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Seasonal Changes in Ocean Subsurface Structure Over the Arabian Sea and Their Association With Tropical Cyclone Characteristics

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Abstract

The upper ocean strongly influences tropical cyclone (TC) development through its thermal structure, heat content, mixed-layer depth, and density stratification. This study examines seasonal changes in subsurface ocean conditions over the Arabian Sea (AS) during 2004–2023 and their association with TC characteristics using high-resolution (0.08°) Hybrid Coordinate Ocean Model (HYCOM) data. We analyze changes in mixed-layer depth (MLD), maximum thermocline depth (MTD), ocean heat content integrated to 200 m (OHC200), density stratification, and subsurface temperature, together with variations in maximum potential intensity (MPI), genesis potential index (GPI), and TC track characteristics. During the pre-monsoon season, MLD decreases, density stratification increases, and OHC200 rises over much of the AS, accompanied by enhanced subsurface warming. During the post-monsoon season, the ocean exhibits a pronounced regional contrast: the southeastern AS is characterized by a shallower mixed layer and stronger stratification, favoring heat retention in the upper ocean, whereas the northwestern AS shows deeper mixing, reduced stratification, and greater subsurface warming. These contrasting oceanic conditions are reflected in the spatial evolution of cyclone-favourable environments, with increasingly favorable conditions extending across much of the AS during the pre-monsoon season but becoming concentrated mainly in the southeastern AS during the post-monsoon season. Consistent with these changes, TC genesis shifts equatorward and cyclolysis poleward during the pre-monsoon season, increasing meridional track extent, whereas the post-monsoon season exhibits a significant equatorward shift in lifetime maximum intensity and a decrease in meridional track extent. The results highlight the importance of subsurface ocean structure, in addition to surface warming, in shaping the seasonal and regional variability of TC characteristics over the Arabian Sea.

Keywords: Arabian Sea; Tropical cyclones; Ocean subsurface structure; Ocean heat content; Mixed-layer depth; Density stratification; Tropical cyclone environment

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1. Introduction

The upper ocean responds more rapidly to atmospheric forcing than the deeper ocean and therefore undergoes substantial temporal and spatial variability. Its thermal and density structure is primarily characterized by a relatively homogeneous mixed layer overlying a region of strong vertical temperature gradients associated with the thermocline. Variations in mixed-layer depth (MLD), thermocline depth, ocean heat content (OHC), and density stratification regulate the distribution and availability of thermal energy in the upper ocean. The depth of the mixed layer has decreased over parts of the tropical and subtropical northern Indian Ocean while increasing over the South Equatorial Ocean, highlighting substantial regional differences in upper-ocean evolution (Gao et al. 2023). The thermal budget of the upper 200 m is controlled primarily by lateral heat advection and vertical heat transport, together with surface fluxes, and these processes determine the spatial distribution of oceanic heat available to the atmosphere (Kumar and Mathew 1997). Changes in density stratification further regulate vertical mixing and the exchange of heat between the surface mixed layer and the subsurface ocean. Seasonal variations in stratification can therefore substantially modify thermocline depth and upper-ocean stability, with enhanced stratification during the summer months associated with changes in thermocline structure (Sallée et al. 2021). These coupled variations in upper-ocean structure are particularly important in regions such as the Arabian Sea, where strong seasonal atmospheric forcing produces pronounced changes in ocean temperature, mixing, and heat storage.

Large-scale climate variability can substantially modify the environmental conditions that regulate tropical cyclone (TC) genesis, intensification, and movement. Variations in sea surface temperature (SST), ocean heat content, atmospheric thermodynamic conditions, and large-scale circulation can alter both the location and intensity of favorable TC environments. For example, the spatial structure of Pacific SST anomalies can influence tropical cyclone migration through its effects on large-scale atmospheric circulation (Zhou et al. 2026). In the Indian Ocean, the Indian Ocean Dipole (IOD) is an important mode of climate variability that modulates TC activity by altering oceanic and atmospheric conditions across the basin. The positive phase of the IOD can suppress TC activity through changes in the coupled ocean–atmosphere environment, including anomalous SST distributions between the western and eastern equatorial Indian Ocean (Yuan and Cao 2013). Among the oceanic factors, OHC is particularly important because it represents the amount of subsurface thermal energy available to sustain air–sea heat exchange during cyclone

passage. Increasing OHC, together with favorable changes in atmospheric thermodynamic conditions such as air-equivalent potential temperature, relative humidity, and potential intensity, can increase the Genesis Potential Index (GPI) and support stronger TC activity. These processes demonstrate that changes below the sea surface, rather than SST alone, can influence the environmental conditions governing TC development and intensification.

The Arabian Sea (AS) generally experiences fewer tropical cyclones than the Bay of Bengal (BoB), where approximately four TCs develop each year compared with one or two over the AS (Evan and Camargo 2011). Nevertheless, the AS has experienced substantial changes in TC activity and intensity in recent decades, while the BoB has shown a decline in overall TC frequency but an increase in the frequency and duration of severe cyclonic storms (Balaji et al. 2018; Singh and Behera 2022). TC activity over the AS also exhibits pronounced seasonal variability. Cyclones developing during May and June are closely associated with the onset and evolution of the Indian summer monsoon, whereas November represents a particularly active month during the post-monsoon season (Evan and Camargo 2011). The mechanisms governing cyclone development also differ between seasons. Subsurface ocean warming provides an important source of thermal energy for cyclogenesis during the pre-monsoon period (March–June), whereas atmospheric thermodynamic instability and mid-tropospheric warming become increasingly important during the post-monsoon period (October–December), particularly over the eastern AS (Abhiram Nirmal et al. 2023). These seasonal differences suggest that the role of the upper and subsurface ocean in regulating TC activity may vary substantially across the AS and warrant a detailed examination of its evolving three-dimensional thermal structure.

Recent advances in satellite observations, direct measurements, reanalysis products, and numerical ocean and atmospheric modelling have substantially improved our ability to investigate changes in tropical cyclone activity and its environmental controls (Mohapatra et al. 2013). Increasing attention has focused on how TCs respond to natural climate variability and anthropogenic climate change, as changes in ocean temperature, subsurface heat content, and large-scale atmospheric circulation can modify the environments that govern cyclone genesis, intensification, and movement (Knutson et al. 2010). However, the spatial and seasonal evolution of subsurface ocean conditions and their relationship with changing TC characteristics over the Arabian Sea remain insufficiently understood. In particular, it is important to determine whether changes in MLD, thermocline structure, OHC, density stratification, and subsurface temperature

occur coherently across the basin or exhibit distinct regional patterns, and how such changes relate to the spatial distribution and evolution of cyclone-favourable conditions. Addressing this issue is essential for improving our understanding of regional TC variability and its implications for forecasting and climate-risk assessment in vulnerable coastal regions. Therefore, this study investigates changes in the upper and subsurface ocean structure over the Arabian Sea during 2004–2023 and examines their association with variations in TC environmental conditions and characteristics. Specifically, we evaluate seasonal changes in MLD, maximum thermocline depth, OHC200, density stratification, and subsurface temperature and relate these changes to variations in MPI, GPI, and TC genesis, lifetime maximum intensity, cyclolysis, and meridional track extent. By examining these relationships separately for the pre-monsoon and post-monsoon seasons, we identify the contrasting regional oceanic environments associated with the evolving characteristics of TCs over the Arabian Sea.

The remainder of the paper is organized as follows. Section 2 describes the data and methodology, including the HYCOM model configuration and its validation (Sect. 2.1) and the methods used to characterize changes in ocean subsurface conditions and tropical cyclone parameters (Sect. 2.2). Section 3 presents and discusses the seasonal and regional changes in upper-ocean and subsurface characteristics and their association with variations in tropical cyclone environments and characteristics. Section 4 summarizes the main findings and their implications for understanding the evolving tropical cyclone environment over the Arabian Sea.

2. Data and Methodology

To examine changes in ocean subsurface characteristics and their association with tropical cyclone activity, several subsurface parameters are analyzed. These include mixed layer depth (MLD), maximum thermocline depth (MTD), average temperature of the near-surface and subsurface layers, density stratification, and OHC of the upper 200m. To study changes in cyclone characteristics, maximum potential intensity (MPI) and genesis potential intensity (GPI) are analyzed, along with observed cyclone genesis migration, Lifetime Maximum Migration along with latitudinal extension of cyclone track. The data utilized in this study are the European Center for Medium-Range Weather Forecasts (ECMWF) fifth generation (ERA5) (Hersbach et al. 2020) with a spatial resolution of 0.25 degrees and a monthly temporal resolution. The cyclone migration data from the International Best Track Archive for Climate Stewardship (IBTrACS) (Knapp et al.

2010) are utilized. The Ocean Surface Current Analyses Real-time (OSCAR) (Dohan 2021) data is utilized for the validation of the simulated surface current.

The HYCOM (HYbrid Coordinate Ocean Model) v2.3.01 one-way nested to global configuration with horizontal resolution at 0.08° , simulated for 20 years of the study period, is utilized for the analysis of ocean characteristics.

2.1 Model Description and Validation

HYCOM is a hydrostatic ocean general circulation model that utilizes a hybrid vertical coordinate system, integrating isopycnic coordinates in the stable, stratified deep ocean, sigma coordinates in the shallow terrain-dominated areas, and z-coordinates in both the well-mixed layer and the extremely shallow coastal regions to address the challenges posed by very thin layers (Bleck 2002; Chassignet et al. 2003; Halliwell 2004). It relies on the fundamental equations wherein the layered continuity equation facilitates a seamless transition among various coordinates. The vertical mixing is modelled using the K-profile Parameterization (KPP) (Large et al. 1994), while the horizontal advection employs the Flux Corrected Transfer type 2 (FCT2) scheme derived from the work of Zalesak (1979), wherein Sea Surface Salinity (SSS) and Sea Surface Temperature (SST) are advected both horizontally and vertically. Density computed via the UNESCO equation of state (Brydon et al. 1999), compared with the reference density of the layer influenced by the movement of its upper and lower interfaces (Halliwell 2004). This regional model setup is incorporated within the globally structured model, specifically designed for the Arabian Sea (AS) region, extending from 4°N to 28°N and 40°E to 80°E , featuring 41 vertical layers, including seven levels within the upper 100m. The open boundary has been established at the equatorial region, the Oman Gulf, and the Gulf of Aden, with Newtonian relaxation implemented for up to 10 grid points; the remaining boundary corresponds to the continent, functioning as a closed boundary. The frictional base is taken into account for this analysis. The dataset employed for surface forcing, known as the Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010), possesses exceptionally high geographical and hourly temporal resolutions. The parameters employed in surface forcing include Sea Surface Temperature (SST), Sea Surface Salinity (SSS), U-wind, V-wind, radiation fluxes, mean sea level pressure (MSLP), and precipitation. At the open boundary, the monthly climatological data derived from the HYCOM global run experiment 53.X timeframe from 1995 to 2010 is employed. The monthly

climatological data of freshwater discharge from each river is utilized. The model is reinitialized utilizing the daily average data from the global run of the HYCOM experiment designated 53.X, which is interpolated to the regional grid.

The model's simulation is juxtaposed with gridded ARGO data available from 2005 to 2019, employing the Taylor diagram (Taylor 2001) (Fig. 1a,b), which incorporates the temporal correlation coefficient (TCC), central root means square difference, and normalized standard deviation. The discovery of the temporal relationship with the Argo data model involves initially interpolating to the Argo grid both horizontally and vertically, followed by computing the spatial average for the designated regions identified as northern AS (12°N-29°N, 40°E-80°E), western AS (4°N-12°N, 40°E-64°E), and eastern AS (4°N-12°N, 64°E-80°E) up to 250m, segmented into 11 vertical levels. The findings indicate a temporal correlation of temperature over 0.7 for the entire AS, together with a centered root-mean-square difference below 0.8. The spatial mean correlation of temperature for the Eastern AS surpasses that of the other two regions, exceeding 0.7, and exhibits a reduced standard deviation. In instances of TCC regarding salinity, values exceed 0.5 in the upper stratum up to 50m in smaller specified areas and throughout the entire AS. The TCC for salinity in the northern AS is weak as compared to other two smaller regions.

Fig. 1c,d represents the surface current of model and Fig. 1e,f represents the surface current of OSCAR data. The model simulated the surface current very close to the observation in both season pre-monsoon and post-monsoon. In pre-monsoon the model overestimate in the Somali coast but this is not more than 0.5 ms^{-1} . Other region estimation is comparable. In the post-monsoon it also overestimates offshore Somali coast. Overall, model picks the pattern of current reversal seasonally along the western coast of India.

2.2 Methodology

The cyclone activity in the North Indian Ocean (NIO) is bimodal (Wahiduzzaman et al. 2022). The April, May, and June (AMJ) constitute the first cyclone season, whereas October, November, and December (OND) represent the subsequent cyclone season. Two selections are typically designated as two distinct seasons, namely pre-monsoon and post-monsoon (Tiwari et al. 2022; Fahad et al. 2023).

The computation of mixed layer depth (MLD) primarily employs three methodologies: the first involves a density threshold (0.03 kg m^{-3}) (Dong et al. 2008), the second utilizes density variability equivalent to a temperature threshold, and the third applies a temperature threshold. The

threshold value for MLD based on temperature threshold is determined using values of 0.2 °C, 0.5 °C, 1 °C, and higher. The thermocline depth is determined by two prevalent techniques: one identifies it as the depth where the temperature reaches 20 °C (Sun et al, 2014), while the other specifies it as the depth of the steepest temperature gradient. In this research, we employed the MLD and MTD derived from the sigmoid function (Romero et al. 2023) adjusted to conservative temperature instead of potential temperature, as it mitigates the compressional temperature variations caused by pressure changes and more effectively equilibrates the influence of turbulence on the temperature profile, which is computed from in-situ temperature, absolute salinity, and density (Ioc 2010). This approach produces favorable outcomes in areas comprising three strata: the mixed layer, the thermocline, and the deep layer. This approach assesses the temperature distribution only to a depth that is double the point at which the Brunt-Väisälä frequency (N^2) reaches its peak, signifying ocean stratification. The mixed layer depth (MLD) is characterized as the depth at which the temperature diminishes by 0.2 °C from the near-surface point (10m). The MTD is defined as the depth at which the temperature rises by 0.2 °C from a deeper position.

The OHC to a depth of z is determined by the following expression-

$$OHC = \rho C_p \int_z^0 \theta dz \quad (1)$$

where θ is the conservative temperature, ρ is the density and C_p is the specific heat at constant pressure. The genesis potential index (GPI), which indicates the theoretically favorable condition for cyclogenesis, is calculated by the formula (Emanuel and Nolan 2004)-

$$I = (10^5 \eta)^{\frac{3}{2}} \left(\frac{RH}{50} \right)^3 \left(\frac{V_{pot}}{70} \right)^3 (1 + 0.1 V_{shear})^{-2} \quad (2)$$

where η is the absolute vorticity in s^{-1} , RH is the relative humidity at 700 hPa, V_{pot} is the potential intensity in $m s^{-1}$, and V_{shear} is the magnitude of wind shear between the pressure levels 850 and 200 hPa in $m s^{-1}$.

The potential intensity (PI) (Bister and Emanuel 1998), which is the measure of theoretically calculated square of the maximum speed, is used, which is expressed as –

$$(Vmax)^2 = \frac{(T_s - T_0) C_k}{T_0 C_D} (h^* - h_0) \quad (3)$$

where Vmax is the maximum velocity a system can achieve theoretically in a given environmental condition, T_s is the surface temperature, T_0 is the outflow temperature, C_k is the drag coefficient, C_k is the enthalpy exchange coefficient, h^* is the saturation enthalpy at the sea surface and h_0 is the enthalpy of the boundary layer air.

Latitudinal patterns in the attributes of tropical cyclones are assessed by least-squares linear regression. The trends' statistical significance is evaluated by the two-tailed Student's t-test.

3. Results and Discussion

The objective of this study is to examine the seasonal and regional changes in subsurface ocean conditions over the Arabian Sea (AS) and to assess their association with variations in tropical cyclone (TC) environmental conditions and characteristics. We first investigate changes in the upper-ocean structure, including mixed-layer depth (MLD), maximum thermocline depth (MTD), ocean heat content integrated to 200 m (OHC200), density stratification, and subsurface temperature. We then examine the corresponding spatial and seasonal variations in maximum potential intensity (MPI), genesis potential index (GPI), and observed TC characteristics. By considering these oceanic and atmospheric indicators together, we identify the contrasting environmental conditions that characterize the pre-monsoon and post-monsoon seasons and assess their consistency with the observed changes in TC characteristics over the AS.

3.1 Seasonal Changes in Oceanic Subsurface Conditions

Figure 2 shows the climatological distribution and long-term trends in mixed-layer depth (MLD) over the Arabian Sea during the pre-monsoon and post-monsoon seasons. The MLD was determined using a 0.2°C temperature criterion applied to conservative temperature, with the threshold depth estimated using a sigmoid-function fit. During the pre-monsoon season, the MLD exhibits relatively weak spatial variability across much of the basin, although comparatively deeper mixed layers occur over the southwestern Arabian Sea, where values exceed 22 m. In contrast, the post-monsoon season is characterized by substantially deeper mixed layers over the northern and eastern Arabian Sea, with MLD generally exceeding 22 m. The relatively shallow

mixed layer over the southeastern Arabian Sea during the pre-monsoon season is consistent with the rapid surface warming that occurs before the onset of the southwest monsoon. Surface warming strengthens the near-surface temperature gradient and increases upper-ocean stability, thereby limiting vertical mixing (Vinayachandran et al. 2007). For further analysis, we distinguish between Region A (14–25°N, 50–70°E) and Region B (4–14°N, 60–78°E), which represent the northern–northwestern and southern–eastern sectors of the basin, respectively. During the post-monsoon season, MLD is generally greater in Region A than in Region B, indicating a pronounced regional contrast in upper-ocean mixing.

The long-term trends in MLD further reveal a seasonal contrast in upper-ocean evolution (Fig. 2c,d). During the pre-monsoon season, MLD decreases over most of the Arabian Sea, with statistically significant reductions occurring over several parts of the basin. This widespread shoaling indicates a tendency toward enhanced upper-ocean stability and reduced vertical mixing during the study period. During the post-monsoon season, the trend pattern becomes more spatially heterogeneous. A statistically significant decrease at the 95% confidence level occurs over the central part of Region B, whereas Region A exhibits a mixture of weak positive and negative trends. The contrasting MLD trends suggest that the post-monsoon upper ocean has evolved differently between the two regions. In particular, the progressive shoaling of the mixed layer in Region B is consistent with increasing near-surface stability, whereas the relatively weak and spatially variable MLD trends in Region A indicate greater variability in vertical mixing. These differences provide an important basis for interpreting the corresponding changes in thermocline structure, stratification, and subsurface heat distribution discussed below.

The climatological distribution of maximum thermocline depth (MTD) also exhibits clear meridional and seasonal differences (Fig. 3). During both seasons, the thermocline is generally deeper between the equator and approximately 15°N and becomes shallower toward the northern Arabian Sea. During the post-monsoon season, particularly deep thermocline conditions occur over the northern Arabian Sea, where MTD exceeds 80 m. Regionally, MTD is generally greater in Region B than in Region A during the post-monsoon season. The combination of a deeper thermocline and relatively shallower mixed layer in Region B indicates stronger vertical separation between the surface mixed layer and the underlying thermocline, favoring the retention of thermal energy within the upper ocean. In contrast, the relatively shallower thermocline and deeper mixed layer in Region A indicate stronger coupling between the surface and subsurface ocean and greater

potential for vertical exchange. During the pre-monsoon season, MTD decreases significantly over much of the Arabian Sea, with particularly pronounced reductions over the central basin. The post-monsoon trends are comparatively weak and spatially heterogeneous, with modest positive and negative changes occurring across Regions A and B. Thus, the pre-monsoon season exhibits a more coherent basin-scale evolution of thermocline structure, whereas the post-monsoon season is characterized by stronger regional differences.

The spatial distribution of ocean heat content integrated to 200 m (OHC200) provides further insight into the seasonal evolution of subsurface thermal energy (Fig. 4). During the pre-monsoon season, OHC200 exhibits relatively limited spatial variability across the Arabian Sea, with values generally exceeding $1.88 \times 10^{10} \text{ J m}^{-2}$ over much of the basin. During the post-monsoon season, OHC200 is lower overall and displays stronger regional variability. Region B has lower OHC200 than Region A, while the southeastern Arabian Sea generally exhibits relatively low values during both seasons. The long-term trends show a widespread increase in OHC200 during the pre-monsoon season, with statistically significant positive trends over most of the basin. During the post-monsoon season, significant increases occur over a larger part of Region A, whereas Region B exhibits comparatively weak and spatially variable trends. The increase in OHC200 indicates that the upper 200 m has gained thermal energy during the study period, although its spatial distribution depends on the combined effects of surface heating, vertical mixing, thermocline structure, and subsurface temperature changes. The stronger post-monsoon increase in Region A is therefore consistent with its deeper mixed layer and greater subsurface warming, whereas the comparatively lower OHC200 in Region B reflects its distinct upper-ocean structure.

Changes in density stratification provide an additional measure of the evolving stability of the upper and subsurface ocean (Fig. 5). During the pre-monsoon season, density stratification increases over most of the Arabian Sea, with statistically significant positive trends over several regions. The widespread increase in stratification indicates a tendency toward greater resistance to vertical mixing and stronger isolation of the surface layer from the underlying ocean. This pattern is broadly consistent with the concurrent decrease in MLD during the same season. In contrast, the post-monsoon season exhibits a pronounced regional dipole in stratification. Region A contains areas of significant negative trends, particularly over its central portion, whereas Region B shows significant increases in stratification. The decrease in stratification over Region A is consistent with its deeper mixed layer and enhanced subsurface warming, which favor stronger vertical

coupling between the upper and deeper ocean. Conversely, the increasing stratification in Region B is consistent with the shallower mixed layer and greater vertical separation between the surface layer and thermocline. These contrasting trends indicate that the post-monsoon Arabian Sea has undergone substantial regional reorganization of its upper-ocean stability rather than a uniform basin-wide change.

The temperature trends between the surface and 400 m further clarify the physical basis of these changes in upper-ocean structure (Fig. 6). During both seasons, temperature increases occur broadly within the upper 100 m, indicating widespread surface and near-surface warming across the Arabian Sea. The relatively coherent warming in this layer suggests that differences in MLD, stratification, and OHC200 cannot be attributed solely to variations in near-surface temperature. Instead, the spatially contrasting temperature changes below 100 m appear to play an important role in reorganizing the vertical thermal structure. During the pre-monsoon season, warming extends through much of the 100–400 m layer, consistent with the concurrent increase in OHC200 and changes in thermocline structure. During the post-monsoon season, Region A exhibits substantially stronger subsurface warming than Region B, whereas temperature trends in Region B are generally weak and predominantly insignificant. The stronger warming below the mixed layer in Region A is consistent with reduced density stratification and a deeper mixed layer, indicating enhanced vertical coupling between the surface and subsurface ocean. In Region B, by contrast, weaker subsurface warming, increasing stratification, and a shallower mixed layer indicate greater upper-ocean stability and reduced vertical exchange. Taken together, the results show that the Arabian Sea has undergone a seasonally and regionally distinct reorganization of its three-dimensional thermal structure: the pre-monsoon season is characterized by widespread shoaling of the mixed layer, increasing stratification, and increasing OHC200, whereas the post-monsoon season exhibits a strong contrast between the more weakly stratified and strongly warming Region A and the more strongly stratified Region B.

3.2 Seasonal Changes in Tropical Cyclone Parameters

The changes in upper-ocean conditions described above are accompanied by distinct seasonal and regional variations in the thermodynamic environment for tropical cyclones. To examine these variations, we consider maximum potential intensity (MPI) and the Genesis Potential Index (GPI) during the pre-monsoon (April–June) and post-monsoon (October–

December) seasons over 2004–2023. MPI provides an estimate of the thermodynamic upper limit of TC intensity, whereas GPI integrates several environmental factors that influence TC genesis. Together, these parameters provide complementary measures of the evolving cyclone-favourable environment. The climatological and trend distributions of MPI and GPI (Figs. 7 and 8) are considered alongside the observed TC characteristics to determine whether the regional changes in the oceanic environment are consistent with changes in the spatial distribution and evolution of cyclones over the Arabian Sea.

The climatological distribution of MPI differs substantially between the two seasons (Fig. 7). During the pre-monsoon season, MPI exceeds 76 m s^{-1} over most of the Arabian Sea, indicating a broadly favorable thermodynamic environment for intense cyclones. The long-term trends show increasing MPI over the northern Arabian Sea, while decreasing trends occur over the southwestern and equatorial regions; however, these trends are not statistically significant. During the post-monsoon season, MPI is generally lower than during the pre-monsoon season and exhibits a pronounced regional contrast. MPI is higher in Region B than in Region A, while Region A shows weak negative trends and Region B exhibits modest positive trends. Although these trends are not statistically significant, their spatial organization is consistent with the contrasting oceanic environments identified in Section 3.1. In particular, the relatively favorable MPI conditions over Region B during the post-monsoon season occur alongside stronger stratification and a shallower mixed layer, whereas Region A is characterized by weaker MPI conditions and greater subsurface warming. These associations suggest that the thermodynamic cyclone environment reflects not only surface temperature but also the underlying structure and distribution of oceanic thermal energy.

The GPI distribution provides further evidence of seasonal and regional differences in the cyclone-favourable environment (Fig. 8). During the pre-monsoon season, GPI increases over the eastern Arabian Sea but decreases over parts of the equatorial, central, and northern basin. These trends are not statistically significant, indicating that the pre-monsoon changes in genesis-favourable conditions are spatially coherent but relatively weak in statistical significance. During the post-monsoon season, GPI is generally higher over the southeastern and southwestern Arabian Sea than during the pre-monsoon season and is higher in Region B than in Region A. Region A shows weak negative trends, whereas predominantly positive trends occur over Region B. Thus, the post-monsoon GPI field develops a clear regional contrast that broadly corresponds to the

contrasting oceanic conditions identified between the two regions. The concentration of increasingly favorable genesis conditions in Region B, together with its relatively shallow mixed layer and enhanced stratification, suggests that upper-ocean heat retention may contribute to maintaining a thermodynamically favorable environment for TC genesis. However, because GPI also depends on atmospheric conditions, these relationships should be interpreted as associations rather than direct causal links.

The observed TC characteristics provide an independent perspective on the seasonal changes in cyclone-favourable environmental conditions (Figs. 9 and 10). Although the number of TC events is relatively small in both seasons, the available IBTrACS record reveals distinct changes in the spatial evolution of cyclone tracks. During the pre-monsoon season, the latitude of genesis shifts equatorward, whereas cyclolysis shifts poleward, resulting in a statistically significant increase in meridional track extent. This expansion is consistent with the widespread pre-monsoon increase in OHC200, the decrease in MLD, and the broad increase in density stratification, together with the spatial evolution of MPI and GPI. During the post-monsoon season, both genesis and cyclolysis shift equatorward, although neither trend is statistically significant. In contrast, the latitude of lifetime maximum intensity (LMI) exhibits a significant equatorward shift at the 95% confidence level, while meridional track extent decreases. These changes are consistent with the pronounced post-monsoon contrast between Regions A and B, where cyclone-favourable conditions become increasingly concentrated toward Region B while conditions over Region A become comparatively less favorable. Overall, the results indicate that the seasonal evolution of TC characteristics is associated with a corresponding reorganization of the upper-ocean thermal structure and cyclone-favourable environment. The pre-monsoon season is characterized by a broader basin-scale evolution toward conditions favorable for more extensive TC tracks, whereas during the post-monsoon season, favorable conditions become more regionally concentrated, particularly over the southeastern Arabian Sea.

4. Summary and Conclusions

This study examined seasonal changes in the upper and subsurface ocean structure over the Arabian Sea during 2004–2023 and assessed their association with variations in tropical cyclone (TC) environmental conditions and characteristics. The analysis considered mixed-layer depth

(MLD), maximum thermocline depth (MTD), ocean heat content integrated to 200 m (OHC200), density stratification, and subsurface temperature, together with maximum potential intensity (MPI), Genesis Potential Index (GPI), and observed TC characteristics. The results reveal pronounced seasonal and regional differences in the evolution of the upper ocean and their correspondence with the changing cyclone environment. During the pre-monsoon season, the Arabian Sea exhibits relatively coherent basin-wide changes, characterized by a decrease in MLD, an increase in density stratification, widespread subsurface warming, and a significant increase in OHC200 over much of the basin. These changes indicate enhanced upper-ocean stability and increased storage of thermal energy within the upper 200 m. During the post-monsoon season, in contrast, the ocean develops a strong regional contrast between Region A (14–25°N, 50–70°E) and Region B (4–14°N, 60–78°E). Region A is characterized by deeper mixing, reduced stratification, and stronger subsurface warming, whereas Region B exhibits a shallower mixed layer, increasing stratification, and weaker subsurface warming. These contrasting changes demonstrate that the evolution of subsurface ocean conditions cannot be adequately described by surface warming alone.

The seasonal reorganization of the oceanic environment is accompanied by corresponding changes in cyclone-favourable conditions and observed TC characteristics. During the pre-monsoon season, MPI remains high over much of the Arabian Sea, while GPI increases over the eastern basin despite regional differences in its trends. The observed TC characteristics show an equatorward shift in genesis and a poleward shift in cyclolysis, producing a statistically significant increase in meridional track extent. These changes are broadly consistent with the widespread increase in OHC200, enhanced density stratification, and shoaling of the mixed layer. During the post-monsoon season, MPI and GPI exhibit a stronger regional contrast, with increasingly favorable genesis conditions concentrated mainly in Region B. The observed TCs show an equatorward shift in lifetime maximum intensity (LMI) at the 95% confidence level and a decrease in meridional track extent, while the trends in genesis and cyclolysis latitude are not statistically significant. The concentration of cyclone-favourable conditions toward Region B occurs alongside increasing stratification and a shallower mixed layer, whereas the comparatively less favorable conditions in Region A coincide with deeper mixing and stronger subsurface warming. Although these spatial relationships do not establish direct causality, their consistency indicates that changes

in subsurface ocean structure form an important component of the evolving TC environment over the Arabian Sea.

Overall, the results demonstrate that the seasonal and regional evolution of TC characteristics over the Arabian Sea is closely associated with changes in the three-dimensional structure of the upper ocean. The pre-monsoon season is characterized by a relatively coherent basin-scale evolution toward a more stable upper ocean with increasing subsurface heat content, whereas the post-monsoon season exhibits a pronounced spatial reorganization of oceanic and cyclone-favourable conditions. These findings emphasize the importance of considering subsurface thermal structure, MLD, thermocline structure, and density stratification in addition to SST when assessing changes in the TC environment. Incorporating these subsurface characteristics into seasonal TC monitoring and prediction frameworks may improve the representation of regional differences in cyclone-favourable conditions over the Arabian Sea and contribute to a better understanding of their implications under a changing climate.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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