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Distribution characteristics of tropical cyclones affecting the Vietnam region during 1992–2022

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ABSTRACT

This research investigates the distribution characteristics of tropical cyclones affecting the Vietnam region, including the mainland and the East Vietnam Sea, from 1992 to 2022. The tropical cyclone activity showed an increasing trend, mainly in the numbers of tropical depressions and typhoons with the sustained maximum wind speed ranging from level 12 to 15 on the Beaufort Wind Scale; however, this trend did not meet the statistical 99% confidence level. The number of tropical cyclones directly affecting the mainland of Vietnam accounted for approximately 32%. Over the East Vietnam Sea, tropical cyclones presented a peak in September and a slump in February. Occurrence frequencies and probabilities were significantly high over the in-shore and off-shore regions from Quang Ninh to Phu Yen, over the North and Center of East Vietnam Sea, where the maximum frequencies could be 0.9 tropical cyclone/year over the Gulf of Tonkin higher than 1.1 tropical cyclone/year passing a grid of 1^{o} longitude-latitude over the north East Vietnam Sea. Meanwhile, the southern offshore areas from Phu Yen - Ca Mau, Ca Mau - Kien Giang, and Thailand Gulf were less influenced by tropical cyclones. The frequency and probability of typhoons were below 0.1 tropical cyclone/year and 0.2%, respectively.

Keywords: Distribution of tropical cyclones, East Vietnam Sea, Vietnam.

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INTRODUCTION

Tropical cyclones (TC) are recognized as one of the most significant natural hazards, capable of causing substantial impact to the environment and human life, particularly over vulnerable coastal regions such as Vietnam. The East Vietnam Sea (EVS), surrounded by densely populated countries and boasting a vibrant maritime activity, is located Northwest of the Pacific Ocean, generating the highest number of tropical cyclones, averaging about 30 cyclones annually [1]. Approximately one-third of these cyclones might affect the EVS [2], underscoring the potential for significant impact.

Moreover, with its high sea-surface temperature, the EVS provides a conductive environment for storm formation and development. Approximately 60% of tropical and 25% of severe tropical storms remain their strengths when passing from the Northwestern Pacific Ocean to the EVS. Nga, D. H. et al., [3] demonstrates that the Northern EVS region has observed tropical storms more frequently in summer than its Southern parts, where the storm season occurs later and weaker. In terms of impacts on the mainland Vietnam region, TCs directly affect the coastal provinces from Quang Ninh to Ha Tinh the most (about 6–8 TCs per year), then reduce by half over the area of Quang Binh - Binh Thuan (nearly 3–5 TCs per year) and finally decrease to less than 3 TCs making landfall in the Southern Vietnam region [4]. Hang, V. T. et al., [5] demonstrated the frequency of tropical cyclones within a grid of 2.5^{o} longitude-latitude, which reaches the highest number of 3 TCs in the middle of northern EVS region, then reduces to about 1.5 TCs when approaching the coast and especially only 0.5 TC over the southern coastal area.

Some studies claimed an increasing number of tropical storms (TSs) over the near-shore Vietnam region, particularly regions belonging to Da Nang - Binh Thuan during 1945–2007 [5]; in contrast, an opposite trend in TS activities over the EVS and TSs making landfall over Vietnam was seen in 1961–2010 [6], 1949–2014 [7]. Wu, L. et al., [8] proved that TSs tended to move more westwardly due to the intensified westward migration of the subtropical Pacific High in 1963–2003 when the number of TSs passing to the EVS, on the other hand, showed a decreasing trend. According to [9], there are nearly 12–13 TCs active over the EVS annually, consisting of 4–5 TCs making landfall in Vietnam (accounting for 38–40%). The highest numbers of TCs active over the EVS (about 2 TCs), and TCs making landfall (around 1 TC) are observed in September. A slight increase of 4.2% was found in 1991–2020, compared to the earlier time from 1961–1990, in which a rise was seen mainly in the number of tropical depressions in December.

In addition, the sixth report of the IPCC proposed that climate change is causing drastic changes in atmospheric factors and circulation, resulting in a large variation and complexity of tropical cyclones, which makes many challenging to predict [10]. Therefore, it is essential to continuously analyze and acknowledge the characteristics of tropical cyclones to improve the predictability and adaptability to natural disasters, emphasizing the ongoing need for research and monitoring in this critical area.

Vietnam's coastal areas have a high potential for energy exploitation and play a huge role in implementing Vietnam's commitments on climate change. Among them, offshore wind is a renewable energy resource with great development potential, especially offshore wind farms in large ocean areas that can generate much more electricity because wind over the ocean is often stronger and more stable than one over land. Building electricity development plans and related transmitter power outputs for every region and sub-region requires a thorough implementation, particularly in terms of assessing energy development potential as well as variation, risks, and impacts on areas with potential for wind exploitation, including factors regarding natural hazards such as tropical storms, strong wind, thunderstorms, lightning, and severe ocean currents which need to be updated regularly to provide information for proper construction and operation plan.

This study will be based on best-track datasets from international to local organizations to analyze statistical characteristics of trajectories, frequencies, and probabilities of tropical cyclones calculated for a 1-degree longitude-latitude grid (approximately 100 km) in

offshore, inshore and over the mainland of Vietnam. The obtained results will contribute to a better understanding of tropical cyclone activities and assist in determining and evaluating their impacts to assess risks related to natural hazards, mainly tropical cyclones in Vietnam and surrounding areas.

DATASETS AND METHODS

Datasets

The best-track dataset, which consists of information related to tropical cyclones, is collected and calibrated from the real-time observation after the monitoring period finishes or the tropical storm or tropical depression (after this, referred to as TC) season ends. The calibration is processed for TC center position, intensity, and wind structure based on analyzing more carefully other products, such as observation from satellites, radars, buoys, numerical prediction products to eliminate or correct errors that might occur during the rush of real-time monitoring. Therefore, this dataset is considered a reliable source of information for studying the characteristics of TCs.

Because TC's position and intensity are determined based on measurements and estimates from observation and calculation, those properties are about to change and differ over time and between agencies/institutes. Specifically, the location of TC is identified with a spatial resolution of 0.1^{o} (approximately 10 km); however, uncertainties will be raised along with intensities, particularly in the case of weak TC when its center is not clear [11]. The intensity of a TC is determined by the maximum sustained surface wind speed within the TC circulation. According to meteorological standards, surface wind is observed (or estimated) at a height of 10m over an open area, not blocked by high buildings or trees. However, the determining standard for wind also diverges between centers around the world, such as the National Oceanic and Atmospheric Administration (NOAA) or the Joint Typhoon Warning Center (JTWC) (USA) take the average wind speed in 1 minute while the others including the Tokyo Regional Specialized Meteorological Center (RSMC) and the Australian Meteorological Agency calculate during 10 minutes. As a result, many concerns can cause TC information to vary between datasets.

This study will use a variety of popular best-track datasets from major centers, such as the Joint Typhoon Warning Center (JTWC), Tokyo Regional Specialized Meteorological Center - Typhoon Center (RSMC), the International Best Track Archive Climate Stewardship (IBTrACS) developed by the United States Atmospheric and Oceanic Administration. Information is collected from https://www.metoc.navy.mil/jtwc/jtwc.html?best-tracks for the JTWC dataset, https://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/besttrack.html for the RSMC dataset, and https://www.ncei.noaa.gov/data/international-best-track-archive-for-clima-te-stewardship-ibtracs/v04r00/access/csv/ for IBTrACS.

In addition, as the study aims to evaluate the impact of natural hazards on Vietnam's sea and land areas, the best-track dataset of the National Center for Hydro-Meteorological Forecasting (NCHMF), the Vietnam Meteorology Hydrology Administration (VNMHA) is also collected and prioritized to use because this operational dataset provides more precise information in the Vietnam region than the others by dint of a dense monitoring network of satellite, radar, buoy and surface observation covering the whole country. The NCHMF is responsible for monitoring, synthesizing, and reporting on hydro-meteorological characteristics, including tropical cyclone activities affecting the Vietnam region. The best-track dataset has been digitalized since 1961, consisting of information on the status and forecast of every TC active within the Vietnam area. Compared to JTWC and RSMC datasets, the best-track of the NCHMF not only includes tropical storms (which have a maximum sustained wind higher or equal to 17.2 m/s) but also tropical depressions (which have Force 6–7 based on the Beaufort Scale, identified within 2 minutes) locating near or over the EVS, inshore or inland of Vietnam. Henceforward, this dataset is abbreviated as "TCVN" within this study.

Methods

Data play as a critical role in research, then it is essential to collect and analyze carefully to ensure the accuracy and reliability of obtaining results. All required TC information (consisting of the longitude and latitude of the center location, the maximum sustained wind speed, and minimum pressure at the center) is accumulated and then pre-processed to obtain a uniform structure for in-depth analysis. Besides, the time serial data must cover long enough, at least 30 years, to represent climate characteristics. After that, it will be used to calculate the statistical properties of frequency and probability of TCs affecting the Vietnam region, including TCs formed either over the EVS or in the Pacific Ocean then moved to the EVS.

Table 1. The Beaufort wind scale

Beaufort Force	Wind Speed		
	$m.s^{-1}$	$Km.h^{-1}$	knots (kts)
0	0–0.2	0–1	0–1
1	0.3–1.5	1–5	1–3
2	1.6–3.3	6–11	4–6
3	3.4–5.4	12–19	7–10
4	5.5–7.9	20–28	11–16
5	8.0–10.7	29–38	17–21
6	10.8–13.8	39–49	22–27
7	13.9–17.1	50–61	28–33
8	17.2–20.7	62–74	34–40
9	20.8–24.4	75–88	41–47
10	24.5–28.4	89–102	48–55
11	28.5–32.6	103–117	56–63
12	32.7–36.9	118–133	64–71
13	37.0–41.4	134–149	72–80
14	41.5–46.1	150–166	81–89
15	46.2–50.9	167–183	90–99
16	51.0–56.0	184–201	100–108
17	56.1–61.1	202–220	109–118

The frequency and probability are calculated on grids with the resolution of 1^{o} (approximately 100 km) longitude×latitude based on the trajectories of TCs. The total number of TCs is interpolated to the nearest grid point by considering the intensity of TCs falling within the grid. Note that although a TC can be observed multiple times in a grid, it is still counted as only 1 TC.

The Theil-Sen slope illustrates the variability in the numbers of TCs during the studied period, and the Man-Kendall index represents the level of statistical confidence [12, 13].

The Beaufort Scale was first made by an Irish naval officer-hydrologist named Francis Beaufort in 1805. After many modifications to suit the reality, this wind scale has been approved by the World Meteorological Organization (WMO) and is being used in many countries globally. According to the 2015 Law on Hydrometeorology and Decision No. 18/2021/QD-TTg [14] of the Prime Minister, wind and wave over Vietnam are classified into 18 levels, from 0 to 17, based on the Beaufort Scale (Table 1). This study also relies on this scale to identify frequencies and probabilities for all TC classes, which are Tropical Depression (TD - the maximum sustained wind speed below 33 knots), Tropical Storm (TS89 - the maximum sustained wind speed belongs to 34–47 knots), Severe Tropical Storm (TS1011 - the maximum sustained wind speed belongs to 48–63 knots), Typhoon (TS1215 - the maximum sustained wind speed belongs to 64–99 knots),

and Super Typhoon (TS16 - the maximum sustained wind speed exceeds 100 knots). Within the scope of this study, tropical storms refer to tropical cyclones, which have a maximum sustained wind higher or equal to 34 knots, and tropical depressions, which have a maximum sustained wind below 33 knots.

RESULTS AND DISCUSSION

Characteristics of tropical cyclone activities over the EVS during 1992–2022

Trajectories of TCs over the EVS show a distinct seasonal variability. In the summer, TCs tend to move northwest and often land in China. In the autumn and winter, TCs' directions gradually shift west to southwest and enter the Vietnam mainland areas.

According to the NCHMF's statistics, from 1992 to 2022, there were 406 TCs active over the EVS, consisting of 129 TDs and 277 TSs. Among 277 TSs, there are 111, 75, 89 cases belonging to TS89, TS1011, and TS1215, respectively, only 2 super typhoons with a maximum sustained wind speed exceeding 100 knots, as shown in Fig. 1.

The various studied datasets present similar trajectories of TCs that passed over the EVS and affected the Vietnam region; however, differ in the starting and ending locations.

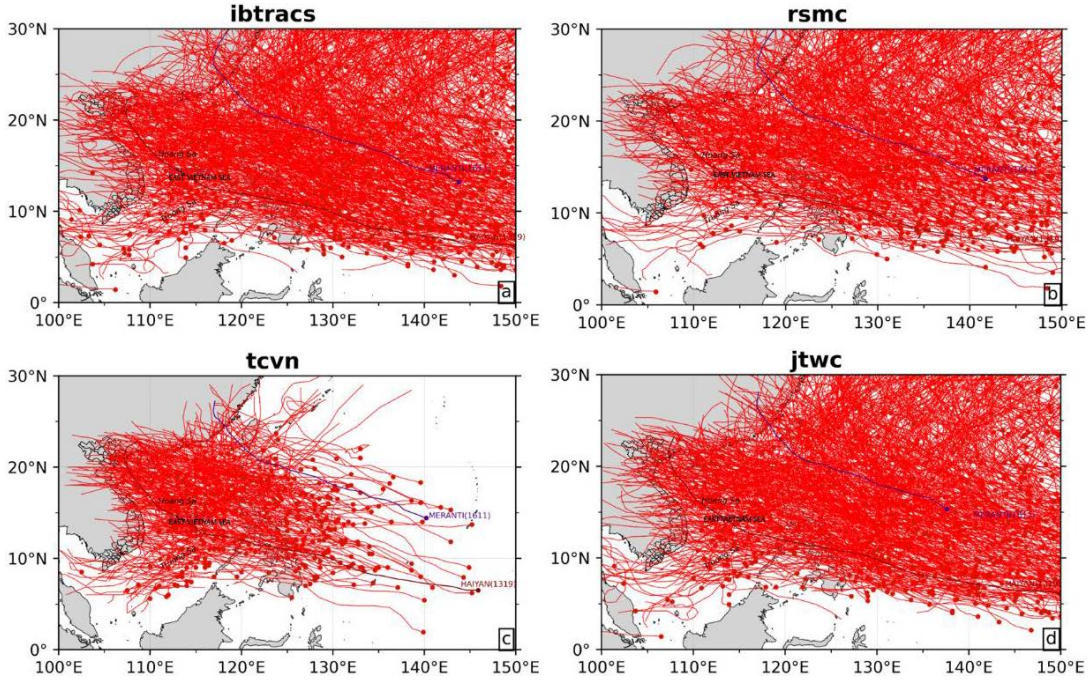

Figure 1. Best tracks of tropical cyclones affecting the Vietnam region during 1992–2022 analyzed from the IBTrACS (a), RSMC (b), TCVN (c) and JTWC (d) dataset. The first position of each tropical cyclone is marked with a green dot. Two typhoons with a maximum sustained wind higher or equal to the force 16 Beaufort Scale over the East Vietnam Sea are shown in violet and brown for MERANTI (1611) and HAIYAN (1319), respectively

As mentioned in section 2, the three datasets, including IBTrACS, JTWC, and RSMC, contain information on all TCs active in the Northwest Pacific region, with the JTWC dataset only containing tropical storms with maximum sustained wind of at least 35 knots or more. On the other hand, the TCVN mainly consists of TCs active over the EVS and ones formed in the Pacific and have a high potential to move to the EVS. Therefore, in the Northwest Pacific Ocean, the number of TCs in the IBTrACS, JWTC, and RSMC datasets is much higher than in the TCVN

dataset. Although these datasets are similar for tropical storms over the EVS, the TCVN dataset also includes tropical depressions over this sea. In addition, Song, J. J. et al., [15] also pointed out that though trajectories of tropical storms are similar between the JTWC and RSMC datasets, there might be discrepancies when considering the activity trend of TCs over the Northwest Pacific region because of dissimilar intensity analysis.

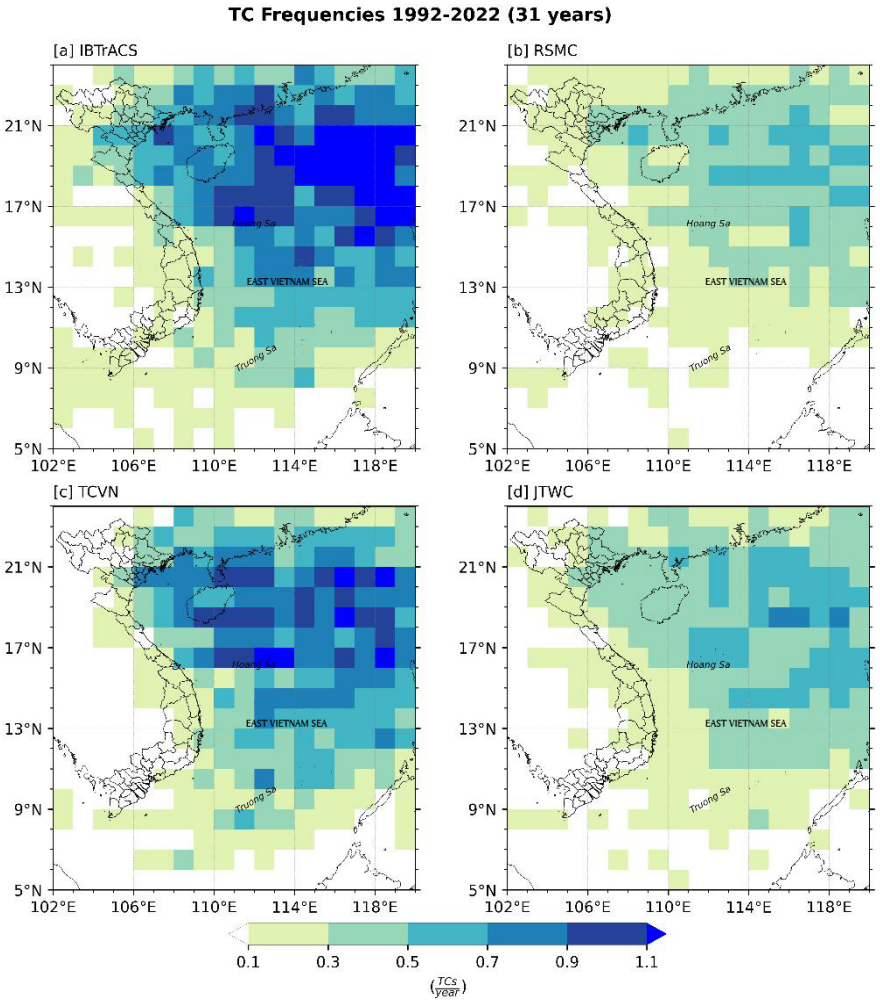

Figure 2. Frequencies of tropical cyclones over the Viet Nam East Sea during 1992–2022 analyzed from IBTrACS (a), RSMC Tokyo (b), TCVN (c) and JTWC (d)

The frequency analysis of TC activities over the EVS (Fig. 2) presents the differences between datasets used in this study. Despite high frequencies of TC activities over the north and center of the EVS, the calculated numbers still differ with a higher or equal to 1.1 TC/1° grid frequencies, showing the most in the IBTrACS, followed by the TCVN, JTWC, and RSMC, subsequently. Additionally, since the TCVN also consists of tropical depressions, the frequencies of TCs affecting the coastal region of Vietnam are higher than in the TCVN than those in the remaining datasets, to be specific, frequencies over the Gulf of Tonkin, coastal regions of the Northeast and Northern Delta region vary from 0.7–1.1 TCs/1° grid. (The distribution map of land and sea for the Vietnam region can be obtained from the official website of the NCHMF https://thoitietvietnam.gov.vn/Kttv/vi-VN/1/index.html).

To investigate the statistical characteristics of tropical cyclones affecting the Vietnam region, serving the assessment of natural disaster risks, further analysis will prioritize the best-track dataset of the NCHMF, also known as the TCVN dataset within the scope of this article.

Based on the statistical analysis for 31 years from 1992 to 2002 (Fig. 3), on average, there are approximately 13 TCs active over the EVS, consisting of 9 tropical storms and 4 tropical depressions. 1994, 1999, 2008, 2011, 2013, 2016, 2017, 2018, and 2020 witnessed more TCs than the average, especially in 2017 with a history record of 25 TCs over the EVS. On the other hand, there have been several years with the total annual TCs below 10, for instance, 1997, which had only 6 TCs.

During the studied period, increasing trends with slopes of 0.03–0.04 TC/31 years are seen in the number of tropical depressions and tropical storms. In addition, in terms of tropical storms, the rise mainly occurs in the case of TS12-15, while the other classes have slight fluctuation. Since the "pvalue" suggests that the significant level of statistical analysis does not meet the 90% confidence level despite increasing trends in quantities of tropical depressions and typhoons, it is necessary to study further to assure about these tendencies.

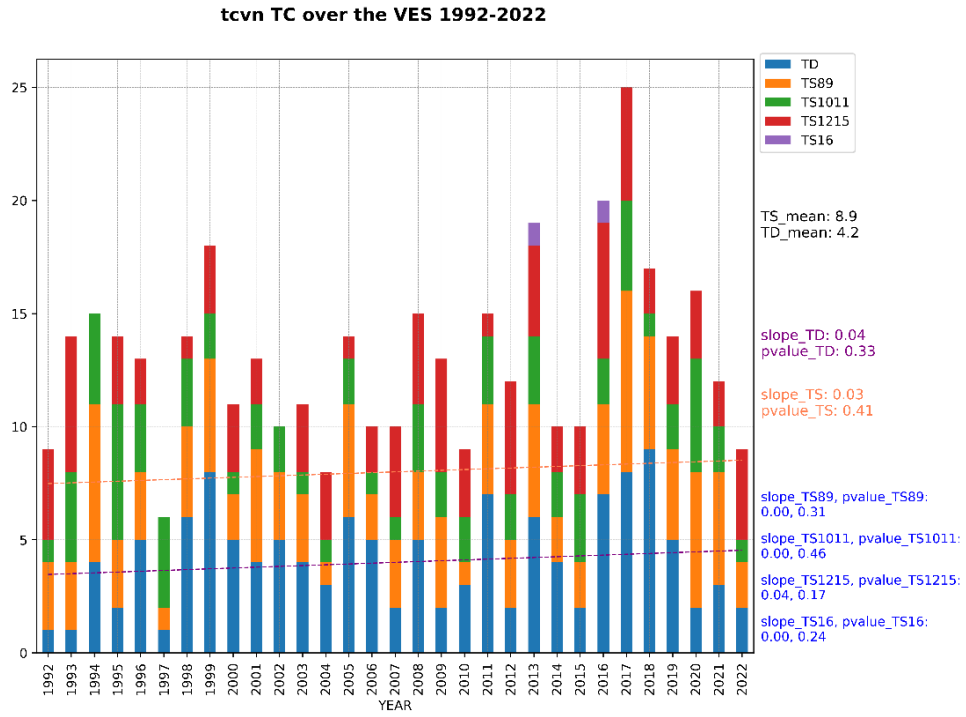

Figure 3. Annual Numbers of Tropical Depression (TD), Tropical Storm Force 8–9 (TS89), Severe Tropical Storm Force 10–11 (TS1011), Typhoons Force 12–15 (TS1215), và Super Typhoons Force 16 or higher (TS16) based on the Beaufort Scale active over the EVS during 1992–2022. TS_mean and TD_mean respectively represent the calculated average of tropical storms and tropical depressions. "slope" and "pvalue" suggest the statistical trend and significant level based on the Theil Sen-Kendall methodology

Of the 406 TCs mentioned above, 130 TCs make landfall in Vietnam, accounting for about 32%. Most of them directly affect the Northern region and Thanh Hoa - Nghe An provinces in the early tropical storm season (from June to August), then expand the impacting location to Ha Tinh - Quang Ngai and the Central Highland region (from September to November). From December to January, TCs impact mostly to Binh Dinh - Binh Thuan and the Southern

region; however, they rarely make landfall in February and March (not shown in Figure). Hence, these trajectories of TCs still follow well with climatological characteristics.

A monthly analysis also reveals out a normal tropical cyclone movement compared to climate (not shown in Figure). From June to September, TCs usually move as a parabola from the center of the Philippines to the EVS, then shift northwestwardly to the North of Vietnam, China or even turn eastward to the Pacific Ocean again because of the steering flow from the western Pacific sub-tropical ridge. During wintertime, from October to February, going align with the southward migration of the intertropical convergence zone (ITCZ) and the influence of cold surge, TCs often move towards the west-northwest to west, even Southwest to the South EVS or Gulf of Thailand in January or February.

There are the least number of TCs active over the Northwestern Pacific and EVS in February and March (Fig. 4), before a soar in June and the following months until October, then a drop since November. On average, from June to December, more than one TC appears per month, of which the most occurrence is 2.2 TCs in September, followed by August and October with 2.1 TCs. From January to May, the quantity reduces to under 0.5 TCs. Typhoons with the maximum sustained wind force of 12–15 Beaufort only happen from April to December, while super typhoons with wind speeds of force 16 or higher are observed in September and November over the EVS.

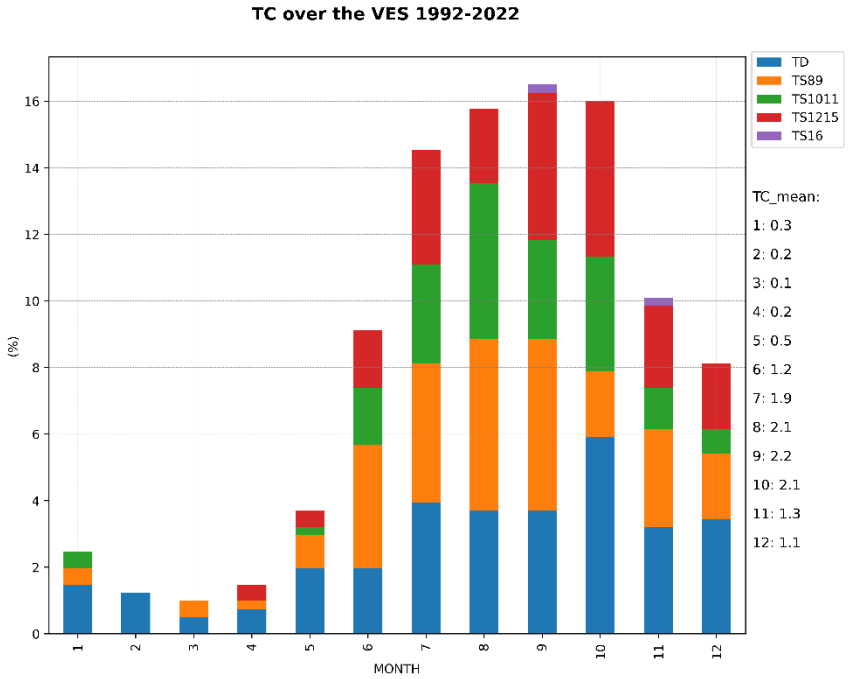

Figure 4. Percentage of Tropical Depression (TD), Tropical Storm Force 8–9 (TS89), Severe Tropical Storm Force 10–11 (TS1011), Typhoons Force 12–15 (TS1215), và Super Typhoons Force 16 or higher (TS16) active over the EVS during 1992–2022 based on monthly analysis. TC_mean represents the calculated average of tropical cyclones by month

Frequency distribution of tropical cyclones over the East Vietnam Sea according to the tropical cyclone classification

Frequency of tropical depression (TD)

Frequency analysis of tropical depressions (the maximum sustained wind speed from 22–33 kts, or 39–61 km.h^{-1}) over the EVS and mainland of Vietnam shows the highest amount of 0.6 TC/year appears to the Northeast of the

Hoang-Sa archipelago. Moreover, tropical depressions are highly active over the North and the Center of EVS from the 110°E meridian outward (0.3–0.6 TC/year). A lesser frequency is witnessed over the South of EVS with no more than 0.4 TCs/year (Fig. 5).

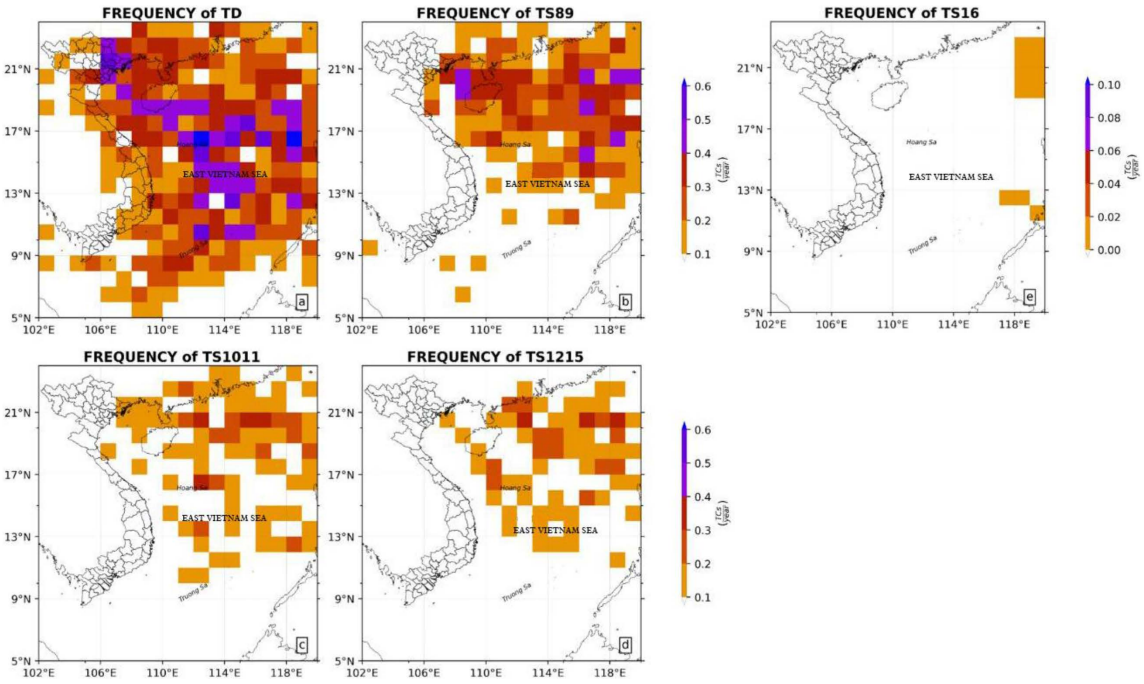

Figure 5. Frequency of Tropical Depression (TD), Tropical Storm Force 8–9 (TS89), Severe Tropical Storm Force 10–11 (TS1011), Typhoons Force 12–15 (TS1215), và Super Typhoons Force 16 or higher (TS16) during 1992–2022 affecting to the Vietnam region analyzed from the TCVN dataset

Regarding the influence on land and onshore regions, the frequency reduces significantly from Binh Thuan to the South. However, it presents the highest over the Northeast, including the Northern Delta region, while the remaining places vary in the 0.1–0.4 TC/year range.

Frequency of tropical storm force 8–9 (TS89)

Accounting for 40% of the number of TCs affecting the Vietnam region during 1992–2022, tropical storms force 8–9 tend to pass mostly over the northern EVS region with a common frequency of 0.2–0.4 TC/year, and higher numbers up to 0.6 TC/year found to the north of latitude 18°N and east of this area. TC activities are remarkably less than 0.2 TCs/year, appearing from the center to the south of EVS.

It is worth noting that the Gulf of Tonkin also received a high number of TS8-9 with a frequency of 0.4–0.6 TC/year.

In terms of distance to the mainland, the subsequent rank goes to the coastal and offshore region from Quang Ninh to Thua Thien Hue, which are affected by TS8-9 the most with a frequency of 0.2–0.4 TC/year. This is followed by a frequency of under 0.1 TC/year over the southern seas from Da Nang - Binh Thuan and Binh Thuan - Ca Mau.

Frequency of severe tropical storm force 10–11 (TS1011)

Tropical cyclones with the maximum sustained wind reaching 48–63 kts (force 10–11 Beaufort Scale) are classified as severe storms that can break trees, houses, electric poles and cause violent seas with over 9.0-meter wave height. A high frequency of TS1011 with a popular number of 0.2–0.4 TC/year is shown over the North of EVS where the largest up to 0.5 TC/year is found in the area from 20–

21°N, 112–116°E. The center of EVS is suffered approximately 0.1–0.3 TC/year, meanwhile only less than 0.1 TC/year affects the south of latitude 10°N, consisting of the Southern EVS region.

Gulf of Tonkin and offshore regions from Quang Ninh - Thanh Hoa are suffered from TS1011 the most with 0.1–0.3 TC/year, compared with the other coastal and offshore regions of Vietnam. TS1011 also affects the coast from Nghe An - Ha Tinh and Quang Nam - Quang Ngai but with a smaller frequency of below 0.2 TC/year. The remaining coastal regions are insignificantly affected by TS1011.

Frequency of typhoon force 12–15 (TS1215)

Tropical cyclones that produce the maximum sustained wind speed force 12–15 (64–99 kts) are considered as typhoons with destructive power and the ability to sink large ships. In the EVS, TS1215 occurs predominantly over the north and the center with frequency ranging from 0.1–0.3 TC/year, except north of latitude 20°N where the frequency can reach 0.4 TC/year as illustrated in Fig. 5.

During 1992–2022, there were several typhoon affecting directly to the mainland of Vietnam with the maximum sustained wind being force 12–13, such as Typhoon KYLE (known as Tropical Storm No. 10 in Vietnam) in 1993, Typhoon NIKI (known as Tropical Storm No. 4 in Vietnam) in 1996, and Typhoon Doksuri (known as Tropical Storm No. 10 in Vietnam) in 2017 subsequently caused mighty wind to areas of Binh Dinh - Phu Yen, the Northern Delta - Thanh Hoa, Ha Tinh - Quang Binh. This study finds out that there are approximately 0.2 TS1215 influence coastal and offshore regions from Quang Ninh - Thanh Hoa, Nghe An - Quang Binh, and Da Nang - Binh Dinh annually, while the rest of the regions suffer under 0.1 TC/year.

Frequency of super typhoon force 16 or higher (TS16)

The statistical analysis shows that 2 tropical cyclones were formed in the Pacific, then moved to the EVS and still have the maximum sustained wind force of 16 (100 knots) or higher, namely Super Typhoon HAIYAN (1319 - referring to Tropical Storm No. 14 in 2013 in Vietnam) and Super Typhoon MERANTI (1611 - referring to Tropical Storm No.5 in 2016 in Vietnam).

Super Typhoon HAIYAN reached a wind speed of 125 kts over the Pacific Ocean and reduced to 100 knots when crossing the longitude 120°E to the EVS, however, it just kept this intensity for 6 hours from 2013110815 to 2013110821 UTC, then became weaker. Super Typhoon MERANTI recorded the wind speed of 120 kts near the EVS, then decreased to 110 kts when entering the EVS, and in 6 hours later, dropped significantly to 95 kts (force 15 Beaufort Scale). While the impacted region caused by Super Typhoon MERANTI concentrated in the northeast EVS and southeast China, Super Typhoon HAIYAN moved west-northwest to the northwest towards the center EVS and then made landfall in Quang Ninh - Thai Binh over the northern Vietnam region.

These two super typhoons mentioned above just kept violent intensities over force 16 in a short time period, then reduced over the EVS. Hence, the frequency of TS16 over the EVS is meager, and mostly appears to the Northest of northern EVS and the surrounding area (12–13°N, 117–120°E).

Probability distribution of tropical cyclones over the East Vietnam Sea according to the tropical cyclone classification

Probability of tropical depression (TD)

The probability of TD occurrence is distributed sparsely over EVS and Vietnam's coastal regions. A probability higher than 5.2% occurs to the northeast of Hoang Sa Islands. The area that lasts along the latitude 17°N and longitude from 113–118°E also receives remarkable probabilities, varying from 4.2–5.2%. Overall, the probability of TD over the north and center EVS averages around 1.2–3.2%; in contrast, the south EVS has a smaller quantity not exceeding 2.2% (Fig. 6).

When accounting for the coastal areas, the highest portion belongs to the Gulf of Tonkin

and Quang Ninh - Thanh Hoa, with the range fluctuating between 2.2 and 3.2%. Notably, the inland regions that belong to the Nothern Delta and Northeast Vietnam also have a significant probability of TD (3.2–4.2%).

Coastal regions from Nghe An - Thua Thien-Hue and Da Nang - Binh Thuan have a popular probability of 0.2–2.2%, except the offshore regions of Thua Thien-Hue and Khanh Hoa are affected by TC with a higher probability of 3.2%.

The probability of TD impact on the coastal region from Binh Thuan - Ca Mau and Ca Mau - Kien Giang is small, under 2.2%.

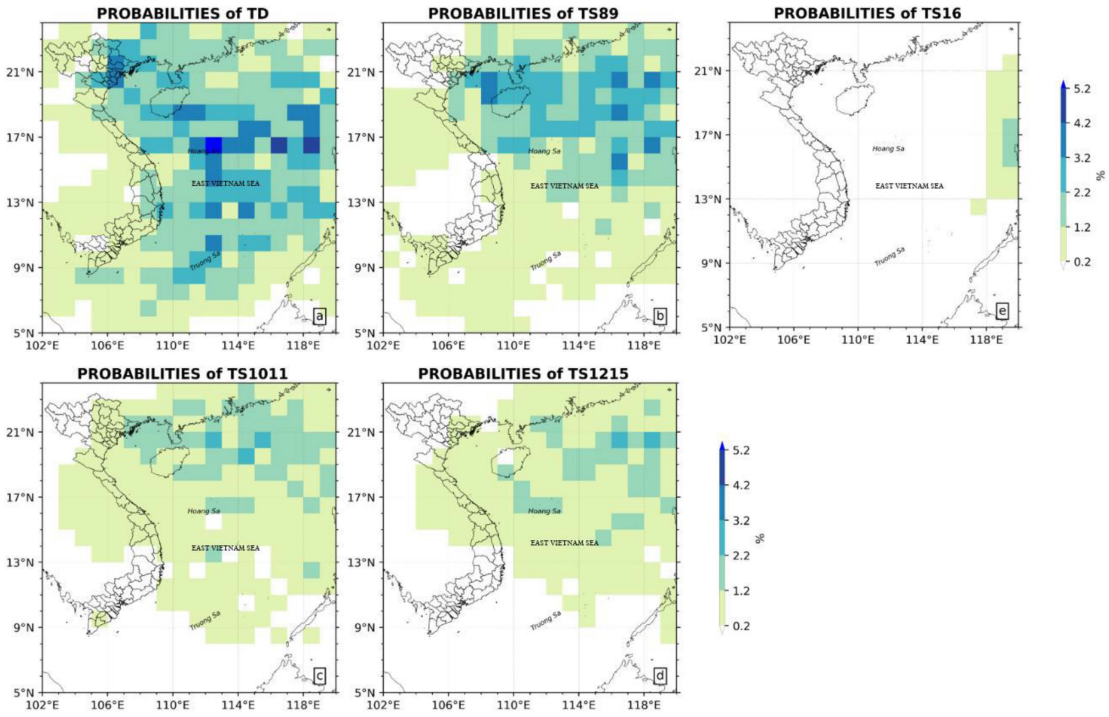

Figure 6. The occurrence probability of Tropical Depression (TD), Tropical Storm Force 8–9 (TS89), Severe Tropical Storm Force 10–11 (TS1011), Typhoons Force 12–15 (TS1215), and Super Typhoons Force 16 or higher (TS16) from 1992 to 2022 affecting the Vietnam region analyzed from the TCVN dataset

Probability of tropical storm force 8–9 (TS89)

The probability of TS89 varies mainly between 1.2–3.2% over the north and center of EVS but reduces significantly to below 1.2% in the area from the latitude 13°N to the South EVS.

In contrast, the Gulf of Tonkin receives a noticeable probability of TS89 (4.2–5.2%), followed by a decline to 1.2–3.2% over the coastal regions from Quang Ninh - Thanh Hoa, and Nghe An - Thua Thien-Hue. The remaining coastal region from Da Nang to the south are even smaller probability of TS89, at under 1.2%.

Probability of severe tropical storm force 10–11 (TS1011)

There is approximately a 0.2–2.2% chance for the TS1011 to occur over the center and south EVS, except an area located north of latitude 20°N and between longitudes 112 and 116°E has a higher probability of up to 3.2%. To the south of latitude 8°N, the probability of TS1011 to occur is even smaller, not exceeding 0.2%.

When the Gulf of Tonkin, including the inshore and offshore regions of Quang Ninh - Thai Binh witnessed a high probability of 2.2% for TS1011, the rest of the areas, such as Thanh

Hoa - Thua Thien-Hue and Da Nang - Ca Mau, had a little chance, below 1.2%.

Probability of typhoon force 12–15 (TS1215)

Typhoons with a force of 12–15 Beaufort generally show a probability of 1.2–2.2% in the center and south EVS within the northern part of latitude 13°N and eastern side of longitude 110°E. In particular, the northeastern region of the North EVS has a higher probability of TS1215, up to 3.2%.

The coastal regions from Quang Ninh to Binh Thuan have a small probability of less than 1.2%, meanwhile it is very rare for TS1215 to occur south of latitude 10°N.

Probability of super typhoon force 16 or higher (TS16)

In parallel with the frequency of super typhoon force 16 or higher analyzed above, its occurrence probability is mostly 0.2–2.2% on the eastern side of EVS.

CONCLUSION

The study collected best-track datasets of tropical cyclones from international specialized centers and local authorized organizations to investigate the characteristics of tropical cyclones affecting the Vietnam region. The collected data were pre-processed and calibrated, then analyzed and calculated statistical properties (including occurrence frequencies and probabilities) during 31 years (1992–2022). Because the information obtained from the IBTrACS, JTWC, and RMSC consist of all tropical cyclones occurring over the northwestern Pacific region (including the East Vietnam Sea), these datasets have more numerous tropical cyclones in comparison with the Vietnamese best-track dataset (known as the TCVN). However, the information over the East Vietnam Sea (EVS) differs insignificantly between these sources. In addition, the TCVN dataset not only provides information on strong tropical cyclones but also tropical depressions active over the EVS with a higher reliability, especially in near-shore cases due to a dense observation network equipped with radars, satellites, radiosonde, surface and bouy stations. Therefore, the TCVN dataset is considered predominantly for analyzing the characteristics of tropical cyclones affecting the Vietnam region within the scope of this study.

Obtained results show that, on average, approximately 13 tropical cyclones (TCs) active over the EVS annually, equivalent to the climatological mean in other studies. The number of TCs tends to increase during the studied period with a slope of 0.03–0.04 TCs/31 years, mainly occurring in tropical depressions and typhoons force 12–15. However, it does not satisfy the statistical condition of 99% confidence level, which requires further analysis to clarify this variation.

The North and center of EVS possess the highest frequencies and probabilities of TCs, especially in the Northern and Northeastern parts of North EVS and the Eastern parts of center EVS, where the maximum windspeed can reach very strong intensities (force 16 Beaufort Scale or higher).

The South EVS is significantly less affected by TCs, mainly TS89 and only about 1.2% of cases have speeds greater than force 10.

For coastal and offshore regions, the Gulf of Tonkin and areas from Quang Ninh - Thanh Hoa receive the most frequency and probability, reaching 0.2 TC/year with force 12–15, causing very rough sea conditions. Lower frequencies and probabilities occur in Nghe An - Thua Thien-Hue and decrease in the southern seas from Da Nang - Ca Mau, Ca Mau - Kien Giang and the Gulf of Thailand. Although the central coast region from Thanh Hoa - Phu Yen has averagely suffered 0.2 TS1215 per year, its occurrence chance is not high, just under 1.2%.

In conclusion, the impact of strong winds caused by tropical cyclones can be huge in the coastal and offshore regions from Phu Yen northward or the north and center EVS. Meanwhile the southern sea from Phu Yen - Binh Thuan, Binh Thuan - Ca Mau, Ca Mau - Kien, and the Gulf of Thailand are less affected by storm winds. Tropical cyclones with intensities higher than force 12 do not exceed 0.1 TC/year, and there is under 0.2% probability

to occur over these northern locations. Notably that beyond 100 km from the shore, the frequency and probability of TCs as well as their intensities may increase remarkably. The achievements of the study contribute to assessing impacts caused by TCs and related consequences, such as strong winds, high waves, and storm surges to serve the response, planning, and construction of infrastructures over the coast and sea of Vietnam.

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