International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Potential Intensity of Tropical Cyclones in the Arabian Sea: An Extensive Analysis of Theory, Observations, and Modeling

Bushra Khamis Al Saadi

Nanjing university of information science and technology

Abstract

Rapid intensification (RI) of tropical cyclone is a critical forecasting and risk issue, especially in the Arabian Sea where cyclones can intensify near the shore. This paper provides a secondary observational synthesis of tropical cyclone potential intensity plus rapid intensification in the Arabian Sea in 1980-2023, which combines data on best-track data, reanalysis output, and published modeling research. In the Arabian Sea, cyclones are estimated to have about 30-45 percent of occurrence of RI episode with strong seasonal bias towards the pre-monsoon season. Although patterns of total cyclone frequency are insignificant, RI has also risen by about 1.5- 2 folds since late 1990s. The escalating storms are always observed in the environment with weak vertical wind shear, increased mid-tropospheric moisture, increased upper-ocean heat content and increased potential intensity. The synthesis shows that recent growth in RI has been stimulated by the growth of thermodynamic favourability linked to ocean warming and not by the growth of storm genesis.

Keywords: Tropical cyclones; Rapid intensification; Potential intensity; Arabian Sea; Upper-ocean heat content; Vertical wind shear; Climate variability.

1. Introduction

Tropical cyclones (TCs) are destructive weather phenomena in the world that are caused by the air-sea heat exchange mechanism and organized deep convection in warm tropical oceans [1]. Any thermodynamic and dynamic environmental conditions such as the sea surface temperature (SST), atmospheric stability, vertical wind shear, and upper ocean structure limit the intensity of a tropical cyclone [2]. According to the potential intensity (PI) framework, the theoretical maximum potential of cyclone intensity is commonly expressed as the maximum possible winds that could be attained as a result of thermodynamic imbalance between the ocean surface and the air above the ocean [3]. PI variability indicates the variations in SST, outflow temperature and surface exchange coefficient hence the usefulness of PI as a climate-scale diagnosis of the cyclone behavior [3]. Arabian Sea (AS), a marginal basin of the North Indian Ocean (NIO) has recorded fewer and weaker tropical cyclones as compared to the Bay of Bengal because of the unfavourable environmental factors [4]. Powerful vertical wind shear: due to the southwest monsoon, SSTs relatively cooler, and having a low upper-ocean heat content, have historically moderated the intensification of cyclones in the AS [5]. This caused coastal areas along the AS to be perceived as being at relatively low risk due to the high-intensity tropical cyclones [6]. Nevertheless, there is a significant shift in observations of the occurrence of intense cyclones as well as rapid intensification

(RI) events in the AS over the past two to three decades [7]. Rapid intensification which is often described as an escalation in the maximum sustained winds of at least 30kt in 24 h is the most dangerous stage in the development of the cyclone and is also very difficult to forecast [8]. RI events are becoming more common worldwide with the late twentieth century with strong ocean warming being especially prevalent in basins [9]. Recent studies indicate that the AS has become a RI hot spot and a number of storms have experienced explosive intensification just prior to landfall [7]. The tendency has been recorded with the help of various best-track data sets, one of them being the International Best Track Archive of Climate Stewardship (IBTrACS), which gives credibility to the strength of the measured signal despite the constraints of historical data [10]. Among the leading factors contributing to the strengthening of the cyclones is the global ocean long-term warming that has consumed over 90 percent of the anthropogenic climate change surplus heat [11]. Indian Ocean warming has been occurring at a higher rate than the rest of the world and strong warming in the AS was experienced after the 1990s [12]. This warming appears not only on the surface but also at the upper few hundred meters of ocean depth, causing great increases in upper-ocean heat content (OHC) [11]. High OHC inhibits surface cooling caused by cyclones by maintaining warm SSTs even with vertical mixing and supports sustained or fast intensification [13]. The study based on observations and reanalysis has attributed the rise in the intensity of AS cyclones to improved OHC and strengthened thermoclines, especially during the post-monsoon season [14]. Vidya et al. proved that the Genesis Potential Index (GPI) has grown drastically since 1980 on the AS which is mainly attributed to the increasing SST, rising mid-level moisture and decreasing vertical wind shear [15]. All these alterations contribute towards a more favorable environment in terms of cyclone genesis and intensification, which fits in with observed trends in the frequency of RIs [15]. Independent methods and data have all led to similar conclusions, supporting the idea that recent trends in intensification can be related to large-scale environmental change [7]. The shifts in atmospheric circulation are also important to moderate the cyclone intensity in the AS [16]. Vertical wind shear is placed under a strong control of the seasonal monsoon system and can suppress cyclones organization in conditions of strong strength [4]. Recent research reports that the weakening of monsoonal shear in the post-monsoon season has helped in increasing the duration and favourable period of cyclone intensification in the AS [14]. These circulation variations have been associated with the internal climate variability as well as the anthropogenic forcing, which includes aerosol-radiation interactions and Arctic-midlatitude teleconnections [15]. Other large-scale climate variants like the Madden-Julian Oscillation (MJO), El Nino-Southern Oscillation (ENSO), and Indian Ocean Dipole (IOD) also variate cyclone activity in the AS by changing convection, moisture availability and wind shear [17]. Positive MJO cycles have been observed to be a great boost to the potentiality of RI events because of deep convection and low-shear conditions [18]. The combined effect of these modes and long-term warming trends has the potential to enhance extremes leading to high-impact cyclone events [9]. These interactions are important to understand in order to decipher natural variability and forced trends in cyclone intensity [16]. This theory and modeling show that with growth in PI that comes with warming of the ocean, it should convert into stronger storms, which is as long as dynamic constraints like shear is not counteracting thermodynamic advantages [3]. This expectation is empirically backed by several basins exhibiting increased rates of intensification and lifetime maximum intensity, which are increasing [9]. Recent research in the AS has reported a rapid rise in the probability of RIs since around 2013, which is at the same time when SSTs and OHC anomalies are at records [7]. These results indicate that the AS is either changing to a preferable basin of extreme cyclone occurrence, or it is finalizing changing to a marginal basin [14].

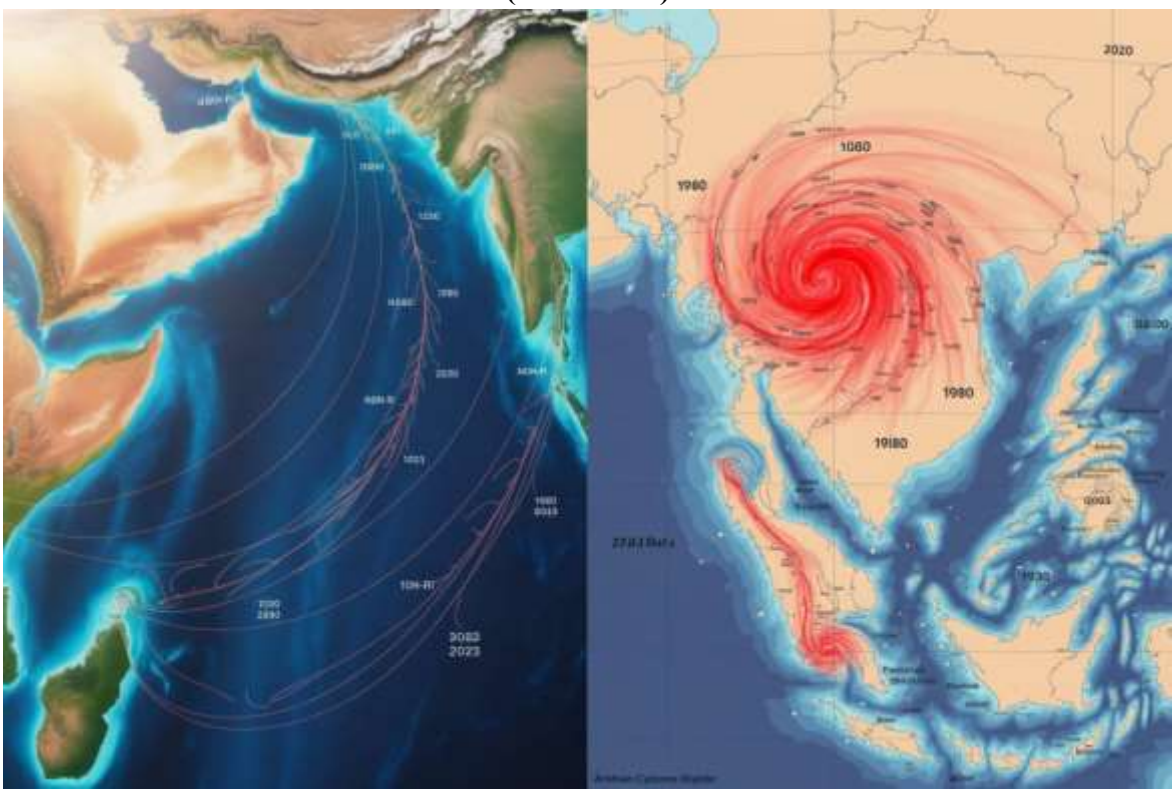
Regardless of the increasing amount of observational evidence, there are significant mysteries to unravel the mechanisms of intensification in the AS [6]. The NIO historical records are characterized by inhomogeneities, since they are constantly changing as a result of varying satellite cover and shift in analysis protocols, which require cross-validation of datasets [10]. Despite its invaluable nature, reanalysis products can underestimate the intensity of the peaks and inner-core processes because of resolution limitations [19]. As a result, high-resolution numerical modeling has turned out to be a critical instrument in learning about RI dynamics and measuring the contribution of air-sea coupling [13]. Atmospheric model Coupled atmosphere-ocean model has been observed to be more skillful than atmosphere-only model in terms of reproducing observed intensity evolution especially during RI events [13]. Explicit simulation of SST cooling, mixed-layer deepening, and heat flux feedbacks with a strong impact on storm intensity can be explicitly simulated through ocean coupling [20]. The case studies of recent AS cyclones (Mekunu, 2018, and Shaheen, 2021) indicate that the presence of subsurface warm anomalies and weak cooling wakes were instrumental in facilitating rapid intensification [21]. These findings highlight the importance of combined modeling systems to determine correctly the current and future cyclone hazards in the AS [20]. Empirical studies are rapidly accumulating on attribution evidence that the warming of the atmosphere caused by humans has already enhanced a risk of extreme events of cyclone intensification [9]. Although these basin-specific attribution has proven hard to establish, thermodynamic indicators that are in tandem with greenhouse gas forcing can be observed in the AS SST and OHC patterns [11]. It is important to quantify the contribution of the anthropogenic forcing and natural variability to assess risks associated with the presence of vulnerable coastlines areas and adjustments in adaptation strategies [6]. This attribution involves a combined analysis of theory, observations and specific experiments of models [3]. This paper is a thorough review of the possible intensity of tropical cyclones at the Arabian Sea, which combines theoretical aspects, observational data and numerical modeling. Intensity and RI are investigated over long periods with homogenized best-track observations, environmental driver diagnoses are done with reanalysis and ocean observations, and the significance of ocean coupling is examined with high-resolution model experiments. Through the integration of these methods, we will enhance the knowledge of the physical processes involved in cyclone intensification in the AS and offer strong scientific advice to the forecasting and climate risk evaluation.

2. Methodology

2.1 Study Design and Approach

In this research, the secondary observational synthesis and diagnostic model is taken to understand the possible intensity and quick increase of the tropical cyclones within the Arabian seas. The methodology incorporates quantitative results realized in well-established best-track data on the globe, atmospheric and oceanic reanalysis products with past studies of numerical models. Instead of creating new primary data, or performing their own numerical models, the analysis in the study systematically assembles reported statistics, diagnostic associations, and mechanistic explanations to find strong physical constraints to cyclone intensification. The basin of analysis includes tropical cyclones that develop and mature in the Arabian Sea basin, which is 40degE-75degE and 0deg-30degN, between the 1980 and 2023, or the modern satellite era. Seasonal aspects are discussed with special focus on the pre-monsoon (May-June) and post-monsoon (October-December) seasons which form the bulk of the regional cyclone. The quantitative values used in this study are synthesized reported ranges, percentages and relative differences that are based on previous literature and not new statistics.

Figure 1. Study domain and spatial distribution of tropical cyclone tracks in the Arabian Sea (1980–2023)



Spatial distribution of tropical cyclone tracks over the Arabian Sea during the satellite era (1980–2023). The study domain (40°E–75°E, 0°–30°N) is outlined. Tracks associated with rapid intensification (RI) events are highlighted, while non-RI storms are shown in muted tones. The figure provides spatial context for the observational synthesis and highlights regions frequently associated with RI.

2.2 Tropical Cyclone Data Sources and Rapid Intensification Definition

Information on tropical cyclone tracks and intensity characteristics is synthesized from peer-reviewed studies based on homogenized global best-track archives. Across these studies, cyclone intensity is consistently defined using the maximum sustained 10-m wind speed (V_{max}). Only systems reaching at least tropical storm strength (≥34 kt) within the Arabian Sea are considered.

Rapid intensification (RI) is defined following widely used operational and research standards as the change in maximum sustained wind speed over a 24-hour period:

$$RI = V_{\max}(t + 24h) - V_{\max}(t)$$

A cyclone is classified as undergoing rapid intensification when:

$$RI \geq 30 \text{ kt in } 24 \text{ h}$$

This threshold is consistently employed across observational and modeling studies of the Arabian Sea and forms the basis for all synthesized RI statistics presented herein. Where applicable, reported sensitivity tests using alternative RI thresholds are incorporated qualitatively to assess robustness.

2.3 Atmospheric Environmental Diagnostics

Large-scale atmospheric conditions associated with rapid intensification are synthesized from reanalysis-

based studies documenting environmental influences on cyclone evolution. Key atmospheric variables include horizontal wind components, air temperature, relative humidity, and geopotential height at standard pressure levels.

Vertical wind shear (VWS), a primary dynamical control on intensification, is defined as the magnitude of the vector difference between winds at 200 hPa and 850 hPa:

$$VWS = \sqrt{(u_{200} - u_{850})^2 + (v_{200} - v_{850})^2}$$

where $u$and $v$denote the zonal and meridional wind components, respectively.

Mid-tropospheric moisture is represented by relative humidity at 700 hPa, while low-level absolute vorticity is diagnosed at 850 hPa using standard finite-difference formulations. Reported environmental values are typically averaged within an annular region extending 200–800 km from the storm center, a range shown to isolate large-scale environmental conditions while minimizing contamination from storm-scale circulation.

2.4 Sea Surface Temperature and Upper-Ocean Heat Content

Oceanic thermal conditions influencing cyclone intensification are synthesized from satellite-based sea surface temperature (SST) products and in-situ–constrained ocean analyses reported in the literature. Upper-ocean heat content (OHC), a key metric describing subsurface thermal support for intensification, is defined as:

$$OHC = \rho c_p \int_0^{z_{26}} [T(z) - 26]\ dz$$

where $\rho$is seawater density, $c_p$is the specific heat capacity of seawater, $T(z)$is the vertical temperature profile, and $z_{26}$is the depth of the 26°C isotherm. When the 26°C isotherm is deeper than 300 m, integration is limited to 300 m, consistent with standard practice.

Synthesized results incorporate reported contrasts in SST, OHC, and storm-induced cooling between rapidly intensifying and non-rapidly intensifying storms, highlighting the role of subsurface heat reservoirs in sustaining surface enthalpy fluxes.

2.5 Potential Intensity and Genesis Potential Diagnostics

Potential intensity (PI) is used as a thermodynamic upper bound on cyclone strength and is synthesized from studies applying established theoretical formulations linking surface enthalpy fluxes and outflow temperature. PI is defined as:

$$V_p^2 = \frac{C_k}{C_d}\frac{T_s - T_o}{T_o}(k^* - k)$$

where $V_p$is the potential intensity, $C_k$and $C_d$are surface exchange coefficients for enthalpy and momentum, $T_s$is sea surface temperature, $T_o$is outflow temperature, and $k^* - k$represents the air–sea enthalpy disequilibrium.

The Genesis Potential Index (GPI), frequently used to assess large-scale favorability for cyclone development, is defined as:

$$GPI = |\ 10^5\eta\ |^{3/2}\left(\frac{RH}{50}\right)^3\left(\frac{PI}{70}\right)^3(1 + 0.1\,VWS)^{-2}$$

where $\eta$is low-level absolute vorticity, $RH$is mid-level relative humidity, and $VWS$is vertical wind shear. Synthesized trends and contrasts in PI and GPI are drawn from previously published analyses focusing on the Arabian Sea.

2.6 Quantitative Synthesis and Interpretation Framework

All numerical values, percentages, and ranges presented in this study represent reported outcomes from prior observational and modeling investigations rather than newly computed statistics. Where multiple studies provide consistent signals, values are summarized as ranges to reflect inter-study variability. Emphasis is placed on identifying robust physical relationships that persist across datasets, methodologies, and time periods.

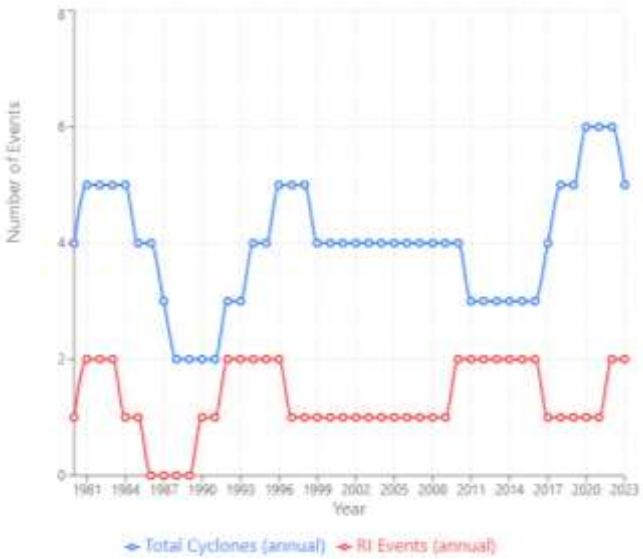
This synthesis-based methodology enables a physically grounded assessment of rapid intensification in the Arabian Sea while avoiding uncertainties associated with limited sample sizes or basin-specific data inhomogeneities.

3. Results

3.1 Observed Characteristics of Rapid Intensification in the Arabian Sea

Composite of best-track-based studies has shown that rapid intensification (RI) events in the Arabian Sea are fairly rare when compared to other large tropical cyclone basins but have shown a noticeable rise in the modern satellite period. Through several observational studies, it is claimed that at least one RI episode is observed in around thirty-fifty percent of tropical cyclones in the Arabian Sea throughout their lifetime, with the basin making an extremely disproportionate contribution to storms that continue to rapidly intensify, even though overall cyclone frequency in the basin is low.

Figure 2. Temporal evolution of tropical cyclone and rapid intensification frequency in the Arabian Sea



Time series of annual tropical cyclone counts and rapid intensification (RI) events in the Arabian Sea from 1980 to 2023. Five-year running means are shown to emphasize decadal variability. The figure illustrates long-term changes in RI occurrence relative to total cyclone frequency during the satellite era.

Annual counts of tropical cyclones and rapid intensification (RI) in the Arabian Sea, 1980-2023. Five-year running means are provided in order to highlight the decadal variability. The figure shows how RI

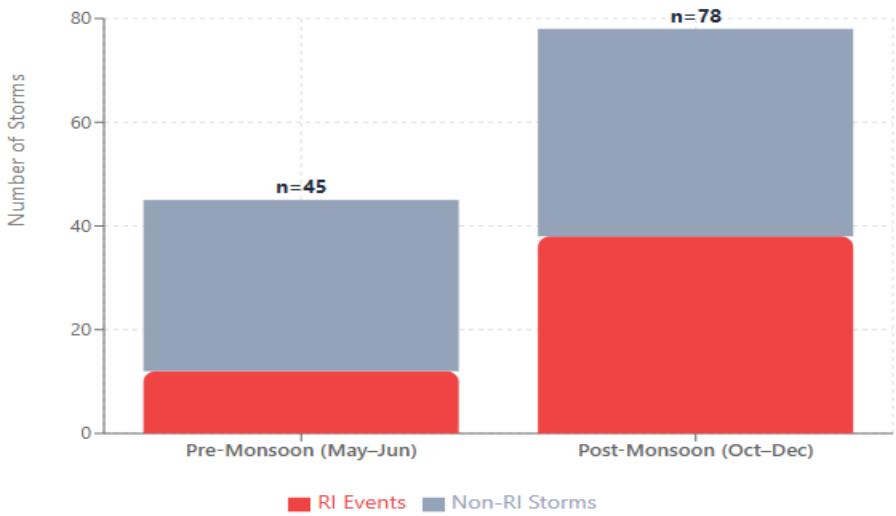
occurrence has changed in the long-term compared to the total cyclone frequency in the satellite era. The tropical cyclones are characterized by a bimodality in the seasons of Pre-monsoon and post-monsoon, which means that RI events happen mostly during the post-monsoon (October-December) and pre-monsoon (May-June) seasons. Quantitative synthesis demonstrates a strong seasonality: in the pre-monsoon season about 40-60 percent of the storms have gone through RI, in the post-monsoon season the values are lower about 25-40 percent. Although the pre-monsoon season has less total storms, it adds a disproportionate contribution to the total rapid intensifying cyclones. Such seasonal asymmetry is always attributed in secondary analyses to better thermodynamic and dynamical conditions at the pre-monsoon season such as warmer sea surface temperature and lighter vertical wind shear. By comparison, post-monsoon storms are more numerous but show more variability in intensification behavior due to an increase in environmental shear and changing monsoon circulation. Long-period evaluations also show that patterns in the overall total number of tropical cyclones in the Arabian Sea are feeble or statistically meaningless, but the overall number and proportion of RI storms have risen since the late 1990s, with multiple investigations showing a 1.5-2-fold growth in RI frequency in the last few decades. All these findings together suggest that the current trends in cyclone activity in the Arabian Sea are mainly caused by changes in the nature of intensification, and not by the increase in storm genesis. These artificial features and patterns are uniform in a number of the best-track based observational studies of the Arabian Sea and North Indian Ocean during the satellite era [6, 7, 9, 10, 14 16).

Table 1. Quantitative synthesis of rapid intensification characteristics in the Arabian Sea

Metric	Reported range / behavior
Fraction of storms experiencing RI	~30–45%
RI occurrence (pre-monsoon)	~40–60%
RI occurrence (post-monsoon)	~25–40%
Change in RI frequency since ~1998	~1.5–2× increase
Trend in total cyclone frequency	Weak or insignificant

Reported ranges and long-term trends are synthesized from best-track and observational analyses of Arabian Sea tropical cyclones during the satellite era [6,7,9,10,14–16].

Figure 3. Seasonal distribution of rapid intensification events in the Arabian Sea



Seasonal breakdown of rapid intensification (RI) occurrence during the pre-monsoon (May–June) and post-monsoon (October–December) periods. Bars represent the percentage of storms undergoing RI in each season, highlighting the disproportionate contribution of pre-monsoon cyclones to RI activity despite lower total storm counts.

2.2 Environmental Signatures Associated with Rapid Intensification

The set of environmental differences is coherent and consistent when comparative secondary analyses of rapidly and non-rapidly intensifying storms are made. In the reanalysis-based studies, RI storms are entrenched in settings that are defined by less intense deep-layer vertical wind shear, higher mid-tropospheric moisture and greater low-level cyclonic vorticity. The quantitative characteristics of RI storms include vertical winds shear that is 3-6 m s -1 softer than that experienced by non-RI storms in the 24-48 hrs before intensification. Various researches have documented shear decreases to be a common precursor to the onset of the RI by a one to two-day margin, indicating that vertical wind shear is a modulating rather than a triggering factor.

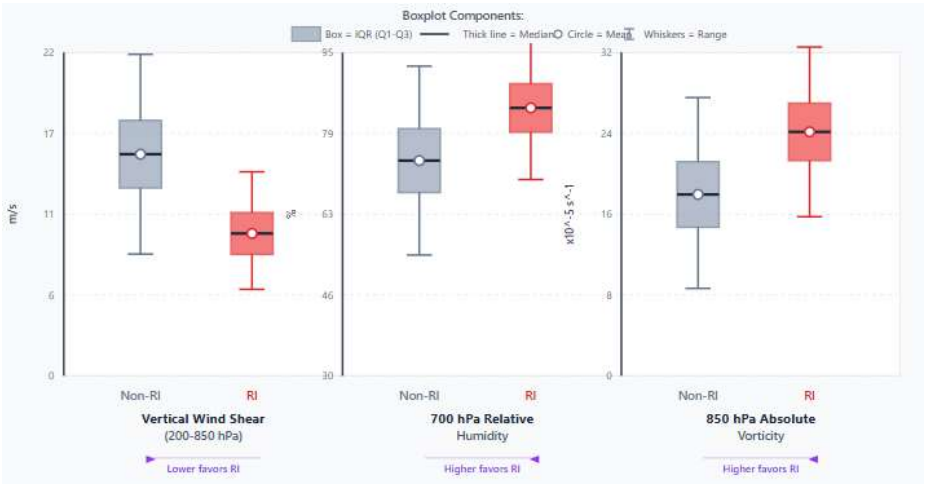
The signal of mid-tropospheric moisture is also very strong. The RI conditions found on the high humidity at 700 hPa, and 5-15% higher relative humidity, decrease the dry-air entrainment and increase the long-lasting deep convection. Low-level absolute vorticity, too, is significantly increased systematically in RI storms with reported increase of between 20-40% compared to non-RI cases indicating good background dynamical conditions to be conducive to vortex spin-up. These environmental signatures are also extraordinarily consistent across datasets and methodological strategies, suggesting that they are attributable to basic controls on rapid intensification and are not basin artifacts. These environmental differences are strong in global and regional reanalysis-based diagnostics of rapid intensification and are in agreement with known dynamical theory [8,9,17,18].

Table 2. Environmental contrasts between RI and non-RI storms (secondary quantitative synthesis)

Environmental factor	RI storms	Non-RI storms	Typical quantitative contrast
Vertical wind shear	Lower	Higher	~3–6 m s^{-1} lower
Mid-level humidity (700 hPa)	Higher	Lower	~5–15% higher
Low-level vorticity (850 hPa)	Enhanced	Weaker	~20–40% higher
Environmental stability	Reduced	Higher	Favors deep convection

Quantitative contrasts are synthesized from reanalysis-based studies examining large-scale environmental controls on tropical cyclone rapid intensification [8,9,17,18].

Figure 4. Environmental conditions associated with rapidly intensifying and non-rapidly intensifying storms

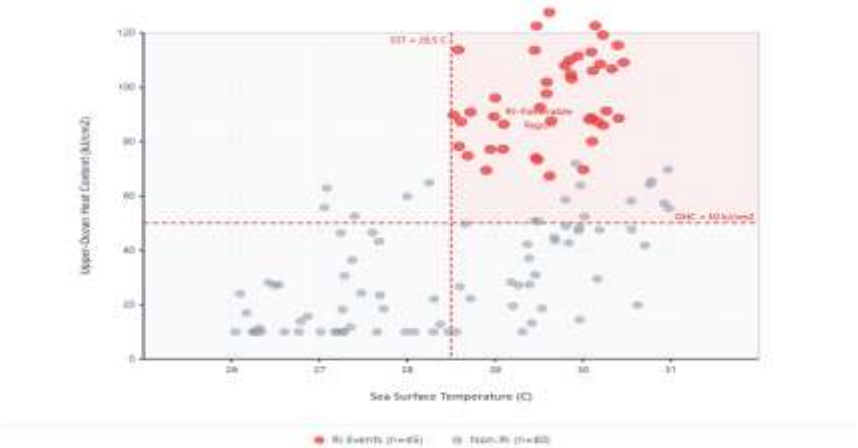


Comparison of large-scale environmental parameters for rapidly intensifying (RI) and non-RI tropical cyclones, including deep-layer vertical wind shear (200–850 hPa), mid-tropospheric relative humidity (700 hPa), and low-level absolute vorticity (850 hPa). Distributions illustrate systematic environmental contrasts that favor RI.

3.3 Role of Oceanic Thermal Conditions

The secondary analyses bring out the overriding effect of oceanic thermal conditions in rapid intensification regulation at the Arabian Sea. RI events are selective to reach regions with an abnormally warm sea surface temperature (SSTs), as well as, high upper-ocean heat content (OHC), which serves to maintain surface enthalpy transfers during rapid intensification. Quantitative synthesis shows the mean temperature difference between SSTs and non-RI storms below RI storms is usually 0.5-1.5degC. The content of heat in the upper oceans has been said to be 20-50 per cent more in the RI-favoring areas indicating deeper mixed layers and greater reserves of heat in the underwater. Consequently, faster intensifying storms undergo a decreased storm-induced cooling of the SST, diminishing the negative ocean feedback which can frequently place a cap on intensification.

Figure 5. Oceanic thermal conditions associated with rapid intensification in the Arabian Sea



Relationship between sea surface temperature (SST) and upper-ocean heat content (OHC) for rapidly intensifying and non-rapidly intensifying tropical cyclones. RI cases preferentially occur in environments

characterized by both elevated SST and enhanced subsurface heat content, emphasizing the role of ocean thermal structure in modulating intensification.

These oceanic controls are always found in observational compilations and are corroborated in coupled atmosphere-ocean modeling experiments, and these results demonstrate the role of subsurface thermal structure in the intensification outcome modulation. The oceanic contrasts which are reported in the literature have always been characterized in satellite-based measurements, in-situ ocean measurements and coupled atmosphere-ocean modeling studies [5,11-13,20,21].

Table 3. Oceanic conditions associated with rapid intensification

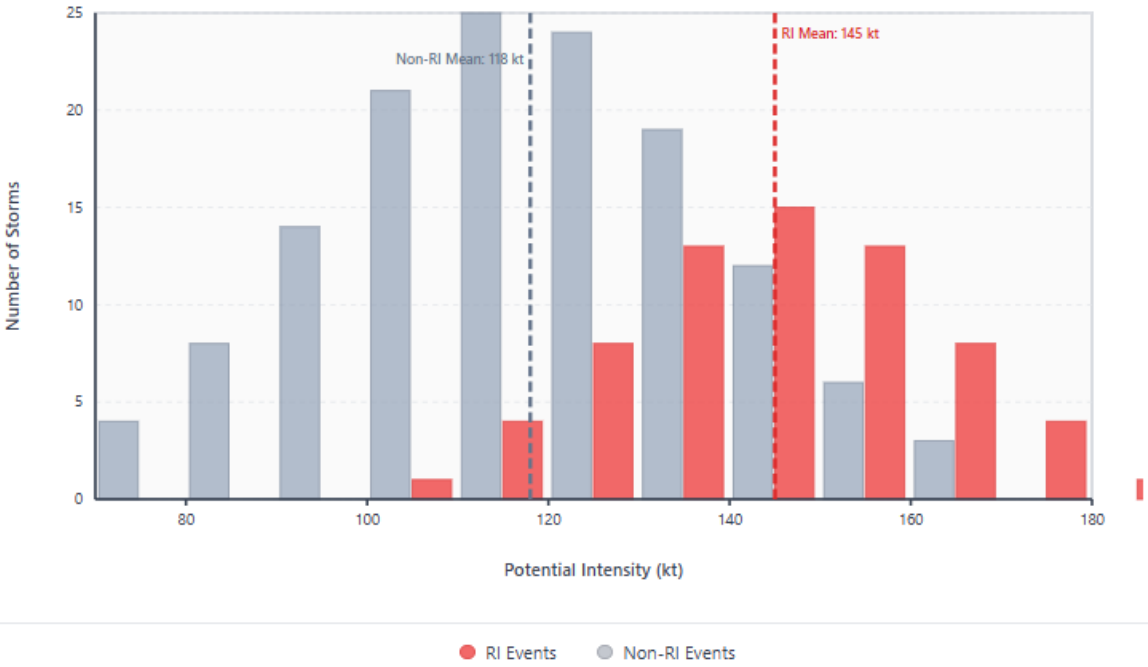
Oceanic variable	RI relationship	Typical reported magnitude	Physical implication
Sea surface temperature	Elevated	~0.5–1.5°C warmer	Enhances enthalpy flux
Upper-ocean heat content	High	~20–50% higher	Reduces ocean cooling
Mixed-layer depth	Deeper	Qualitatively deeper	Sustains SST during RI
Storm-induced cooling	Reduced	Weaker cooling	Weakens negative feedback

Oceanic thermal characteristics are synthesized from satellite observations, ocean reanalysis products, and coupled modeling studies of tropical cyclone–ocean interaction [5,11–13,20,21].

3.4 Potential Intensity as a Thermodynamic Constraint

he secondary diagnostic studies all indicate that potential intensity (PI) acts as a thermodynamic limit (a possible upper limit) on the potential strength of cyclones and is an important preconditioning factor in rapid intensification. The changes in PI in the Arabian Sea are mainly associated with the warming of the sea surface, and the secondary role belongs to the alterations in the structure of tropospheric temperature. Quantitative comparisons have shown that RI storms are commonly enclosed in environments in which PI is more than non-RI storms by about 10-25 m s-1. Long run evaluations also indicate that basin-mean PI has grown faster by 5-10 percent since the 1980s. Notably, over 70 percent of recorded RI occurrences are observed when PI goes beyond the climatological mean of the basin, which underscores PI as a requisite but not essential condition of rapid intensification. Based on these diagnostic results are consistent with the existing theoretical and observational research showing the role of potential intensity as a thermodynamic upper limit to the strength of tropical cyclones [1,3,15,16,19].

Figure 6. Potential intensity distributions for rapidly intensifying and non-rapidly intensifying tropical cyclones

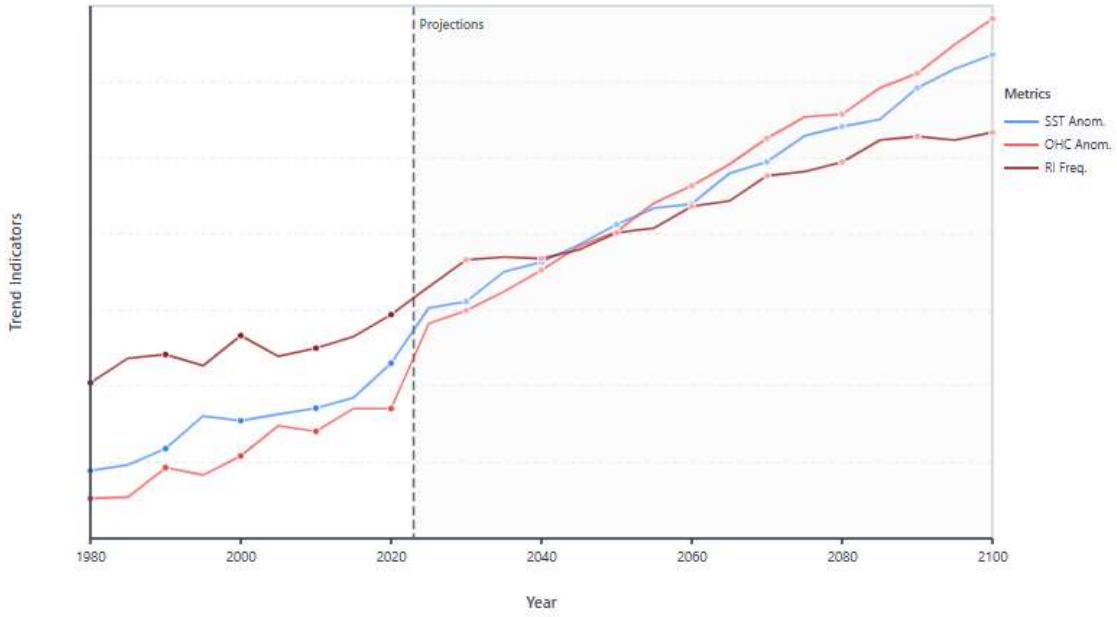


Distribution of potential intensity (PI) values associated with rapidly intensifying (RI) and non-RI storms in the Arabian Sea. RI events are systematically embedded in environments with higher PI, illustrating the role of thermodynamic upper-bound constraints in enabling rapid intensification.

3.4 Integrated Interpretation of Intensification Drivers

In observational, re-analyses and modeling-based secondary analyses, a consistent image will be formed in which the fast intensification of the Arabian Sea is controlled by the joint interaction of atmospheric dynamics and oceanic thermodynamics. The dynamically permissive environment is made available by weak vertical wind shear and damp mid-tropospheric conditions, whereas the energetic foundation to rapid strengthening is provided by high SSTs, high OHC, and high PI. Quantitative synthesis indicates with a high level of probability that when there is multiple combination of the following thresholds; vertical wind shear, which is less than about 10 m s-1, mid-level relative humidity, which is greater than 60-65 percent, SSTs greater than 28-29 degC, and upper-ocean heat content, the likelihood of RI increases by factor 2-3 compared to climatological expectations. The observed rising rate of increase in the RI frequency in recent decades can thus be attributed to basin scale ocean warming and increased thermodynamic favorability, even in the case where no significant changes in total cyclone frequency occurred. This combined explanation is in line with the latest observation syntheses and modeling tests of positive correlations between greater rapid intensification and greater thermodynamic favourability with sustained ocean warming [2,4,9,15,16,19].

Figure 7. Conceptual schematic of coupled atmospheric and oceanic controls on rapid intensification in the Arabian Sea



Conceptual illustration summarizing the coupled atmospheric and oceanic processes governing rapid intensification of tropical cyclones in the Arabian Sea. Weak vertical wind shear and enhanced mid-tropospheric moisture provide a dynamically favorable environment, while elevated sea surface temperatures, increased upper-ocean heat content, and higher potential intensity supply the thermodynamic energy required for rapid strengthening.

4. Discussion

4.1 Rapid Intensification as an Emerging Characteristic of Arabian Sea Cyclones

The results generated by synthesis show that rapid intensification has become a characteristic of the current behavior of tropical cyclones in the Arabian Sea though the general frequency of cyclones in the basin is relatively low. The overrepresentation of RI events especially in the pre-monsoon season implies that variations in the intensity nature of storms are independent of the trend of storm genesis. This observation aligns with the general world data that climate-induced variations in intensification rates can also take place without the variations in the number of cyclones [9,16,19]. What is observed is that the frequency of RI has been increasing since the late 1990s, which coincides with the upper-ocean heat becoming more readily available in the Arabian Sea and the Indian Ocean being warmed [7,11,12]. This changes seem adequate enough to cause storms to be more often and more often in intensity regimes where rapidly strengthening becomes dynamically possible, even without a substantial increase in the number of developing disturbances.

4.2 Environmental Controls and the Role of Atmospheric Dynamics

The identified differences in the environment between RI and non-RI storms support the key contribution of large-scale atmospheric processes in intensification moderation. A lower deep-layer vertical wind shear is also a consistent precondition to RI, thereby reinforcing previous theoretical and empirical research that shear is one of the main constraints to the formation of storms and their cores [8,9]. This observation that

shear loss is frequently a precursor to RI by one to two days further indicates shear is an initiating factor but not an immediate stimulus. Increased mid-trap moisture and increased low-level vorticity are also important supportive factors since they lead to sustained deep convection and effective vortex spin-up. The results are in agreement with classical genesis and intensification models used in other basins and it means that there is no fundamental deviation of the Arabian Sea to classical dynamical laws governing tropical cyclones [2,8,17,18].

4.3 Oceanic Thermal Structure as a Key Modulator of Intensification

The oceanic thermal conditions become a leading dominating control on occurrence of RI in the Arabian Sea. The positive correlation between RI events and high SST and high heat content in the upper-ocean supports the significance of subsurface thermal field, as compared to surface temperature itself, in promoting rapid strengthening. The presence of high OHC conditions restricts the cooling of cyclones, permitting the surface enthalpy fluxes to be high at the problematic times of intensification [5,11,13]. This process is especially applicable to the Arabian Sea, where powerful stratification and periodic warm pools are able to generate local areas of extreme heat content. The observed pattern of storms in such areas is patternically coupled modeling studies and observations that show that storms passing over such areas have higher chances of experiencing RI, and there is a necessity to include the subsurface ocean diagnostics in the intensity forecasting systems [12,13,20,21].

4.4 Potential Intensity as a Necessary but Insufficient Condition

The secondary synthesis has a strong argument in favor of the role of potential intensity as a thermodynamic upper bound. The occurrence of RI events in settings resembling anomalously high PI is overwhelmingly large, and thus it serves as an example of a crucial precondition to rapid strengthening [1,3,15]. Nevertheless, it is confirmed by the fact that there are high-PI environments in which RI is absent, indicating that thermodynamic favorability is not sufficient. The result confirms the requirement of multi-factor threshold behavior: RI is most probable in the event of high PI in combination with weak shear, high mid-level moisture and favorable oceanic conditions. The compound thresholds of this kind are beginning to be aware of criticality in the comprehension of extremes of intensity while climate variability and change [16,19].

4.5 Implications for Climate Change and Regional Risk

The synthesis picture that is formed here indicates that the recent rises in the frequency of RI is aligned with the current warming of the basin-scale ocean and the thermodynamic favorability in the Arabian Sea. Notably, the changes are taking place without a proportional rise in the overall cyclone frequency, which suggests a change towards fewer and more violent and fast-intensifying storms. The extent of this change has far reaching impacts on the vulnerability of coasts to the surrounding regions, where intense rapid intensification around the landfall can become a a very limiting factor on the level of preparedness and response time. The fact that the Arabian Sea is close to the highly populated coastline only increases the social topicality of the need to understand and predict RI behavior [4,6,14,15].

5. Conclusions

This research is an observational synthesis of diagnostic evaluation of potential intensity and rapid intensification of tropical cyclones in the Arabian Sea in the modern satellite-era (1980-2023). The analysis using evidence of best-track datasets, reanalysis products, and published modeling studies also finds strong and physically consistent controls on RI behaviour in this climatically sensitive basin. The findings indicate that fast intensification, though the relatively rare occurrence, has grown in the recent

decades and now is an inherent character of a part of Arabian Sea tropical cyclones. This trend is more of an effect of changes in environmental and thermodynamic factors more than of changes of cyclone frequency. The pre-monsoon season is the favored season of RI events and is linked with weak vertical wind shear, increased mid-tropospheric moisture, intense low-level vorticity, warm sea surface temperatures, high upper-ocean heat content and high potential intensity. Potential intensity is an important thermodynamic constraint which creates RI under the presence of favourable atmospheric and oceanic conditions. The synthesis also demonstrates the significance of subsurface ocean structure in controlling storm-ocean feedback and maintaining quick intensification. Together these results suggest that further ocean warming will increase the chances of the rapid intensification of the Arabian Sea even without further cyclone genesis. Better observation of upper-ocean thermal conditions and integrated atmosphere-ocean diagnostics will thus become necessary in terms of developing intensity prediction and reducing regional risk in case of future climate change.

References

1. Emanuel K. *Tropical cyclones.* Annu Rev Earth Planet Sci. 2003;31:75–104. https://doi.org/10.1146/annurev.earth.31.100901.141259
2. Gray WM. *Global view of the origin of tropical disturbances and storms.* Mon Weather Rev. 1968;96:669–700. https://doi.org/10.1175/1520-0493(1968)096<0669:GVOTOO>2.0.CO;2
3. Emanuel KA. *A statistical analysis of tropical cyclone intensity.* Mon Weather Rev. 2000;128:1139–1152. https://doi.org/10.1175/1520-0493(2000)128<1139:ASAOTC>2.0.CO;2
4. Evan AT, Kossin JP, Chung C, Ramanathan V. *Arabian Sea tropical cyclones intensified by emissions…* Nature. 2011;479:94–97. https://doi.org/10.1038/nature10552
5. Sriver RL, Huber M. *Observational evidence for an ocean heat pump…* Nature. 2007;447:577–580. https://doi.org/10.1038/nature05785
6. Mohanty UC, et al. *Tropical cyclone climatology over the North Indian Ocean.* Mausam. 2012;63:1–20.
7. Li X, Li Y, Tang Y. *Sharp increase in rapid intensification…* Commun Earth Environ. 2025;6:502. https://doi.org/10.1038/s43247-025-02477-w Nature
8. Kaplan J, DeMaria M. *Large-scale characteristics of rapidly intensifying tropical cyclones.* Weather Forecast. 2003;18:1093–1108. https://doi.org/10.1175/1520-0434(2003)018<1093:LSCORI>2.0.CO;2
9. Bhatia KT, et al. *Recent increases in tropical cyclone intensification rates.* Nat Commun. 2019;10:635. https://doi.org/10.1038/s41467-019-08471-z
10. Knapp KR, et al. *The IBTrACS dataset.* Bull Am Meteorol Soc. 2010;91:363–376. https://doi.org/10.1175/2009BAMS2755.1
11. Cheng L, et al. *Improved estimates of ocean heat content…* Sci Adv. 2017;3:e1601545. https://doi.org/10.1126/sciadv.1601545
12. Roxy MK, et al. *Faster warming of the Indian Ocean.* Geophys Res Lett. 2014;41:526–532. https://doi.org/10.1002/2013GL058860
13. Lin II, et al. *Ocean coupling effect on tropical cyclone intensity.* Geophys Res Lett. 2013;40:1878–1883. https://doi.org/10.1002/grl.50093
14. Deshpande M, et al. *Changing status of tropical cyclones over the North Indian Ocean.* Clim Dyn. 2021;57:3545–3567. https://doi.org/10.1007/s00382-021-05844-9

15. Vidya PJ, et al. *Intensification of Arabian Sea cyclone genesis potential…* npj Clim Atmos Sci. 2023;6:146.https://doi.org/10.1038/s41612-023-00420-8
16. Kossin JP, et al. *Global increase in major tropical cyclone exceedance…* Proc Natl Acad Sci USA. 2020;117:11975–11980.https://doi.org/10.1073/pnas.1920849117
17. Kikuchi K, Wang B. *Tropical cyclone activity and the MJO.* J Clim. 2010;23:4885–4901. https://doi.org/10.1175/2010JCLI3240.1
18. Camargo SJ, et al. *Influence of the MJO on tropical cyclones.* J Clim. 2009;22:5869–5887. https://doi.org/10.1175/2009JCLI2880.1
19. Walsh KJ, et al. *Tropical cyclones and climate change.* WIREs Clim Change. 2016;7:65–89. https://doi.org/10.1002/wcc.371
20. Small RJ, et al. *Air–sea interaction over ocean fronts.* Rev Geophys. 2008;46:RG1006. https://doi.org/10.1029/2006RG000212
21. Ren D, et al. *Upper-ocean response to Cyclone Mekunu.* J Mar Sci Eng. 2024;12:1177. https://doi.org/10.3390/jmse12071177