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Characterizing the Tropical Cyclones Activity over Arabian Sea (1982–2021)

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Abstract: The current study looks at how the characteristics of Arabian Sea tropical cyclones (TCs) change over time. The results show that in the pre-monsoon (April–June) and the post-monsoon (October–December), the activity of TCs > 34 knots, including cyclonic storm (CS), severe cyclonic storm (SCS), very severe cyclonic storm (VSCS), extreme severe cyclonic storm (ESCS), and super cyclonic storm (Sup. CS), has significantly increased, while the tendency of TCs < 34 knots, depressions and deep depressions (Ds) over the Arabian Sea has only slightly increased. Most of the TC activity in the first two decades (1982–2001) over the Arabian Sea activated on the eastern side, while in the last two decades (2002–2021), there was an expansion toward the southwest region of the Arabian Sea, especially in the post-monsoon season. The composite analysis of environmental parameters over the Arabian Sea reveals that the negative anomalies of outgoing longwave radiation (OLR) and the positive anomalies of relative humidity at 500 hPa (RH–500 hPa) in the first decade (1982–1991) and the second decade (1992–2001) are more concentrated on the eastern side of the Arabian Sea, leading to increased activity for TCs. Decades three (2002–2011) and four (2012–2021) demonstrated a wide distribution of weak vertical wind shear (VWS) and strong convection (OLR and RH–500 hPa) over the Arabian Sea basin. This led to TCs occurring more frequently and stronger, especially in the post-monsoon season. SST over the Arabian Sea was sufficient for tropical storm activity (≥26.5 °C) for both typical seasons.

Keywords: Arabian Sea; tropical cyclones; environmental parameters; composite analysis

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1. Introduction

Tropical cyclones are weather systems defined by an enormous and revolving mass of moist air on a much greater scale that is generated over the warm ocean waters. References [1,2] asserts that tropical cyclones are catastrophic events that cause damage and destruction due to their huge energetic strength provided by the water. The intensive TCs cause rising in the sea level due to the low atmospheric pressure and strong winds leading to sudden flooding in the coastal region; this is called a storm surge [3]. Due to the energy derived from the open ocean, these systems eventually lead to the formation of enormous vortices that are characterized by whirling winds, dense clouds, and intense precipitation [4]. In recent years, the increasing number of intensive TCs over the Arabian Sea that make landfall on the coastal regions has increased the death rate and damage. Gonu killed 78 people and caused about USD 4 billion in damages [5], while cyclones Phet and Megh [6] killed 47 and 18 people, respectively. A brief review about storm surges and their modeling over the North Indian Ocean (NIO) was made by [7]. Several studies have been conducted to understand their behavior and the factors that contribute to their occurrence [8–13] The dynamics of TCs, particularly their origin and intensity, are difficult to completely explain. Moist convection and condensation influence large circulation indices, hence amplifying the cyclone disturbances, as noted in [14]. The global shallow-water model calculations used by [15] indicate that the vortex trapping increases with peak height, topographic length scale, and latitude (larger topographic β effect), whereas [16] shows that the instabilities of cyclone vortices are triggered by the beta-effect.

There are two primary basins that make up the NIO, the Arabian Sea and the Bay of Bengal. According to [8], it is one of the tropical regions that creates favorable conditions for the genesis of cyclones. Refs. [17,18] studied that around seven percent of all TCs across the world had their origins in the North Indian Ocean. Figure 1 depicts the Arabian Sea, which is the western basin of the North Indian Ocean. It is located between the longitudes of 50° and 80° East and the latitudes of 5° and 25° North. The impact of Arabian Sea TCs is enormous on communities, both socially and economically, despite the fact that they only account for three percent of all TCs [8,19]. Over the Arabian Sea, a notable proportion of TCs materialize in the vicinity of the Laccadive Islands, which are 11° North and 73° East [20]. The North Indian Ocean regularly experiences five to six systems that are severe enough to meet the criteria for the TC classification and have wind speeds of at least 34 knots [21]. From a climatological point of view, TCs activity in the Arabian Sea and the Bay of Bengal exhibits characteristics that are distinct from those observed in storms occur in other basins [22]. The annual pattern of TCs activity over these two basins exhibits a significant bimodal characteristic, exhibiting peaks during the transitional monsoon periods of April to June and October to December, while other basins experience a singular, dominant peak [8,23,24]. This underscores how the bimodality of these two basins sets them apart from other basins. The first peak of TCs activity occurs between the end of April and the beginning of June, and the second peak occurs between the end of September and the beginning of December [25,26].

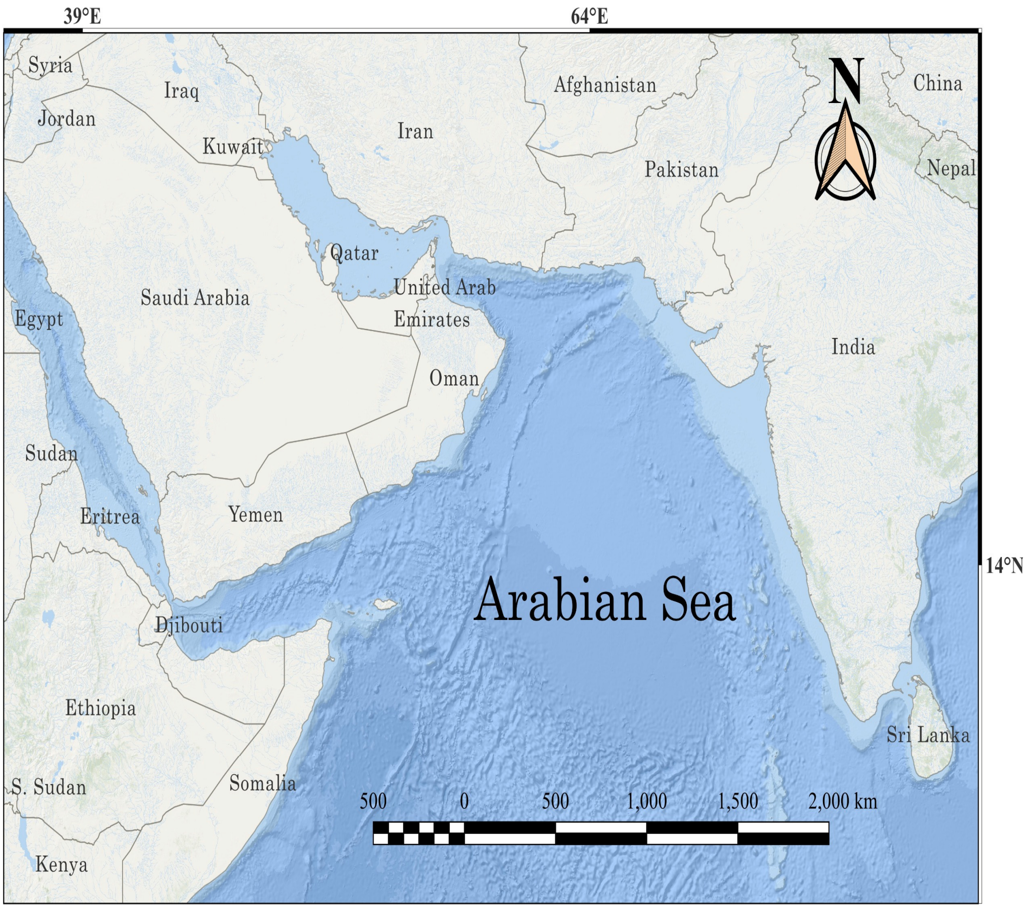

Figure 1. The domain of the study area (Arabian Sea).

Previous studies have revealed that TCs occurrence is changing and gaining strength over different geographic regions, including the North Pacific [27] and the North Atlantic [28]. The study [29] recorded a consistent augmentation in both quantity and proportion of TCs severity across all basins (1979–2004). Substantiated the escalation in the strength of most TCs globally throughout the satellite period (1981–2006) [30]. Most of the prior studies concentrated on the NIO in general by comparing the two basins or only concentrated on the Bay of Bengal since it has more TCs activity, while the studies focusing on the basin of the Arabian Sea individually are very limited. The frequency at which TCs are formed in the NIO region follows a different annual cycle compared to the North Tropical Atlantic, Western North Pacific, and Eastern North Pacific regions [31–33]. The North Tropical Atlantic, Western North Pacific, and Eastern North Pacific experience a single peak TC season, which occurs from July to October. Earlier research has also documented a remarkable variability in the occurrence and strength of TCs within the Bay of Bengal and Arabian Sea [26]. Refs. [34–36] demonstrated a notable increase in the occurrence of Very Severe Cyclonic Storms (VSCSs) over the NIO, spanning from 1981 to 2014. Also, a new study on the increasing of intensive TCs over NIO [37] reveals that the increase in Extremely Severe Cyclonic Storm (ESCS) is due to weakening summer monsoon circulation while [38] relates the change in TCs intensity over NIO to the eddies (warm and cold core). Conversely, ref. [39] observed no marked progression in the yearly incidence of Cyclonic Storm (CS) or Severe Cyclonic Storm (SCS) over the Arabian Sea (1996–2010). Refs. [40,41] reported that the frequency of the TC over the Arabian Sea exhibited a more rapid increase as compared to the Bay of Bengal. Ref. [19] found no statistically significant trend over the period 1891–2008 in the frequency of TCs over the Arabian Sea. However, from 1979 onwards, there has been an observable rise in TC activity in the Arabian Sea region [42–44]. Ref. [26], examined the connection between the environmental conditions of the Arabian Sea and TC activity from a climatological point of view. There are four main thermodynamic factors affecting TC activity over all tropical oceans, which are sea Surface temoerature (SST), relative humidity (RH)-500 hPa, outgoing longwave radiation (OLR), and vertical wind shear (VWS). The interplay of these factors is sufficient to characterize the primary drivers of cyclogenesis and TC intensity in the region. SST is critical because it provides the thermal energy required for TC formation and contributes to TC intensification [45–47]. Warmer ocean surfaces enhance evaporation and atmospheric moisture content, fueling the convection processes that lead to cyclogenesis, while mid-tropospheric moisture is essential for sustaining deep convection within a TC, and without enough moisture, the TC cannot form or intensify [48–50]. At this level, sufficient RH prevents dry air intrusion, which can weaken or inhibit TC development. OLR is another important factor. It serves as an indicator of convective activity and cloud-top temperatures. Lower OLR values correspond to stronger convection, which is a key component in TC formation and intensification. Also, the findings indicate that harmoniously structured extensive-scale circumstances can generate specific environments, particularly weak VWS, that are apt for tropical cyclogenesis in the favorable season periods. It is a significant dynamic factor for TCs activity [26,51–53].

Over the years, the classification of low-pressure systems used by the Indian Meteorological Department (IMD) has undergone several different modifications. These modifications have been based on observational networks, analytical tools, and procedures. The comprehensive examination of this classification has been discussed by [54]. The IMD (2008) states that up to 1974, there were essentially three different categories of TCs: depressions, CS, and SCS.

The year 1999 saw additional modifications to the classification criteria due to the utilization of microwave-based satellite products, meteorological buoys, high wind speed recorders, scatterometer-based sea surface wind observation, and an increase in confidence in intensity estimation based on Dvorak's technique and radars [55,56]. For wind speeds ranging from 64 to 119 knots, the term "SCS" was changed to "VSCS", and a new term, "super CS" (SuCS), was introduced for wind speeds beyond 120 knots. As seen in Table 1, the IMD has lately begun using the classification of TCs.

Table 1. Tropical cyclone classification according to IMD for North Indian Ocean.

System	Wind Speed in km/h	Wind Speed in Knots (m/s)
Low-pressure area (L)	Less than 31	Less than 17 (09)
Depression (D)	31–49	17–27 (9–14)
Deep depression (DD)	50–61	28–33 (15–17)
Cyclonic storm (CS)	62–88	33–47 (18–24)
Severe cyclonic storm (SCS)	89–118	48–63 (25–32)
Very severe cyclonic storm (VSCS)	119–165	64–89 (33–46)
Extreme severe cyclonic storm (ESCS)	166–220	90–119 (47–61)
Super cyclonic storm (Sup. CS)	221 or more	120 (62) or more

Note: 1 Knot = 0.514 m/s = 1.852 km/h.

In this study, the authors are concerned with the characteristics of TCs over the Arabian Sea (frequency, intensity, and genesis) and relate them to the environmental condition by investigating different environmental parameters. By conducting an analysis of these characteristics over the Arabian Sea region, we aim to gain a thorough understanding of TCs characteristics in this complex region. In our next article, we will study more about TCs activity like track, energy metrics, and its duration and the relationship between the TCs activity and global circulation indices.

This paper has four sections. We describe our study's data and methods in Section 2. Section 3 discusses the main findings, including TC activity in terms of frequency, intensity, and genesis. In Section 4, we summarize our findings.

2. Data and Methods

The Regional Specialized Meteorological Centre-India Meteorological Department (RSMC-IMD) has created a digitized dataset of tropical storms that occurred in the Arabian Sea between 1982 and 2021. This dataset was constructed based on the current categorization and criteria, which can be seen in Table 1. In order to determine the development of the various tropical storm categories beginning with D/DD and ending with SuCS over the Arabian Sea, the data on TCs from RSMC-IMD (1982–2021) has been gathered and evaluated. For analysis purposes, the D and DD forms of depression have been combined into a single category; from this point forward, they will simply be referred to as Ds. RSMC has provided the data with frequency, intensity, and genesis data (intensity, the name of the storm, its date and location of genesis, its peak wind speed, and its landfall position) of Ds, CS, SCS, and intensity storms [57,58]. Different types of tropical cyclones that make landfall along the coasts of the Arabian Sea region are gathered in order to analyze the landfall characteristics. Environmental parameters such as SST, RH-500 hPa, OLR-500 hPa, and VWS were obtained from the national centers for environmental prediction (NCEP), and by using the national oceanic and atmospheric administration (NOAA)Physical Sciences Laboratory (PSL), composites of these parameters were created in this investigation for the 1982 to 2021 period [59].

Each TC was ranked according to the months, seasons, and decadal trends, in addition to their frequency and intensity. The Arabian Sea surrounds a region ranging from 5°–25° N to 50°–80° E. For genesis investigation, it is divided into four distinct areas (A1–A4). Figure 2 depicts the geographical scope of these four areas. Usually, researchers use this method of area division to gain a deeper understanding of the characteristics of TCs, particularly in the genesis location [60,61]. This approach helps establish a direct relationship between the physical environment and TC activity.

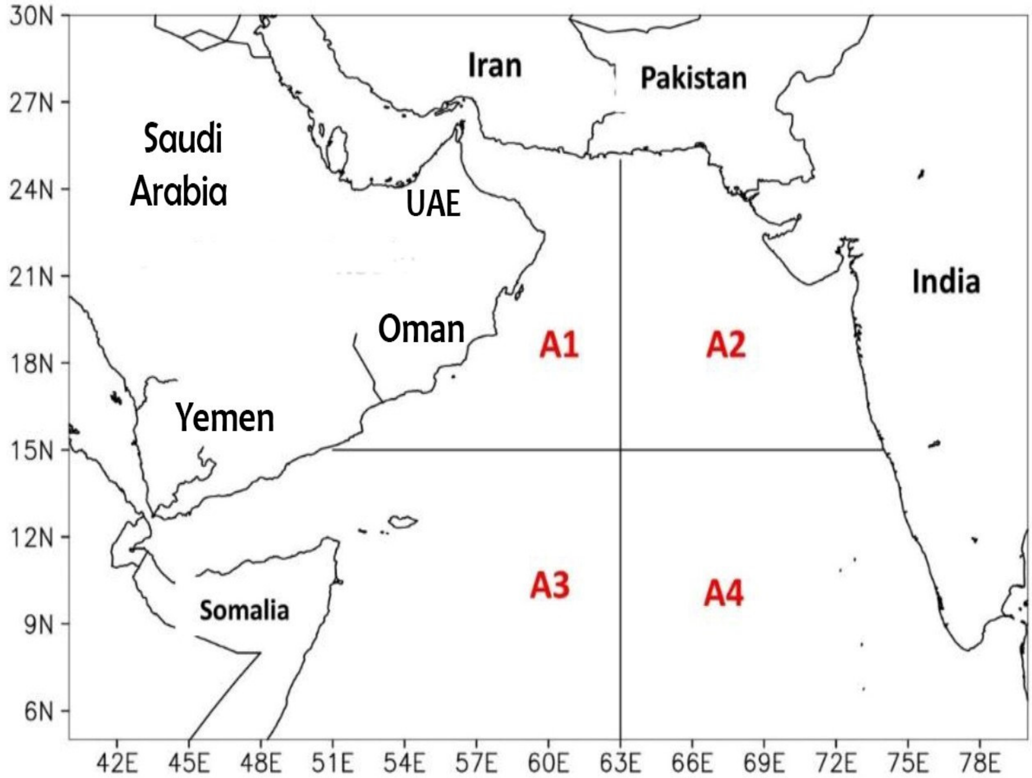

Figure 2. The Specified areas designated for the different regions over Arabian Sea: A1 (15°–25° N and 51°–62.9° E), A2 (15°–25° N and 63°–75° E), A3 (05°–14.9° N and 51°–62.99° E), and A4 (05°–14.9° N and 63°–78° E). (UAE on the map is United Arab Emirates).

3. Results and Discussion

3.1. Frequency and Intensity of TCs over the Arabian Sea

3.1.1. Monthly and Seasonally

According to the classification of TCs that is given in Table 1 by the IMD, two groups of TCs are now being investigated: (i) TCs that are less than 34 knots (Ds) and (ii) TCs greater than 34 knots which are classified as CS, SCS, VSCS, ESCS, and SuCS depending on the wind speed. Figure 3 illustrates the monthly distribution of TCs over the Arabian Sea. From this figure, we can see that the May, June, October, and November months have the strongest activity of TCs over the Arabian Sea, less activity in January, July, August, and September, and no activity in February and April. Also, June has the highest frequency of TCs over the Arabian Sea.

Figure 4 illustrates that the period from October to December, known as the post-monsoon season, experiences the highest level of TC activity. Between 1982 and 2021, 87 TC events were observed in the Arabian Sea. Out of the total of 87 TC events, 2 (2%) occurred during the winter, 33 (38%) during the pre-monsoon period, 50 (57.5%) during the post-monsoon period, and 2 (2%) during the monsoon period. In general, it is obvious that there is more TCs activity during the post-monsoon season for the categories of CS, SCS, VSCS, ESCS, and SuCS (Table 2). Since winter and monsoon seasons have less activity for TCs over the Arabian Sea, this study concentrates more on the other two seasons, which are the pre-monsoon and post-monsoon seasons.

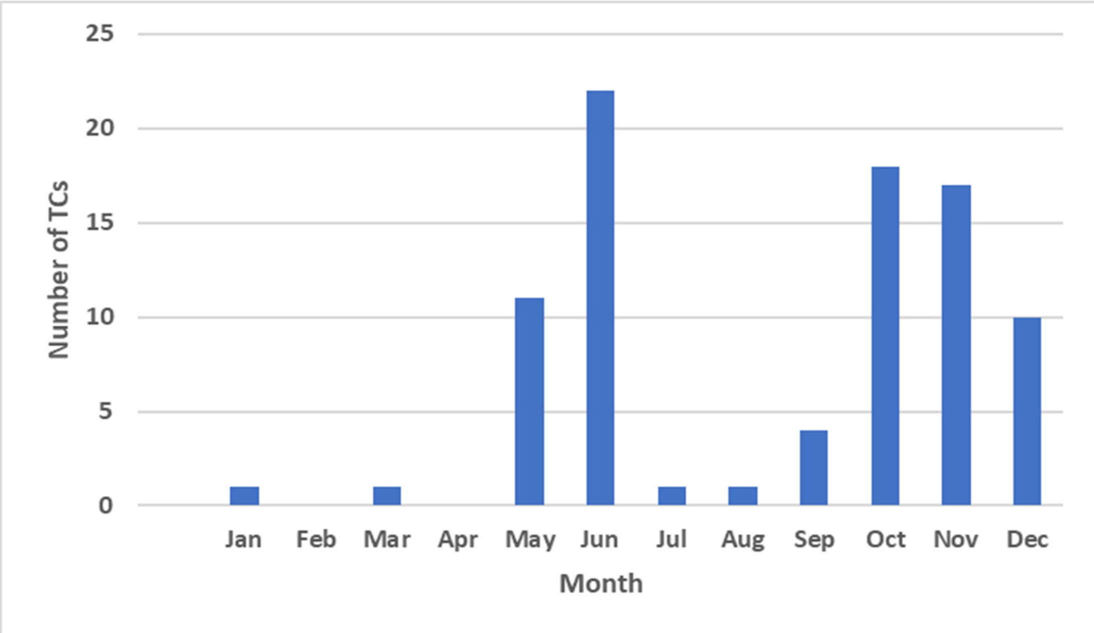

Figure 3. Number of TCs (sum) according to IMD classification of TCs for each month in the year over the Arabian Sea (1982–2021).

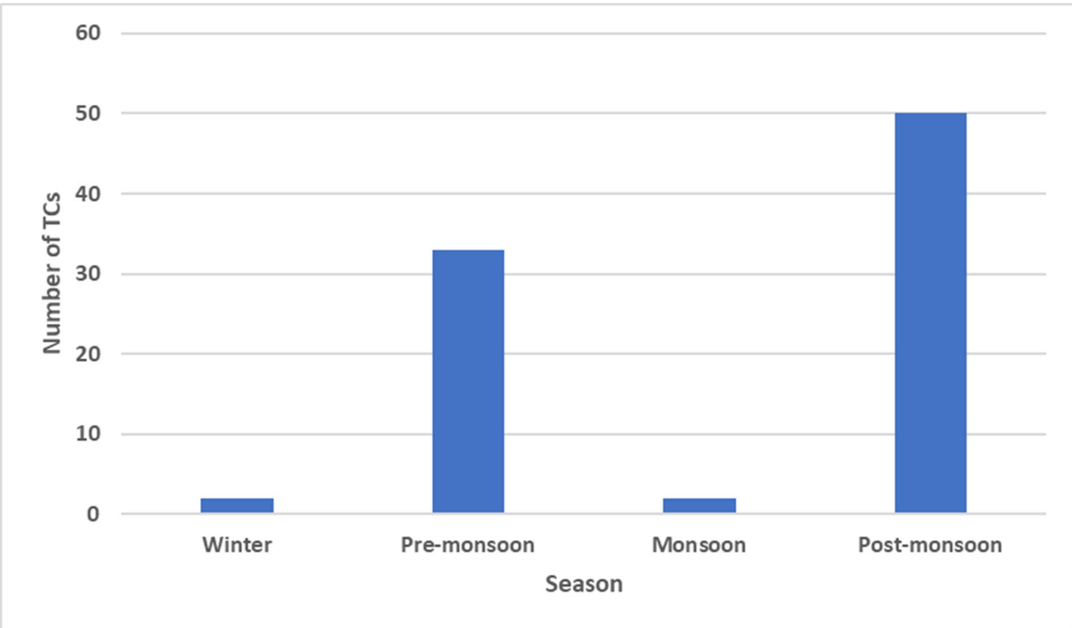

Figure 4. Number of TCs (sum) according to IMD classification of TCs in each season over Arabian Sea during the study period. Winter (January–march), Pre-monsoon (April–June), Monsoon (July–September), and Post-monsoon (October–December).

Table 2 below presents the seasonal record of TCs in the Arabian Sea basin from 1982 to 2021. The analysis reveals a frequent and abundant occurrence of TCs during the two main seasons of peak activity. Tropical storms are infrequently formed over the Arabian Sea from July to August due to the presence of strong VWS in the North Indian Ocean region [62]. According to Table 2, 56% of TCs during the entire period originated in the post-monsoon season and 44% in the pre-monsoon season. Regarding CSs, the distribution was roughly comparable between the two seasons. However, the category of SCS accounted for 60% during the pre-monsoon and 40% in the post-monsoon; 75% of VSCS originated in the post-monsoon. In contrast to these two active seasons, there was a complete absence of action for TCs that are greater than 34 knots (CS, SCS, VSCS, ESCS, and SuCS) throughout the winter and the season that occurred between them (monsoon), spanning from July to the first half of September.

Table 2. The seasonal record of TCs which are greater than 34 knots in the Arabian Sea basin based on IMD severity classification (1982–2021).

Season	CS	SCS	VSCS	ESCS	SuCS
Winter	0	0	0	0	0
Pre-monsoon	8	4	2	5	1
Monsoon	0	0	0	0	0
Post-monsoon	8	6	6	4	1

3.1.2. Annual and Decadal

The annual average frequency of TC activity over the Arabian Sea during 1982–2021 was 2.18. There were no recorded TCs in the Arabian Sea in the years 1987, 1991, 2000, and 2017.

A total of 42 Ds and 45 intensive TCs < 34 knots were reported in the Arabian Sea, corresponding to an annual frequency of 1.05 Ds and 1.13 for TCs < 34 knots between 1982 and 2021. Additionally, a large trend increases of the intensive TCs and a slightly increasing trend of Ds over the Arabian Sea. (Figure 5). During the first 10 years, the frequency of TCs > 34 knots was very low and there were only 2 events occurred in the first decade (1982–1991). Since 1992, there has been a significant increase with at least one event per year.

The following TCs, named Gonu (2007), Bandu (2010), Phet (2010), Keila (2011), Nilofar (2014), Ashoba (2015), Megh (2015), Sagar (2018), Mekuno (2018), Luban (2018), and Shaheen (2021), have occurred recently in the Arabian Sea. The TCs originate over the Arabian Sea and have made landfall on countries' coasts. Table 3 presents the decadal distribution of TCs activity in the Arabian Sea region over the last four decades (DE1, 1982–1991; DE2, 1992–2001; DE3, 2002–2011; and DE4, 2012–2021). According to Table 3, the average frequency of TCs in the four decades was 1.3, 2, 2.4, and 3, respectively. Furthermore, it demonstrates that the frequency of TC activity has been gradually increasing over the last thirty years. Even though there were a large number of disturbances throughout the first decade (DE1), only two TCs greater than 34 knots formed out of the total of forty-five that occurred during the entire period. Over the remaining three decades, there was at least one TC greater than 34 knots that was extremely active each year. The DE4 (DE1) decade had the highest (lowest) number of intensive TCs recorded, respectively, which was 30 (13). Since 2014, which is within DE4, there has been a general pattern that indicates a significant increase in the quantity of intensive TC activity.

Table 3. Decadal distribution of Tcs events in the Arabian Sea Basin based on severity.

Decades (DEs)	Ds	CS	SCS	VSCS	ESCS	SUCS	Tot
1982–1991 (DE1)	11	1	0	0	1	0	13
1992–2001 (DE2)	5	6	4	2	3	0	20
2002–2011 (DE3)	14	4	4	1	0	1	24
2012–2021 (DE4)	12	5	2	4	6	1	30

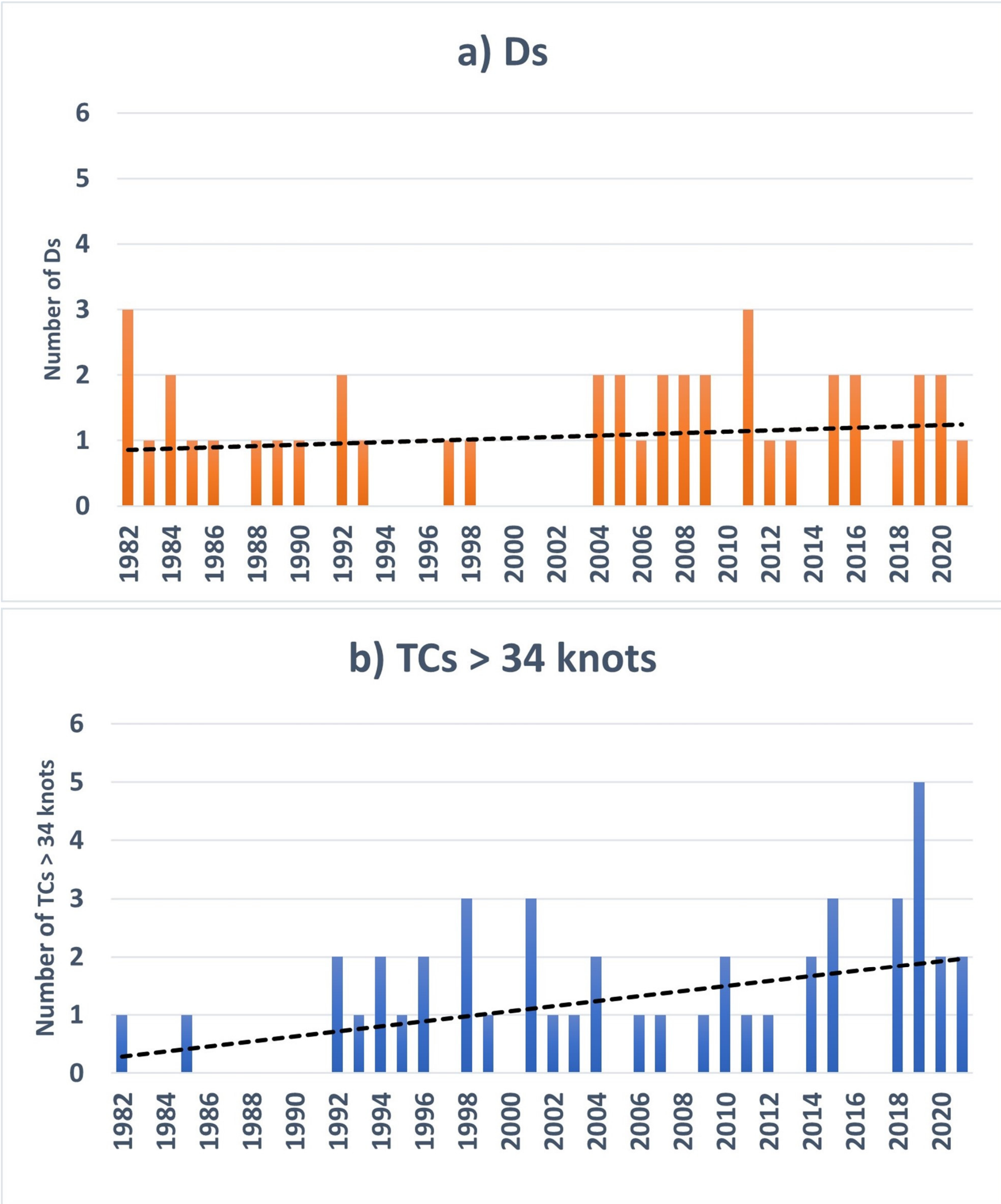

Figure 5. Annual distribution of TCs number according to IMD classification of TCs for (**a**) Ds (TCs < 34 knots), and (**b**) TCs > 34 knots over the Arabian Sea basin (1982–2021) with their trend lines.

3.2. Genesis of TCs over the Arabian Sea

Table 4 divides the Arabian Sea into four distinct areas: A1 (15°–25° N and 51°–62.99° E), A2 (15°–25° N and 63°–80° E), A3 (05°–14.99° N and 51°–62.99° E), and A4 (05°–14.99° N and 63°–78° E). This table also provides information about the total number of genesis sites in each of the four selected areas for different time periods. There has been a total of 87 genesis points across the full-time span from 1982 to 2021 that have been identified as the origin of TCs. The highest number of occurrences have been seen in regions A4 (41) and A2 (32), respectively. While the lowest number of occurrences is observed in A1 (1) and A3 (13).

Table 4. Specified areas designated for the different regions and number of occurrences.

Area	A1	A2	A3	A4
Latitude and longitude	15°–25° N; 51°–62.9° E	15°–25° N; 63°–75° E	05°–14.9° N; 51°–62.9° E	05°–14.9° N; 63°–78° E
Number of occurrences	1	32	13	41

When considering the distribution of Ds and TCs > 34 knots during the two seasons over the Arabian Sea, it becomes evident from Figure 6 that more than two-thirds of pre-monsoon TCs were situated on the eastern side (A2 and A4). Moreover, during this season, all Ds originated above 15° N (A1 and A2), with a greater concentration on the eastern side (A2). For the strong categories of TCs which are greater than 34 knots, out of the 20 formed during this season, 16 were located on the right side of 63° E (A2 and A4), with a higher concentration over A4.

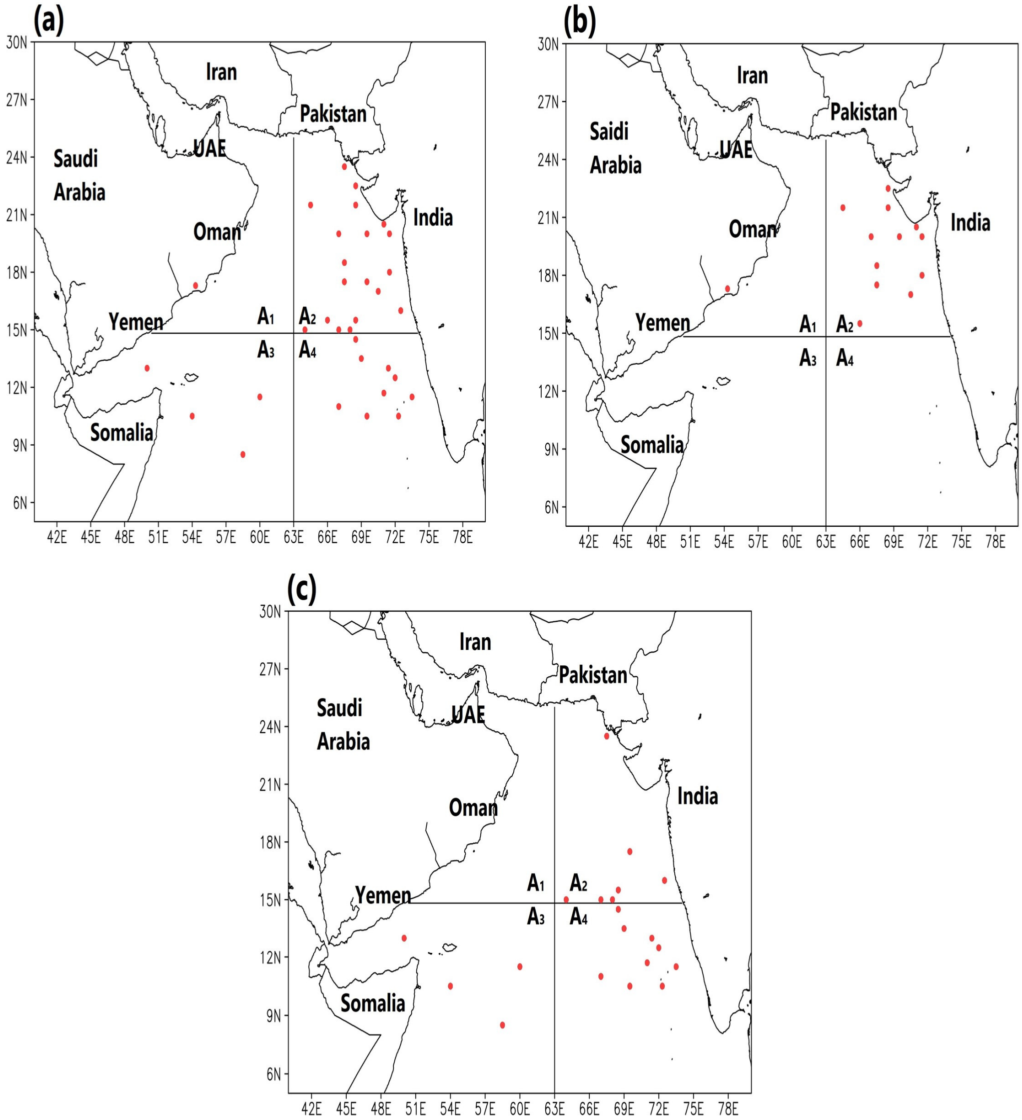

Figure 6. Geographical distribution of tropical cyclone genesis location (red dots) for pre-monsoon season in the four areas of Arabian Sea A1–A4. (**a**) all TCs categories according to IMD classification of TCs, (**b**) Ds genesis points, and (**c**) TCs genesis points (>34 knots). (UAE on the map is United Arab Emirates).

A considerable number of TCs are formed over the Arabian Sea below 15 degrees North (A3 and A4) during the post-monsoon season, which begins at the end of September and continues until the end of December. This season is characterized by the occurrence of TCs, as seen in Figure 7. Compared to the pre-monsoon season, an increase in the activity of TCs towards the southwest of the Arabian Sea basin (A3) is observed in the pre-monsoon season. In addition, with the exception of three instances, all the Ds that occurred during the post-monsoon season originated below 15 degrees north latitude (A3 and A4), and the eastern side (A4) indicated a higher concentration of TC activity. In terms of the intensive TCs, out of twenty-five that occurred, the twenty developed during this season were located on the eastern side of 63 degrees east (A2 and A4) and exhibited meridional variability.

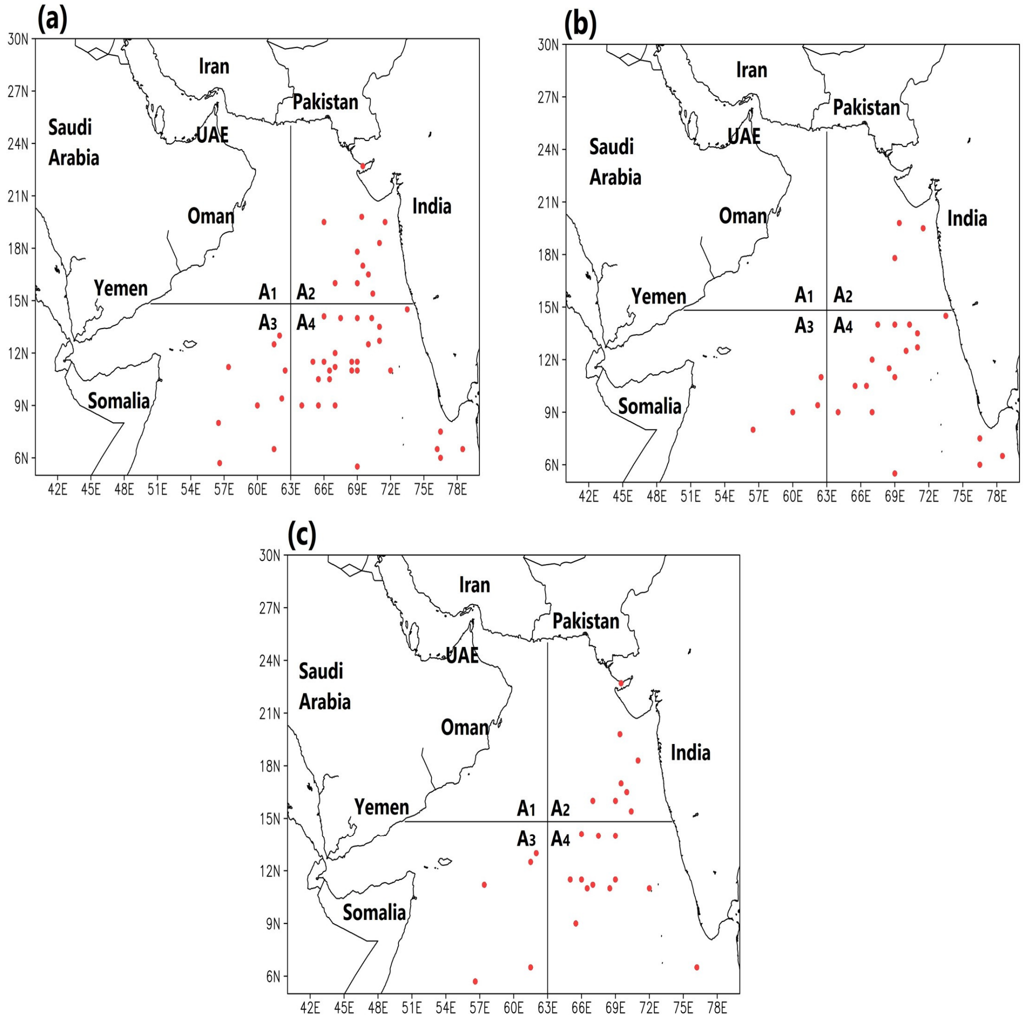

Figure 7. Geographical distribution of tropical cyclone genesis location (red dots) for post-monsoon season in the four areas of Arabian Sea A1–A4 (**a**) all TCs categories according to IMD classification of TCs, (**b**) Ds genesis points, and (**c**) TCs genesis points (>34 knots). (UAE on the map is United Arab Emirates).

According to Table 5, the majority of TCs originated in areas A2 and A4 in DE1 and DE2, with percentages of 97% and 95% of TCs that occurred, respectively. In DE3, A2 had the highest number of TCs, followed by A4 and A3 in that order. Within DE4, the formation of tropical storms primarily occurred in the southern regions (A3 and A4) of the Arabian Sea, accounting for 73% of all occurrences. The remaining storms formed in the northern regions (A1 and A2) of the basin.

Table 5. Numbers of tropical cyclones distributed in the four specified regions over the Arabian Sea, during different periods.

Region	1982–2001	1982–1991	1992–2001	2002–2021	2002–2011	2012–2021
A1	0	0	0	1	0	1
A2	13	7	6	19	12	7
A3	1	0	1	12	4	8
A4	19	6	13	22	8	14
Total	33	13	20	54	24	30

When the two 20-year periods (1982–2001 and 2002–2021) are compared, it is possible to demonstrate that the frequency of TCs increased by approximately 64 percent in the second era in comparison to the first period (Table 5). According to the differences that are displayed in Table 5 between the four areas, A1 and A3 have the least number of TCs across all of these four areas during the first period of the 20-year period. On the other hand, there is a slight increase in the generation of TCs over A1 during the second period and a significant increase over A3 during the same period.

The locations where the genesis occurs have been observed to be the most prominent in the eastern region of the Arabian Sea (A2 and A4), as indicated in Table 5 and Figure 8. Also, there is an expansion of TC genesis distribution over the Arabian Sea towards the southwest of the basin (A3) in the second period of the 20-year period.

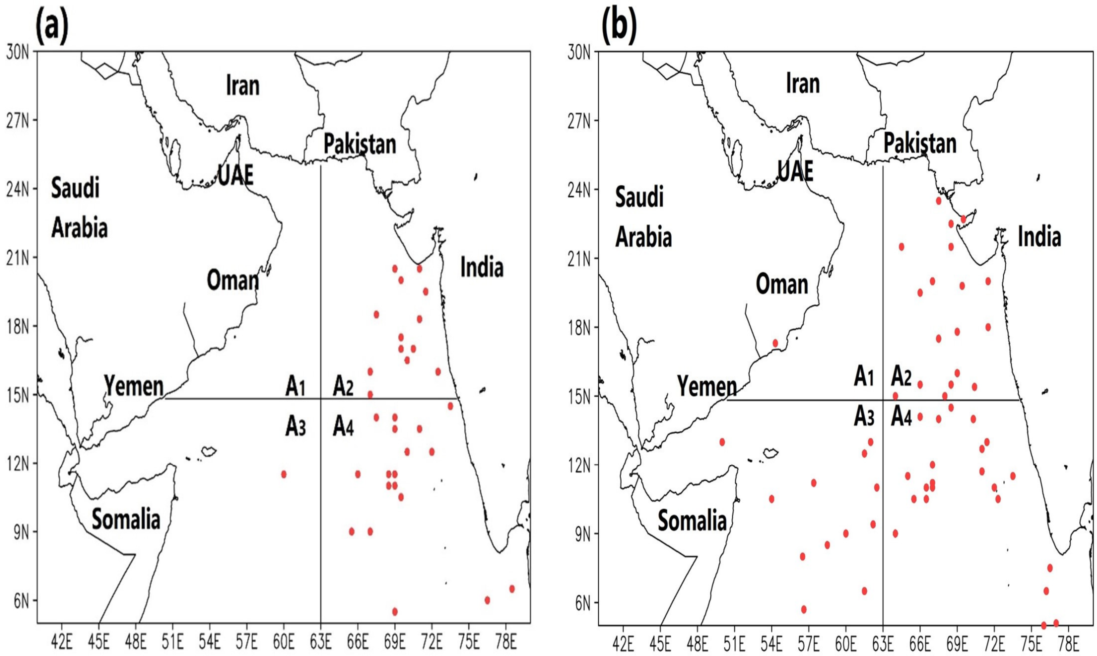

Figure 8. The geographical distribution of tropical cyclone genesis location in the four areas of Arabian Sea A1–A4. (**a**) 1982–2001 and (**b**) 2002–2021. (UAE on the map is United Arab Emirates).

3.3. Influence of Environmental Factors on Tropical Cyclones Genesis and Intensity

A major distinction may be seen in the origin location, quantity, and intensity of TCs that occur over the Arabian Sea for seasons and decades, as demonstrated by the preview sections. The findings of this study are consistent with those of earlier research. References [8,26,63–65] found that the dynamical and thermodynamic factors SST, RH, OLR, and VWS are responsible for controlling the creation and intensification of TCs.

During the pre-monsoon season, SST gradually increased from one decade to the next, hence supplying TCs genesis with both moisture and energy [8,66,67]. The pre-monsoon SST reaches 30 °C and more in the center areas of the basin during DE3, and it has expanded significantly over the last decade in most of the basin area, this is one of the factors that has played a good role in increasing the TCs activity in the last two decades. A lower temperature in the western basin of the Arabian Sea compared to the eastern side causes fewer TCs to originate during this season. However, during the post-monsoon season, SST did not increase, but it is still sufficient around the threshold for TC activity (≥26.5 °C) to enhance the convection over the basin, which is necessary for TCs activity (Figure 9).

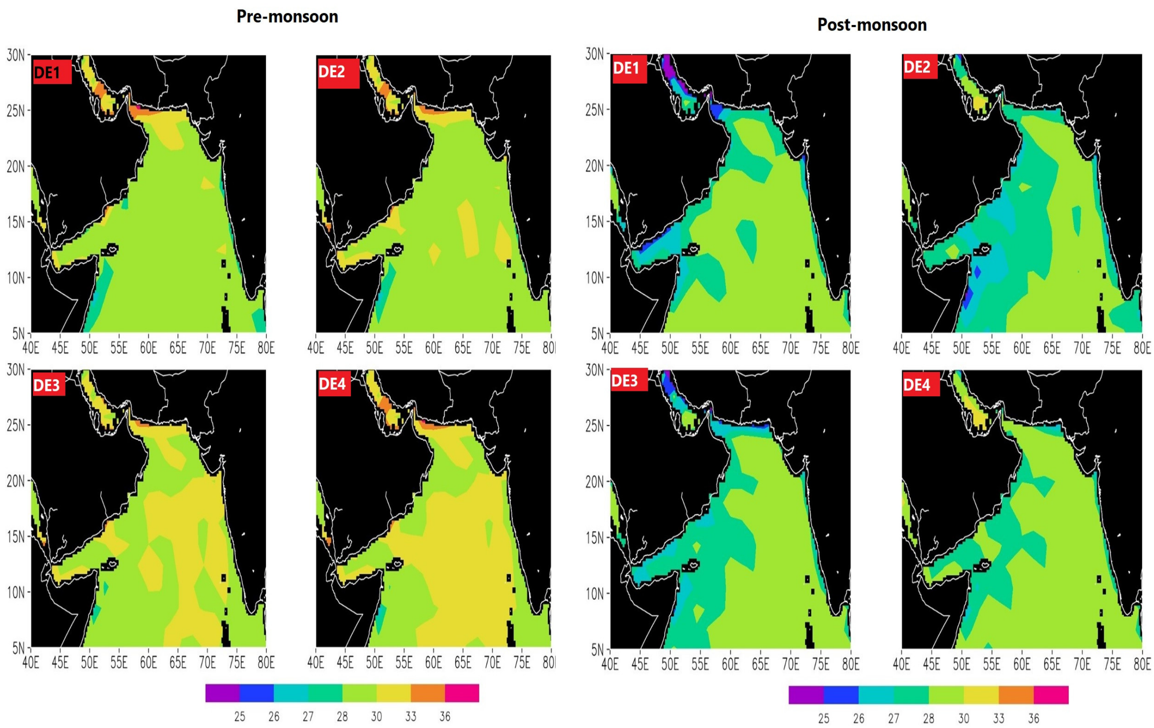

Figure 9. The composite means of SST (°C) over Arabian Sea for the four different decades (DE1, DE2, DE3, and DE4) for Pre-monsoon and post-monsoon seasons.

Both seasons maintain the SST at 26.5 °C, meeting the empirical criterion for the genesis of TC. However, there is a noticeable variation in TC activity throughout these two seasons each year. This suggests that other inhibiting elements, such as RH, VWS, and OLR, may potentially affect TC's activity and it is important to confirm this.

Both the RH positive anomalies and the OLR negative anomalies have had a strong concentration on the eastern side of the Arabian Sea during the first two decades in both pre-monsoon and post-monsoon seasons, which has led to an increase in the number of TCs. However, in the most recent decades, it has expanded on the majority of the Arabian Sea area, causing an increase in the frequency and intensity of TCs, as shown in Figures 10 and 11. Additionally, the increase in both OLR and RH over the Arabian Sea can be seen in both of the figures during the last two decades. VWS is an additional significant feature that contributes to the favourability of TCs due to its impact. It is essential to have a weak VWS in order to contribute to the genesis of TCs. According to [68], it is more advantageous to have low VWS while forming an upper-level warm core since it promotes the development of tropical disturbances. This occurs because a low VWS creates favorable conditions for tropical disturbance development. Figures 10 and 11 also show that VWS is not the primary factor influencing the changes in TC characteristics during the pre-monsoon period in each decade. However, it still plays an important role in TCs activity.

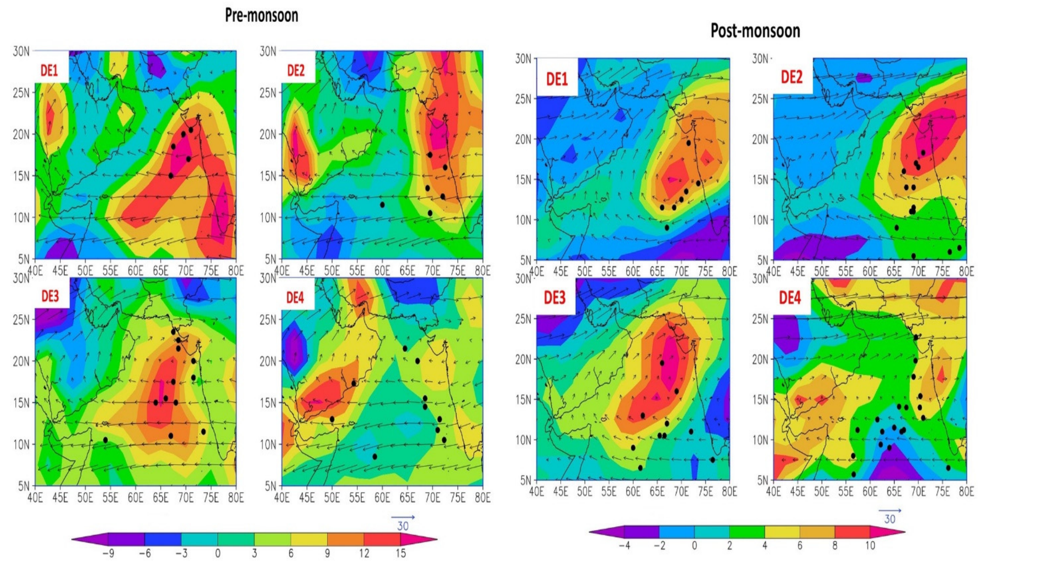

Figure 10. The composite anomalies of RH-500 hPa (%) and VWS (m/s) over Arabian Sea in four different decades (DE1, DE2, DE3, and DE4) for pre-monsoon and post-monsoon, black dots are the genesis locations of TCs.

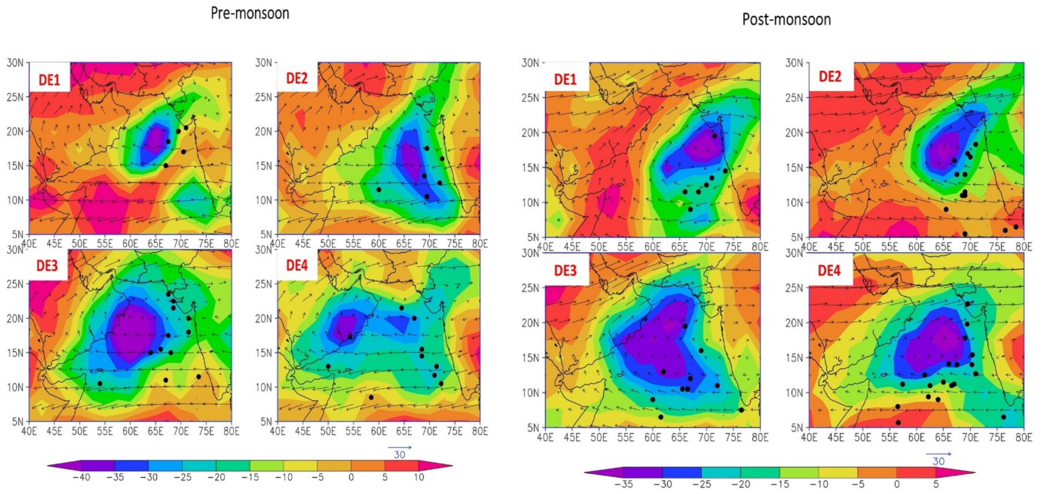

Figure 11. The composite anomalies of OLR-500 hPa (W m^{-2}) and VWS (m/s) over Arabian Sea in four different decades (DE1, DE2, DE3, and DE4) for pre-monsoon and post-monsoon, black dots are the genesis locations of TCs.

For the first two decades (DE1 and DE2) of the post-monsoon season, there was a concentration of significantly higher than average levels of RH-500 hPa anomalies and significantly lower than average levels of OLR-500 hPa anomalies on the eastern side of the Arabian Sea. This resulted in more favorable conditions for the development of TCs. However, during DE3 and DE4, these anomalies steadily increased towards the west and southwest, causing more activity in the Arabian Sea.

Regarding VWS, its influence was extremely modest during the first two decades (DE1 and DE2), but in the most recent two decades, it has emerged as a substantial contributing element among RH and OLR in influencing the changes between seasons and decades in the characteristics of TCs. Thus, in terms of VWS, we can conclude that VWS is one of the primary contributing factors in TCs activity over the Arabian Sea and since it had higher values in the pre-monsoon compared to the post-monsoon, it caused less activity of TCs. During this season, there has been no significant increase or reduction in SST; hence, it is not possible to determine whether or not SST has had an effect on the characteristics of TCs over the past four decades.

Hence, changes in the rate at which the sea surface warms up, especially before the monsoon season, and the way the VWS is spread out over the basin during both peak seasons cause changes in the TCs activity (frequency, intensity, and genesis) over the Arabian Sea. The increased mid-relative humidity and decreased outgoing longwave radiation increased the atmospheric instability, resulting in a favorable condition for TCs activity. The results of this study can provide decision-makers with a better understanding of developing risk assessment strategies for the coastal areas in the Arabian Sea.

4. Conclusions

The current work utilizes both the RSMC-IMD dataset and the NCEP-NCAR reanalysis data to produce long-term climate science data on the Arabian Sea TCs, including their frequency, intensity, and origins, for the years 1982–2021. By analyzing SST, RH-500 hPa, VWS, and OLR over the Arabian Sea, this study also aimed to examine the interaction between the TCs and their large-scale conditions and environmental factors. It demonstrates that the combination of dynamic conditions and hydrothermal conditions leads to seasonal, yearly, and decadal variations in the TCs' activity over the Arabian Sea. There was an asymmetry in the bimodal distribution of TCs over the Arabian Sea, with two peaks. The highest peak occurs during the post-monsoon season, and the other one occurs during the pre-monsoon season. The Arabian Sea created a total of 87 TCs, with an average of 2.18 per year. During the post-monsoon season, more frequent TCs are found than in the pre-monsoon season. According to the decadal trend of TCs activity across the Arabian Sea, the frequency has been increasing in DE3 and especially in DE4.

The results have demonstrated that the eastern side of the Arabian Sea (right to 63 degrees east) comprises the most favorable places for the genesis of the two active seasons in DE1 and DE2. This is due to increased convection on the eastern side of the basin. Over the last two decades, there has been a significant increase in the positive RH and negative OLR anomalies over the Arabian Sea (Figures 10 and 11). This expansion has led to an increase in TC activity, particularly in DE4. The meridional distribution highlighted the difference between the two seasons. During the post-monsoon period, there was a discernible trend to originate below 15 degrees north latitude, particularly in the most recent decade (DE4). On the other hand, during the pre-monsoon period, the meridional distribution was approximately equal above and below 15 degrees north.

As a result of relatively high VWS and moderate OLR and RH, the composite analysis demonstrates that there were fewer TCs during the pre-monsoon season in comparison to the post-monsoon season. The third and fourth decades of the post-monsoon season show an increase in the number of tropical storms that developed in the south and southwest of the Arabian Sea as compared to the first twenty years. Strong OLR and RH, as well as declining VWS over the Arabian Sea, explain this. The SST does not appear to be a crucial factor in the changes observed in the activity of the TCs of two mean seasons and four decades across the basin. This is because the climatological mean SST over the Arabian Sea is quite high. This outcome is somewhat different from earlier results showing only one factor, such as RH or VWS, to be more significant [26,68]. This is mostly due to our focus on evaluating changes in TCs activity in the Arabian Sea and analyzing seasonal, yearly, and decadal characteristics. As a result, we acquired and highlighted joint initiatives based on critical environmental criteria. Furthermore, we demonstrated that the activity of TCs and related environmental variables varies throughout seasons, years, and decades and may have a relationship with global circulation indices. This is intriguing and warrants additional examination.

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References

1. Riehl, H. *Climate and Weather in the Tropics*; Academic Press: Cambridge, MA, USA, 1979.
2. Tiwari, G.; Rameshan, A.; Kumar, P.; Javed, A.; Mishra, A.K. Understanding the post-monsoon tropical cyclone variability and trend over the Bay of Bengal during the satellite era. *Q. J. R. Meteorol. Soc.* **2021**, *148*, 1–14. [CrossRef]
3. Resio, D.T.; Westerink, J.J. Modeling the physics of storm surges. *Phys. Today* **2008**, *61*, 33–38. [CrossRef]
4. Rathore, L.S.; Mohapatra, M.; Geetha, B. Collaborative mechanism for tropical cyclone monitoring and prediction over north Indian ocean. In *Tropical Cyclone Activity over the North Indian Ocean*; Springer International Publishing: Berlin/Heidelberg, Germany, 2016; pp. 3–27. [CrossRef]
5. Cyclone, R.T. *Report on Cyclonic Disturbances over the North Indian Ocean During 2013*; RSMC: New Delhi, India, 2014; pp. 1–235.
6. IMD. *Extremely Severe Cyclonic Storm, 'Megh' over the Arabian Sea (05–10 November 2015): A Report*; Cyclone Warning Division India Meteorological Department: New Delhi, India, 2015.
7. Dube, S.K.; Jain, I.; Rao, A.D.; Murty, T.S. Storm surge modelling for the Bay of Bengal and Arabian Sea. *Nat. Hazards* **2009**, *51*, 3–27. [CrossRef]
8. Gray, W.M. Global view of the origin of tropical disturbances and storms. *Mon. Weather Rev.* **1968**, *96*, 669–700. [CrossRef]
9. Emanuel, K. 100 Years of Progress in Tropical Cyclone Research. *Meteorol. Monogr.* **2018**, *59*, 15.1–15.68. [CrossRef]
10. Klotzbach, P.J.; Bowen, S.G.; Pielke, R.; Bell, M. Continental U.S. hurricane landfall frequency and associated damage: Observations and future risks. *Bull. Am. Meteorol. Soc.* **2018**, *99*, 1359–1376. [CrossRef]
11. Benedetto, K.M.; Trepanier, J.C. Climatology and spatiotemporal analysis of north atlantic rapidly intensifying hurricanes (1851–2017). *Atmosphere* **2020**, *11*, 291. [CrossRef]
12. Peduzzi, P.; Chatenoux, B.; Dao, H.; De Bono, A.; Herold, C.; Kossin, J.; Mouton, F.; Nordbeck, O. Global trends in tropical cyclone risk. *Nat. Clim. Change* **2012**, *2*, 289–294. [CrossRef]
13. Mendelsohn, R.; Emanuel, K.; Chonabayashi, S.; Bakkensen, L. The impact of climate change on global tropical cyclone damage. *Nat. Clim. Change* **2012**, *2*, 205–209. [CrossRef]
14. Rostami, M.; Zeitlin, V. Influence of condensation and latent heat release upon barotropic and baroclinic instabilities of vortices in a rotating shallow water f-plane model. *Geophys. Astrophys. Fluid Dyn.* **2017**, *111*, 1–31. [CrossRef]
15. Kuo, H.-C.; Williams, R.T.; Chen, J.-H.; Chen, Y.-L. Topographic effects on barotropic vortex motion: No mean flow. *J. Atmos. Sci.* **2001**, *58*, 1310–1327. [CrossRef]
16. Rostami, M.; Zeitlin, V. Evolution, propagation and interactions with topography of hurricane-like vortices in a moist-convective rotating shallow-water model. *J. Fluid Mech.* **2020**, *902*, A24. [CrossRef]
17. Wahiduzzaman, M.; Oliver, E.C.J.; Wotherspoon, S.J.; Holbrook, N.J. A climatological model of North Indian Ocean tropical cyclone genesis, tracks and landfall. *Clim. Dyn.* **2016**, *49*, 2585–2603. [CrossRef]
18. Wahiduzzaman, M.; Cheung, K.; Luo, J.-J.; Bhaskaran, P.K.; Tang, S.; Yuan, C. Impact assessment of Indian Ocean Dipole on the North Indian Ocean tropical cyclone prediction using a Statistical model. *Clim. Dyn.* **2021**, *58*, 1275–1292. [CrossRef]
19. Singh, O.P.; Khan, T.M.A.; Rahman, S. Changes in the frequency of tropical cyclones over the North Indian Ocean. *Meteorol. Atmos. Phys.* **2000**, *75*, 11–20. [CrossRef]
20. Galvin, J.F.P. The weather and climate of the tropics: Part 7—Tropical revolving storms. *Weather* **2008**, *63*, 327–333. [CrossRef]
21. Mohanty, U.C.; Osuri, K.K.; Pattanayak, S.; Sinha, P. An observational perspective on tropical cyclone activity over Indian seas in a warming environment. *Nat. Hazards* **2011**, *63*, 1319–1335. [CrossRef]
22. Pattanaik, D.R. Variability of oceanic and atmospheric conditions during active and inactive periods of storms over the Indian region. *Int. J. Clim.* **2005**, *25*, 1523–1530. [CrossRef]
23. Li, Z.; Yu, W.; Li, K.; Wang, H.; Liu, Y.; Liu, L. Environmental conditions modulating tropical cyclone formation over the Bay of Bengal during the Pre-Monsoon Transition Period. *J. Clim.* **2019**, *32*, 4387–4394. [CrossRef]
24. Mohapatra, M.; Kumar, V.V. Interannual variation of tropical cyclone energy metrics over North Indian Ocean. *Clim. Dyn.* **2016**, *48*, 1431–1445. [CrossRef]
25. Galvin, J.F.P. The weather and climate of the tropics: Part 6—Monsoons. *Weather* **2008**, *63*, 129–137. [CrossRef]

26. Evan, A.T.; Camargo, S.J. A climatology of Arabian Sea cyclonic storms. *J. Clim.* **2011**, *24*, 140–158. [CrossRef]
27. Emanuel, K. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* **2005**, *436*, 686–688. [CrossRef] [PubMed]
28. Goldenberg, S.B.; Landsea, C.W.; Mestas-Nuñez, A.M.; Gray, W.M. The recent increase in Atlantic hurricane activity: Causes and implications. *Science* **2001**, *293*, 474–479. [CrossRef]
29. Webster, P.J.; Holland, G.J.; Curry, J.A.; Chang, H.-R. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* **2005**, *309*, 1844–1846. [CrossRef]
30. Elsner, J.B.; Kossin, J.P.; Jagger, T.H. The increasing intensity of the strongest tropical cyclones. *Nature* **2008**, *455*, 92–95. [CrossRef]
31. Cao, X.; Wu, R.; Bi, M. Contributions of different time-scale variations to tropical cyclogenesis over the western North Pacific. *J. Clim.* **2018**, *31*, 3137–3153. [CrossRef]
32. Cao, X.; Wu, R.; Bi, M.; Lan, X.; Dai, Y.; Zhao, J. Contribution of different time-scale variations to the tropical cyclogenesis environment over the northern tropical Atlantic and comparison with the western North Pacific. *J. Clim.* **2019**, *32*, 6645–6661. [CrossRef]
33. Cao, X.; Wu, R.G.; Feng, J.; Zhang, X.P.; Dai, Y.F. Contrasting contributions of different time scale variations of environmental factors to tropical cyclogenesis over the eastern North Pacific. *Atmos. Sci. Lett.* **2021**, *22*, e1037. [CrossRef]
34. Ng, E.K.W.; Chan, J.C.L. Interannual variations of tropical cyclone activity over the north Indian Ocean. *Int. J. Clim.* **2011**, *32*, 819–830. [CrossRef]
35. Baburaj, P.P.; Abhilash, S.; Mohankumar, K.; Sahai, A.K. On the epochal variability in the frequency of cyclones during the pre-onset and onset phases of the monsoon over the North Indian Ocean. *Adv. Atmos. Sci.* **2020**, *37*, 634–651. [CrossRef]
36. Balaji, M.; Chakraborty, A.; Mandal, M. Changes in tropical cyclone activity in north Indian Ocean during satellite era (1981–2014). *Int. J. Clim.* **2018**, *38*, 2819–2837. [CrossRef]
37. Swapna, P.; Sreeraj, P.; Sandeep, N.; Jyoti, J.; Krishnan, R.; Prajeesh, A.G.; Ayantika, D.C.; Manmeet, S. Increasing frequency of extremely severe cyclonic storms in the North Indian Ocean by anthropogenic warming and southwest monsoon weakening. *Geophys. Res. Lett.* **2022**, *49*, e2021GL094650. [CrossRef]
38. Jangir, B.; Swain, D.; Ghose, S. Influence of eddies and tropical cyclone heat potential on intensity changes of tropical cyclones in the North Indian Ocean. *Adv. Space Res.* **2020**, *68*, 773–786. [CrossRef]
39. Mohapatra, M.; Bandyopadhyay, B.K.; Tyagi, A. Construction and quality of best tracks parameters for study of climate change impact on tropical cyclones over the North Indian Ocean during satellite era. In *Monitoring and Prediction of Tropical Cyclones in the Indian Ocean and Climate Change*; Springer: Berlin/Heidelberg, Germany, 2014; pp. 3–17.
40. Simpkins, G. Arabian Sea cyclone changes. *Nat. Rev. Earth Environ.* **2021**, *2*, 588. [CrossRef]
41. Deshpande, M.; Singh, V.K.; Ganadhi, M.K.; Roxy, M.K.; Emmanuel, R.; Kumar, U. Changing status of tropical cyclones over the north Indian Ocean. *Clim. Dyn.* **2021**, *57*, 3545–3567. [CrossRef]
42. Deo, A.A.; Ganer, D.W.; Nair, G. Tropical cyclone activity in global warming scenario. *Nat. Hazards* **2011**, *59*, 771–786. [CrossRef]
43. Rajeevan, M.; Srinivasan, J.; Kumar, K.N.; Gnanaseelan, C.; Ali, M.M. On the epochal variation of intensity of tropical cyclones in the Arabian Sea. *Atmos. Sci. Lett.* **2013**, *14*, 249–255. [CrossRef]
44. Evan, A.T.; Kossin, J.P.; Chung, C.E.; Ramanathan, V. Arabian Sea tropical cyclones intensified by emissions of black carbon and other aerosols. *Nature* **2011**, *479*, 94–97. [CrossRef]
45. Xu, J.; Wang, Y.; Tan, Z.-M. The relationship between sea surface temperature and maximum intensification rate of tropical cyclones in the North Atlantic. *J. Atmos. Sci.* **2016**, *73*, 4979–4988. [CrossRef]
46. Whitney, L.D.; Hobgood, J.S. The relationship between sea surface temperatures and maximum intensities of tropical cyclones in the eastern North Pacific Ocean. *J. Clim.* **1997**, *10*, 2921–2930. [CrossRef]
47. Yu, J.; Lv, H.; Tan, S.; Wang, Y. Tropical Cyclone-Induced Sea Surface Temperature Responses in the Northern Indian Ocean. *J. Mar. Sci. Eng.* **2023**, *11*, 2196. [CrossRef]
48. Kaplan, J.; DeMaria, M.; Knaff, J.A. A revised tropical cyclone rapid Intensification index for the Atlantic and eastern North Pacific basins. *Weather Forecast.* **2010**, *25*, 220–241. [CrossRef]
49. Hendricks, E.A.; Peng, M.S.; Fu, B.; Li, T. Quantifying environmental control on tropical cyclone intensity change. *Mon. Weather Rev.* **2010**, *138*, 3243–3271. [CrossRef]
50. Wu, L.; Su, H.; Fovell, R.G.; Wang, B.; Shen, J.T.; Kahn, B.H.; Hristova-Veleva, S.M.; Lambrigtsen, B.H.; Fetzer, E.J.; Jiang, J.H. Relationship of environmental relative humidity with North Atlantic tropical cyclone intensity and intensification rate. *Geophys. Res. Lett.* **2012**, *39*, L20809. [CrossRef]
51. Park, M.-S.; Elsberry, R.L.; Harr, P.A. Vertical wind shear and ocean heat content as environmental modulators of western North Pacific tropical cyclone intensification and decay. *Trop. Cyclone Res. Rev.* **2012**, *1*, 448–457.
52. Zeng, Z.; Wang, Y.; Wu, C.-C. Environmental dynamical control of tropical cyclone intensity—An observational study. *Mon. Weather Rev.* **2007**, *135*, 38–59. [CrossRef]
53. Zeng, Z.; Chen, L.; Wang, Y. An observational study of environmental dynamical control of tropical cyclone intensity in the Atlantic. *Mon. Weather Rev.* **2008**, *136*, 3307–3322. [CrossRef]
54. Mohapatra, M.; Bandyopadhyay, B.K.; Tyagi, A. Best track parameters of tropical cyclones over the North Indian Ocean: A review. *Nat. Hazards* **2011**, *63*, 1285–1317. [CrossRef]
55. Raghavan, S. Observational aspects including weather radar for tropical cyclone monitoring. *Mausam* **2013**, *64*, 89–96. [CrossRef]
56. Raghavan, S. Radar observations of tropical cyclones over the Indian Seas. *Mausam* **1997**, *48*, 169–188. [CrossRef]

57. RSMC. Available online: https://rsmcnewdelhi.imd.gov.in/ (accessed on 22 May 2024).
58. Bhatla, R.; Raj, R.; Singh, M. Climatology of recurvature of tropical cyclone over Bay of Bengal and Arabian Sea. *Mausam* **2018**, *69*, 437–442. [CrossRef]
59. Monthly/Seasonal Composites: NOAA Physical Sciences Laboratory. Available online: https://psl.noaa.gov/cgi-bin/data/composites/printpage.pl (accessed on 22 May 2024).
60. Rao, D.V.B.; Srinivas, D.; Satyanarayana, G.C. Trends in the genesis and landfall locations of tropical cyclones over the Bay of Bengal in the current global warming era. *J. Earth Syst. Sci.* **2019**, *128*, 194. [CrossRef]
61. Mahala, B.K.; Nayak, B.K.; Mohanty, P.K. Impacts of ENSO and IOD on tropical cyclone activity in the Bay of Bengal. *Nat. Hazards* **2014**, *75*, 1105–1125. [CrossRef]
62. Li, Z.; Yu, W.; Li, T.; Murty, V.S.N.; Tangang, F. Bimodal character of cyclone climatology in the Bay of Bengal modulated by monsoon seasonal cycle. *J. Clim.* **2013**, *26*, 1033–1046. [CrossRef]
63. Wang, B.; Xu, S.; Wu, L. Intensified Arabian Sea tropical storms. *Nature* **2012**, *489*, E1–E2. [CrossRef]
64. Murakami, H.; Vecchi, G.A.; Underwood, S. Increasing frequency of extremely severe cyclonic storms over the Arabian Sea. *Nat. Clim. Change* **2017**, *7*, 885–889. [CrossRef]
65. Camargo, S.J.; Emanuel, K.A.; Sobel, A.H. Use of a genesis potential index to diagnose ENSO effects on tropical cyclone genesis. *J. Clim.* **2007**, *20*, 4819–4834. [CrossRef]
66. Singh, V.K.; Roxy, M. A review of ocean-atmosphere interactions during tropical cyclones in the north Indian Ocean. *Earth-Sci. Rev.* **2022**, *226*, 103967. [CrossRef]
67. Gray, W.M. Hurricanes: Their formation, structure and likely role in the tropical circulation. In *Meteorology over the Tropical Oceans*; Royal Meteorological Society: Reading, UK, 1979; pp. 155–218.
68. DeMaria, M. The effect of vertical shear on tropical cyclone intensity change. *J. Atmos. Sci.* **1996**, *53*, 2076–2088. [CrossRef]