rapid intensification of tropical cyclones. In this context, the study examines how such heatwaves may have contributed to the formation of TC Gulab in the BoB, its persistence over land after landfall, and its eventual re-intensification into TC Shaheen in the AS. By analyzing the temporal and spatial extent of these MHWs during the cyclonic events, the research seeks to provide a more comprehensive understanding of the oceanic processes that might have supported these rare and complex meteorological phenomena.

The temperature column of the ocean plays a crucial role in influencing the formation, intensity, and trajectory of cyclones, also known as hurricanes or typhoons, depending on the region. As the ocean's temperature rises, it can have significant effects on cyclone development and behaviour.

Warm ocean waters provide the energy that fuels cyclone formation and intensification. When SSTs exceed a certain threshold (typically around 26 °C), it provide the necessary heat and moisture for tropical cyclones to develop and strengthen. As the ocean's temperature column warms, it increases the likelihood of encountering these favorable conditions more frequently and over larger areas. Additionally, warmer ocean temperatures can lead to increased evaporation rates, resulting in greater moisture content in the atmosphere above the ocean surface. This moisture-rich environment provides additional fuel for cyclone development and can contribute to the formation of stronger and more intense storms. Furthermore, warmer ocean temperatures can influence the vertical stability of the atmosphere, which is essential for the organization and maintenance of cyclone structures. Warmer water near the ocean surface can create more instability in the atmosphere, allowing cyclones to develop more efficiently and potentially reach higher intensities.

The interaction between cyclones and warmer ocean temperatures can also affect their behavior and track. The findings are expected to contribute to the broader field of tropical meteorology and oceanic science by highlighting the significance of marine heatwaves as a critical factor in cyclone formation and intensification, particularly in regions like the BoB and the AS, where such interactions are not yet fully understood.

Author Contributions

Conceptualization, M.K.K.; methodology, M.K.K. and T.P.; software, T.P.; formal analysis, M.K.K. and T.P.; writing—original draft preparation, M.K.K. and T.P.; writing—review and editing, M.K.K.; visualization, T.P.; supervision, M.K.K. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

In the Data and Methodology section, we provide the website links for all datasets used in this study.

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Conflicts of Interest

The authors declare that there is no conflict of interest.

References

[1] Darmaraki, S., Somot, S., Sevault, F., et al., 2019. Future Evolution of Marine Heatwaves in the Mediterranean Sea. Climate Dynamics. 53, 1371–1392. DOI: https://doi.org/10.1007/s00382-019-04661-z

[2] Hobday, A.J., Alexander, L.V., Perkins, S.E., et al., 2016. A Hierarchical Approach to Defining Marine Heatwaves. Progress in Oceanography. 141, 227–238. DOI: https://doi.org/10.1016/j.pocean.2015.12.014

[3] Pearce, A.F., Lenanton, R., Jackson, G., et al., 2011. The 'Marine Heat Wave' off Western Australia During the Summer of 2010/2011. Fisheries Research Report No. 221. Government of Western Australia Department of Fisheries: North Beach, Western Australia, pp. 1–40.

[4] Jacox, M.G., Alexander, M.A., Amaya, D., et al., 2022. Global Seasonal Forecasts of Marine Heatwaves. Nature. 604, 486–490. DOI: https://doi.org/10.1038/s41586-022-04573-9

[5] Kumar, S., Chakraborty, A., Chandrakar, R., et al., 2023. Analysis of Marine Heatwaves over the Bay of Bengal During 1982–2021. Scientific Reports. 13, 14235. DOI: https://doi.org/10.1038/s41598-023-39884-y

[6] Li, Z., Wu, G., Xu, C., et al., 2024. Summer Marine Heatwaves in the Tropical Indian Ocean Associated with an Unseasonable Positive Indian Ocean Dipole Event. Frontiers in Marine Science. 11, 1425813. DOI: https://doi.org/10.3389/fmars.2024.1425813

[7] Kuttippurath, J., Maishal, S., Anjaneyan, P., et al., 2023. Recent Changes in Atmospheric Input and Primary Productivity in the North Indian Ocean. Heliyon. 9(7), e17940. DOI: https://doi.org/10.1016/j.heliyon.2023.e17940

[8] Krishnapriya, M.S., Varikoden, H., Anjaneyan, P., et al., 2023. Marine Heatwaves During the Pre-Monsoon Season and Their Impact on Chlorophyll-a in the North Indian Ocean in 1982–2021. Marine Pollution Bulletin. 197, 115783. DOI: https://doi.org/10.1016/j.marpolbul.2023.115783

[9] Akhila, R.S., Kuttippurath, J., Sarojini, B.B., et al., 2022. Observed Tropical Cyclone-Driven Cold Wakes in the Context of Rapid Warming of the Arabian Sea. Journal of Operational Oceanography. 16(3), 236–251. DOI: https://doi.org/10.1080/1755876X.2022.2068260

[10] Krishna, K.M., 2009. Intensifying Tropical Cyclones over the North Indian Ocean During Summer Monsoon—Global Warming. Global and Planetary Change. 65(1–2), 12–16. DOI: https://doi.org/10.1016/j.gloplacha.2008.10.007

[11] Nadimpalli, R., Mohanty, S., Pathak, N., et al., 2021. Understanding the Characteristics of Rapid Intensity Changes of Tropical Cyclones over North Indian Ocean. SN Applied Sciences. 3, 68. DOI: https://doi.org/10.1007/s42452-020-03995-2

[12] Rathore, S., Goyal, R., Jangir, B., et al., 2022. Interactions Between a Marine Heatwave and Tropical Cyclone Amphan in the Bay of Bengal in 2020. Frontiers in Climate. 4, 861477. DOI: https://doi.org/10.3389/fclim.2022.861477

[13] Shenoi, S.S.C., Shankar, D., Shetye, S.R., 2002. Differences in Heat Budgets of the Near-Surface Arabian Sea and Bay of Bengal: Implications for the Summer Monsoon. Journal of Geophysical Research. 107(C6), 1–14. DOI: https://doi.org/10.1029/2000JC000679

[14] Kumar, S., Lal, P., Kumar, A., 2020. Turbulence of Tropical Cyclone ‘Fani’ in the Bay of Bengal and Indian Subcontinent. Natural Hazards. 103, 1613–1622. DOI: https://doi.org/10.1007/s11069-020-04033-5

[15] Murty, T., El-Sabh, M., 1984. Cyclones and Storm Surges in the Arabian Sea: A Brief Review. Deep Sea Research Part A Oceanographic Research Papers. 31(6–8), 665–670.

[16] Najah, A., van der Merwe, R., Al Shehhi, M.R., 2025. Review of Tropical Cyclones Impacting the Western Arabian Sea and Oman. Journal of Operational Oceanography. 18(1), 21–39. DOI: https://doi.org/10.1080/1755876X.2024.2444753

[17] Naskar, P.R., Pattanaik, D.R., 2023. Variations of Central Pressure of Intense Tropical Cyclones over the Bay of Bengal with Latent Heat Flux and Other Parameters. Journal of Earth System Science. 132, 44. DOI: https://doi.org/10.1007/s12040-023-02065-6

[18] Yanase, W., Satoh, M., Taniguchi, H., et al., 2012. Seasonal and Intraseasonal Modulation of Tropical Cyclogenesis Environment over the Bay of Bengal During the Extended Summer Monsoon. Journal of Climate. 25(8), 2914–2930. DOI: https://doi.org/10.1175/JCLI-D-11-00208.1

[19] Roxy, M., Tanimoto, Y., 2007. Role of SST over the Indian Ocean in Influencing the Intraseasonal Variability of the Indian Summer Monsoon. Journal of the Meteorological Society of Japan Series II. 85(3), 349–358. DOI: https://doi.org/10.2151/jmsj.85.349

[20] Jaiswal, N., Jishad, M., Deb, S.K., et al., 2023. Analysis of Atmospheric and Oceanic Conditions During Unusual Occurrence of Tropical Cyclone Gulab and Shaheen in North Indian Ocean. Journal of Earth System Science. 132, 109. DOI: https://doi.org/10.1007/s12040-023-02129-7

[21] Levitus, S., Antonov, J.I., Boyer, T.P., et al., 2012. World Ocean Heat Content and Thermosteric Sea Level Change (0–2000 m), 1955–2010. Geophysical Research Letters. 39(10), L10603. DOI: https://doi.org/10.1029/2012GL051106

[22] Oliver, E.C.J., 2019. Mean Warming Not Variability Drives Marine Heatwave Trends. Climate Dynamics. 53, 1653–1659. DOI: https://doi.org/10.1007/s00382-019-04707-2

[23] Oliver, E.C.J., Donat, M.G., Burrows, M.T., et al., 2018. Longer and More Frequent Marine Heatwaves Over the Past Century. Nature Communications. 9, 1324. DOI: https://doi.org/10.1038/s41467-018-03732-9

[24] Elzahaby, Y., Schaeffer, A., Roughan, M., et al., 2021. Oceanic Circulation Drives the Deepest and Longest Marine Heatwaves in the East Australian Current System. Geophysical Research Letters. 48(17), e2021GL094785. DOI: https://doi.org/10.1029/2021GL094785

[25] Elzahaby, Y., Schaeffer, A., Roughan, M., et al., 2022. Why the Mixed Layer Depth Matters When Diagnosing Marine Heatwave Drivers Using a Heat Budget Approach. Frontiers in Climate. 4, 838017. DOI: https://doi.org/10.3389/fclim.2022.838017

[26] Li, Y., Ren, G., Wang, Q., et al., 2023. Record-Breaking Marine Heatwave in Northern Yellow Sea During Summer 2018: Characteristics, Drivers and

Ecological Impact. Science of The Total Environment. 904, 166385. DOI: https://doi.org/10.1016/j.scitotenv.2023.166385

[27] Choi, H.Y., Park, M.S., Kim, H.S., et al., 2024. Marine Heatwave Events Strengthen the Intensity of Tropical Cyclones. Communications Earth & Environment. 5, 69. DOI: https://doi.org/10.1038/s43247-024-01239-4

[28] Pun, I.F., Hsu, H.H., Moon, I.J., et al., 2023. Marine Heatwave as a Supercharger for the Strongest Typhoon in the East China Sea. npj Climate and Atmospheric Science. 6, 128. DOI: https://doi.org/10.1038/s41612-023-00449-5

[29] Cione, J.J., Uhlhorn, E.W., 2003. Sea Surface Temperature Variability in Hurricanes: Implications With Respect to Intensity Change. Monthly Weather Review. 131, 1783–1796. DOI: https://doi.org/10.1175//2562.1

[30] Zhang, H., He, H.L., Zhang, W.Z., et al., 2021. Upper Ocean Response to Tropical Cyclones: A Review. Geoscience Letters. 8, 1. DOI: https://doi.org/10.1186/s40562-020-00170-8

[31] Elzahaby, Y., Schaeffer, A., 2019. Observational Insight Into the Subsurface Anomalies of Marine Heatwaves. Frontiers in Marine Science. 6, 745. DOI: https://doi.org/10.3389/fmars.2019.00745

[32] Jackson, J.M., Johnson, G.C., Dosser, H.V., et al., 2018. Warming From Recent Marine Heatwave Lingers in Deep British Columbia Fjord. Geophysical Research Letters. 45(18), 9757–9764. DOI: https://doi.org/10.1029/2018GL078971

[33] Heidemann, H., Ribbe, J., 2019. Marine Heatwaves and the Influence of El Niño Off Southeast Queensland, Australia. Frontiers in Marine Science. 6, 56. DOI: https://doi.org/10.3389/fmars.2019.00056

[34] Intergovernmental Panel on Climate Change (IPCC), 2018. Strengthening the Global Response in the Context of Sustainable Development and Efforts to Eradicate Poverty. In: Masson-Delmotte, V., Zhai, P., Pörtner, H.O., et al. (eds.). Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways. World Meteorological Organization: Geneva, Switzerland. pp. 313–444.

[35] Vellore, R.K., Deshpande, N., Priya, P., et al., 2020. Extreme Storms. In: Krishnan, R., Sanjay, J., Gnanaseelan, C., et al. (eds.). Assessment of Climate Change Over the Indian Region. Springer: Singapore. pp. 155–173. DOI: https://doi.org/10.1007/978-981-15-4327-2_8