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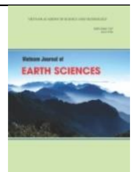

Impacts of EL NIÑO-Southern oscillation on tropical cyclone activity over the coastal zones of Vietnam

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ABSTRACT

The activity of El Niño - Southern Oscillation (ENSO) has been found to alter the characteristics of tropical cyclones (TCs) worldwide. This paper examines how ENSO influences the active time, occurence frequencies, and intensities of TCs over the coastal zones of Vietnam. The study uses Best Track Data in the Western North Pacific region from 1961 to 2020. The wind speed fields of all TCs over the coastal zones are calculated using a semi-empirical model with a square grid of 0.05° resolution. The results show that the frequencies of TCs over the coastal zones decrease during El Niño years, whilethe TC intensities increase significantly compared to those in Neutral years. Meanwhile, TC intensities over all coastal zones during La Niña years, and some coastal zones during El Niño years, decrease significantly compared to those in Neutral years. The magnitudes of both the increase and decrease in TC frequencies and intensities over the coastal zones vary significantly. Moreover, the active time of TCs during La Niña years in some coastal zones is shorter and occurs later than during the Neutral years.

Keyword: ENSO, Vietnam coastal zones, Tropical Cyclone, intensity, frequency.

1. Introduction

One of the most significant effects that the El Niño - South Oscillation (ENSO) has on the climate is its ability to alter the characteristics of Tropical Cyclones (TCs) worldwide. In addition to ENSO, various large-scale factors, such as the stratospheric Quasi-Biennial Oscillation, and local factors, such as monsoon intensity, vertical movement of the troposphere, changes in Sea Surface Temperature (SST), also influence TC activity (Chan, 1995; Landsea, 2000).

Recent studies on the effects of ENSO on TC activity in the Western North Pacific (WNP) and the East Sea (ES) regions have revealed a strong influence of ENSO on TC activity, particularly in the locations where TCs form (Ha et al., 2012; Li et al., 2012; Zhao and Wang, 2019). During El Niño (EN) years, the TC-forming regions tend to shift towards the southest (Chan 1985, 2000; Wang

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and Chan, 2002). In September and October, TC activity over the ES is lower than normal but tends to be above normal, especially in the late season in the eastern part of the WNP (Chan, 2000). Strong EN events can significantly affect TC activity over the WNP, while moderate EN events may not exhibit the same impact (Wu et al., 2017). TC frequency tends to decrease, but TC intensity increases (Camargo and Sobel, 2005; Zhang et al., 2015; Walsh et al., 2016; Zhao et al., 2016). During La Niña (LN) years, the ES tends to experience more TCs in September and October (Chan, 2000). On an interannual time scale, ENSO is well-known as a major factor in modulating the interannual variability of TC activity over the WNP (Chan, 2000; Wang and Chan, 2002; Zhao et al., 2011). In September, October, and November, or the late season of EN years, the number of TC landfalls in the landmasses around the WNP, except for the Japanese and Korean peninsula areas, significantly decreases (Zhang et al., 2012; Choi et al., 2019). In the late LN seasons, the number of TC landfalls in China increases considerably. These variations in the number of TC landfalls in mainland China are associated with changes in TC formation locations (Wu et al., 2004). TC formation increases in the eastern part, while TC frequencies decrease in the western part of the WNP in all three EN types, including Eastern Pacific El Niño (EPE), Central Pacific El Niño (CPE), and Mixed El Niño (ME) (Song et al., 2020).

In the WNP region, the TC frequencies in EN and LN years are 27-28 TCs peryear, fewer than in Neutral (Ne) years (28-29 TCs per year). Typhoons account for the highest proportion in EN years (68.5%), and the lowest in LN years (52.1%). In the ES, TC intensity in EN years is much stronger than in LN years (Phong and Chinh, 2017). The TC frequencies in EN, LN and Ne years are 8-9 TCs per year, 12-13 TCs per year, and 11-12 TCs per year, respectively. Typhoons constitute the highest proportion in EN years (53.1%), and the lowest in Ne year (45.0%) (Duy et al., 2016).

TC activity over the Vietnam Coastal Zones (VCZs) is also significantly influenced by ENSO. The TC frequency in the Northern coastal zone tends to decrease, whereas those in the Central and Southern coastal zones increase (Tuyen, 2007). The TC frequencies fluctuates widely among coastal zones and show a tendency to decrease gradually from North to South (Duy et al., 2016; Toan et al, 2014). The trends of variation in TC frequencies over the years in different regions vary; some rise, while others decline (Toan et al., 2014). In LN years, the TC frequencies are higher than those in EN years (Hang et al., 2010; Thuy et al., 2015).

This paper presents the impact of EN and LN on the frequencies, intensities and active time of TCs during the period 1961-2020 over five coastal zones (CZs) of Vietnam. Each CZ is defined as a sea area located within approximately 200km from the shoreline. The five CZs include: CZ1 (the Northern provinces from Quang Ninh to Ninh Binh), CZ2 (the North Central Provinces from Thanh Hoa to Quang Trị), CZ3 (the Mid-Central Provinces from Thua Thien - Hue to Binh Dinh), CZ4 (the South Central provinces from Phu Yen to Binh Thuan), and CZ5 (the Southern Provinces from Ba Ria-Vung Tau to Ca Mau) (Fig. 1).

Figure 1. Map of Vietnam illustrating its five coastal zones

2. Data and Method

2.1. Data

2.1.1. ENSO years

The National Oceanic and Atmospheric Administration (NOAA) uses the Oceanic Niño Index (ONI) as the standard to determining EN and LN events. The ONI is the running 3-month mean Sea Surface Temperature Anomaly (SSTA) for the Niño 3.4 region (the central Pacific region within the range of 5°N–5°S, 120°–170°W). Events are defined as five consecutive overlapping 3-month periods with anomalies at or above +0.5°C for EN events and at or below -0.5°C for LN events. In more detail, EN is categorized into four levels: Weak (0.5 to 0.9 SSTA), Moderate (1.0 to 1.4), Strong (1.5 to 1.9), and Very Strong (≥2.0) events.

Meanwhile, LN is divided into three levels: Weak (-0.5 to -0.9), Moderate (-1.0 to -1.4), and Strong (-1.5 to -1.9).

TCs are predominantly active over the VCZ from June to December (Duy et al. 2016). Hence, in this study, the indices used to classify the ENSO years are the mean values of 5 ONIs from June to December, including JJA, JAS, ASO, SON, and OND. The classification results of ENSO years in the period 1961-2020 are presented in Table 1.

Table 1. List of EN and LN years

NOAA		**Average of 5 ONI**		**NOAA**		**Average of 5 ONI**	
1963-64	ME	1963	ME	1964-65	WL	1964	WL
1965-66	SE	1965	SE	1970-71	ML	1970	WL
1968-69	ME	1968	WE	1971-72	WL	1971	WL
1969-70	WE	1969	WE	1973-74	SL	1973	SL
1972-73	SE	1972	SE	1974-75	WL	1974	WL
1976-77	WE	1976	WE	1975-76	SL	1975	ML
1977-78	WE	1977	WE	1983-84	WL	1988	ML
1979-80	WE	1982	SE	1984-85	WL	1995	WL
1982-83	VSE	1986	WE	1988-89	SL	1998	ML
1986-87	ME	1987	SE	1995-96	ML	1999	ML
1987-88	SE	1991	WE	1998-99	SL	2000	WL
1991-92	SE	1994	WE	1999-00	SL	2007	ML
1994-95	ME	1997	VSE	2000-01	WL	2010	ML
1997-98	VSE	2002	ME	2005-06	WL	2011	WL
2002-03	ME	2004	WE	2007-08	SL	2016	WL
2004-05	WE	2006	WE	2008-09	WL		
2006-07	WE	2009	WE	2010-11	SL		
2009-10	ME	2015	VSE	2011-12	ML		
2014-15	WE	2018	WE	2016-17	WL		
2015-16	VSE			2017-18	WL		
2018-19	WE			2020-21	WL		

Note: WE=Weak El Niño, ME=Moderate El Niño, SE=Strong El Niño, VSE=Very Strong El Niño, WL=Weak La Niña, ML=Moderate La Niña, SL=Strong La Niña

2.1.2. Best track data

Analysis of the best track data from the Regional Specialized Meteorological Center (RSMC), Unisys Weather (UW), and China Meteorological Administration (CMA) sources shows that the CMA source is the most complete (Duy et al., 2016). Therefore, the best track data from the CMA source are used in this study. The data include the maximum wind speeds (W_{max}), positions and barometric pressures at the centers of TCs at 0h, 6h, 12h, and 18h (GMT) during the lifetime of all TCs active in the WNP from 1961 to 2020. Data before 1961 are not used because the number of TCs in the pre-satellite years of the 1950s might be underestimated (Chan, 1985; Wu et al., 2004).

The results of data processing usingthe Geographic Information System (GIS) tool show that, during period 1961–2020, there were 802 active TCs over the ES.

2.1.3. Wind field data of TC

The wind fields of ten active TCs over the VCZs during the period 2013-2020 are used to validate the wind fields estimated by Takahashi semi-empirical model, as detailed below. These wind speed fields (m/s) at 10 m above sea level were recorded at all grid points with a resolution of 0.5° × 0.5° at 0h, 6h, 12h, and 18h (GMT) throughout their lifetime. The wind field data are sourced from the Global Forecast System (GFS) of the National Centers for Environmental Information - NOAA. Further details on the ten selected TCs are provided in Table 2.

Table 2. Errors in the wind speed values of 10 TCs obtained from Takahashi's semi-empirical model

TC name	Time (GMT)	$\overline{W}_{NOAÂ}$ (m/s)	$\overline{W}_{Model}$ (m/s)	Relative error (%)
JEBI	02/08/2013	16.0	18.5	15.5
WUTIP	29/09/2013	18.3	21.4	17.2
NARI	13/10/2013	17.9	20.2	12.8
HAIYAN	09/11/2013	19.9	22.9	15.2
KUJIRA	23/06/2015	15.5	13.8	-10.8
DIANMU	18/08/2016	15.4	16.7	8.5
DOKSURI	14/09/2017	18.7	16.2	-13.2
DAMREY	03/11/2017	17.8	20.3	14.2
BEBINCA	15/08/2018	14.9	16.7	12.2
MOLNVE	27/10/2020	17.3	19.4	12.2

2.2. Method

To determine the active time, frequencies, and intensities of TCs in the CZs, the wind speed fields during the lifetime of all active TCs over the ES in the period 1961-2020 are calculated using Takahashi semi-empirical model. This model, recommended for computing TC wind fields in the ES (Dinh Van Manh et al., 2018), assigns a TC as active over a CZ if its maximum wind speed in the CZ, denoted as W_{maxCZ} exeeds 10.8 m/s, equivalent to level 6 according to the Beaufort starndard. This criterion allows a TC to be considered active over multiple CZs, even if its best track does not pass through any specific CZ. This approach differs from previous studies that considered a TC active over a CZ only if its best track passed through it, resulting in an insufficient determination of the total number of active TCs over the CZs.

Semi-empirical model is used to calculate the wind speed fields at 10m above sea level for all active TCs over the ES. In this model, the wind speed at a point that is a distance r away from the TC center is expressed as:

$$\vec{W}_r = \vec{W} + \vec{W}_\varphi + \vec{W}_c + \vec{W}_{ac}$$

In which : $\vec{W}$ is the wind speed in the case of a symmetrical TC, $W = W_{\max}\dfrac{2\sqrt{r/R}}{1+(r/R)}$;

$\vec{W}_\varphi$ is the adjustment component of wind speed due to friction, $\vec{W}_\varphi = \vec{W}\cos(\varphi)$;

$\vec{W}_c$ is the adjustment component of wind speed due to the movement of the TC center, $W_c = V_t \exp\left(-2\pi r 10^{-3}\right)$;

$\vec{W}_{ac}$ is the adjustment component of wind speed due to continental influence, $W_{ac} = W\left(1 - \dfrac{\alpha r}{1+r^2}\max(\cos\varphi, 0)\right)$.

Where: R and W_{max} are the maximum radius and wind speed of the TC, R is determined by experimental correlations with the barometric pressure decrease at the TC center,

V_t is the moving speed of the TC center,

φ is the angle between the wind speed vector and moving direction of the TC center.

The input parameters of the model include: the W_{max}, positions and barometric pressures at the centers throughout the lifetime of the TCs; the sizes and steps of the calculated grid; and the experimental correlation values between R and barometric pressures at the TC centers.

In this study, the model uses a square grid with a resolution of 0.05° within the range of

2°-24°N, 100°-120°E, covering the entire ES. The model's calculations are validated using the wind fields of ten TCs active in the VCZ. The calculation errors of the results, when compared with the wind speed data received from NOAA for these TCs, are presented in Table 2, wherein $\overline{W}_{\max\_NOAA}$ and $\overline{W}_{\max\_\mathrm{mod}}$ are the mean of maximum wind speeds during a day before TC landfall (including 4 observations: 0h, 6h, 12h, 18h) given respectively by NOAA and model.

On the basis of wind field calculation results, the W_{maxCZ} for all TCs in the VCZ and CZs are determined.

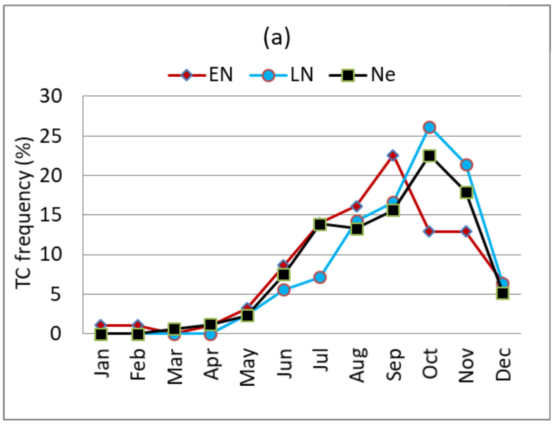
3. Results

3.1. Effects of EN and LN on the frequency and active time of TCs over the coastal zones

The calculated results show that during the period 1961-2020, there were 392 active TCs over the VCZ. The average TC number was 6.5 TCs per year, ranging from 1 TC per year (2002) to 12 TCs per year (1964, 1970, and 1990). Among these TCs, 93 TCs occurred in the EN years (4.9 TCs/year), 126 TCs in the LN years (8.4 TCs/year), and 173 TCs in the Ne years (6.7 TCs/year). Therefore, compared to the TC frequency over the VCZ in the Ne year, the frequency decreased by 46% in the EN years, and increased by 27% in the LN years. Notably, the numbers of TCs in the strong EN years were much less than average (e.g. 2 in 1997 and 3 in 2015).

The main active time of TCs, commonly referred to as the storm season (defined as months with a TC frequency greater than or equal to 9%), over the VCZ in the EN and Ne years was from July to November, whereas in the LN years, it was from August to November. Hence, the storm season over the VCZ in the EN years coincides with the storm season in the Ne years, but is later and shorter by about 1 month in the LN years (Fig. 2a).

Within the CZs, the highest number of TCs occurred in CZ2 (219 TCs), and the lowest in CZ5 (53), with CZ1 (188), CZ3 (210), and CZ4 (119) falling in between (Table 3). A southward shift in the storm seasons was recorded, specifically from June to October over CZ1 and CZ2, from July to November over CZ3, and from October to December over CZ4 and CZ5 (Fig. 2b).



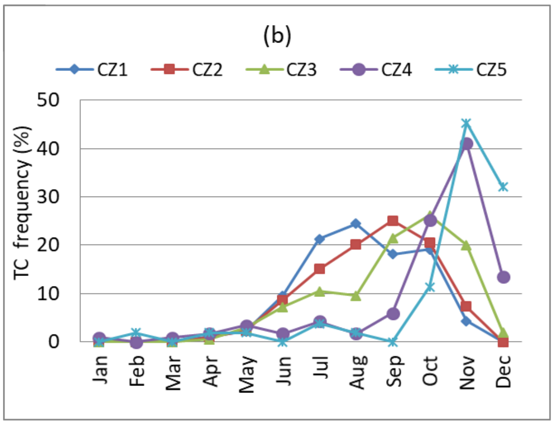


Figure 2. Monthly active TC frequencies: (a) over the VCZ in EN, LN and Ne years; (b) over the CZs

Table 3. Monthly numbers of active TCs over the CZs and their total number in the EN, LN and Ne years

Month	CZ1			CZ2			CZ3			CZ4			CZ5		
	N_{EN}	N_{LN}	N_{Ne}	N_{EN}	N_{LN}	N_{Ne}	N_{EN}	N_{LN}	N_{Ne}	N_{EN}	N_{LN}	N_{Ne}	N_{EN}	N_{LN}	N_{Ne}
Jan	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Feb	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Mar	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Apr	1	0	1	1	0	1	0	0	1	0	0	2	0	0	1
May	0	2	2	1	1	3	2	2	2	1	1	2	1	0	0
Jun	6	5	7	2	7	10	5	2	8	1	1	0	0	0	0
Jul	12	9	19	8	9	16	6	6	10	1	2	2	0	1	1
Aug	15	14	17	13	14	17	5	7	8	1	1	0	1	0	0
Sep	10	10	14	15	17	23	16	13	16	4	3	0	0	0	0
Oct	5	15	16	5	24	16	7	22	26	3	7	20	2	1	3
Nov	1	2	5	1	6	9	5	18	19	11	16	22	6	8	10
Dec	0	0	0	0	0	0	2	1	1	5	5	6	3	7	7
Sum	50	57	81	46	78	95	48	71	91	28	36	55	14	17	22

In CZ1, the TC frequency ranged from 0 TC per year (1999 and 2004) to 8 TCs per year (1971, 1989) with an average of 3.1 TCs per year. The average TC frequencies in the EN, LN, and Ne years were 2.6 TCs per year, 3.8 TCs per year, and 3.1 TCs per year, respectively. Compared to the Ne years, the TC frequency decreased by 15% in the EN years and increased by 22% in the LN years (Fig. 4). The storm season in CZ1 during the EN, LN, and Ne years was the same, from June to September. The months with the most TCs were August (EN), October (LN), and July (Ne). In conclusion, over CZ1 in the LN years, TCs were most active in the last month of the storm season (Fig. 3a).

CZ2 recorded the most significant TC frequency fluctuations in the EN and LN years. The average frequency was 3.7 TCs per year, with the highest being 9 TCs per year (1971). There were two years without active TC (1976 and 2004). The average frequencies were 2.4 TCs per year in the EN years, 5.2 TCs per year in the LN years, and 3.7 TCs per year in the Ne years. In comparison with the Ne years, the TC frequency decreased by 33% in the EN years and increased by 42% in the LN years (Fig. 4). The storm season started from July to October in the EN years, from June to October in the LN years, and from June to November in the Ne years. The month with the most TCs was September in the EN and Ne years, and October in the LN years. Similar to CZ1, the most active time for TCs in this area in the LN years was the last month of the storm season (Fig. 3b).

Over CZ3, the average TC frequency was 3.5 TCs per year, ranging from no active TC (1976) to 10 TCs (1990). The respective average frequencies estimated for the EN, LN, and Ne years were 2.5 TCs per year, 4.7 TCs per year, and 3.5 TCs per year. Thus, compared to the Ne years, the TC frequency decreased by 28% in the EN years and increased by 35% in the LN years. The storm season in the EN years coincided with the Ne years, from July to November, while that in the LN years was one month shorter, from August to November. The month with the most TCs was September in the EN years and October in the LN and Ne years (Fig. 3c).

The average TC frequency over CZ4 was 2.0 TCs per year with the maximum number of 6.0 TCs per year in 1990. There were 12 years without any active TC, accounting for 20%. The average frequencies were 1.5 TCs per year in the EN years, 2.4 TCs per year in the LN years, and 2.1 TCs per year in the Ne years. Hence, compared with the NE years, the frequency declined by 28% in the EN years and rose by 35% in the LN years.

The storm season in the EN year was from September to December, whereas that in the LN and Ne years was one month later and shorter, from October to December. The month with the most TCs in all three ENSO states was November (Fig. 3d).

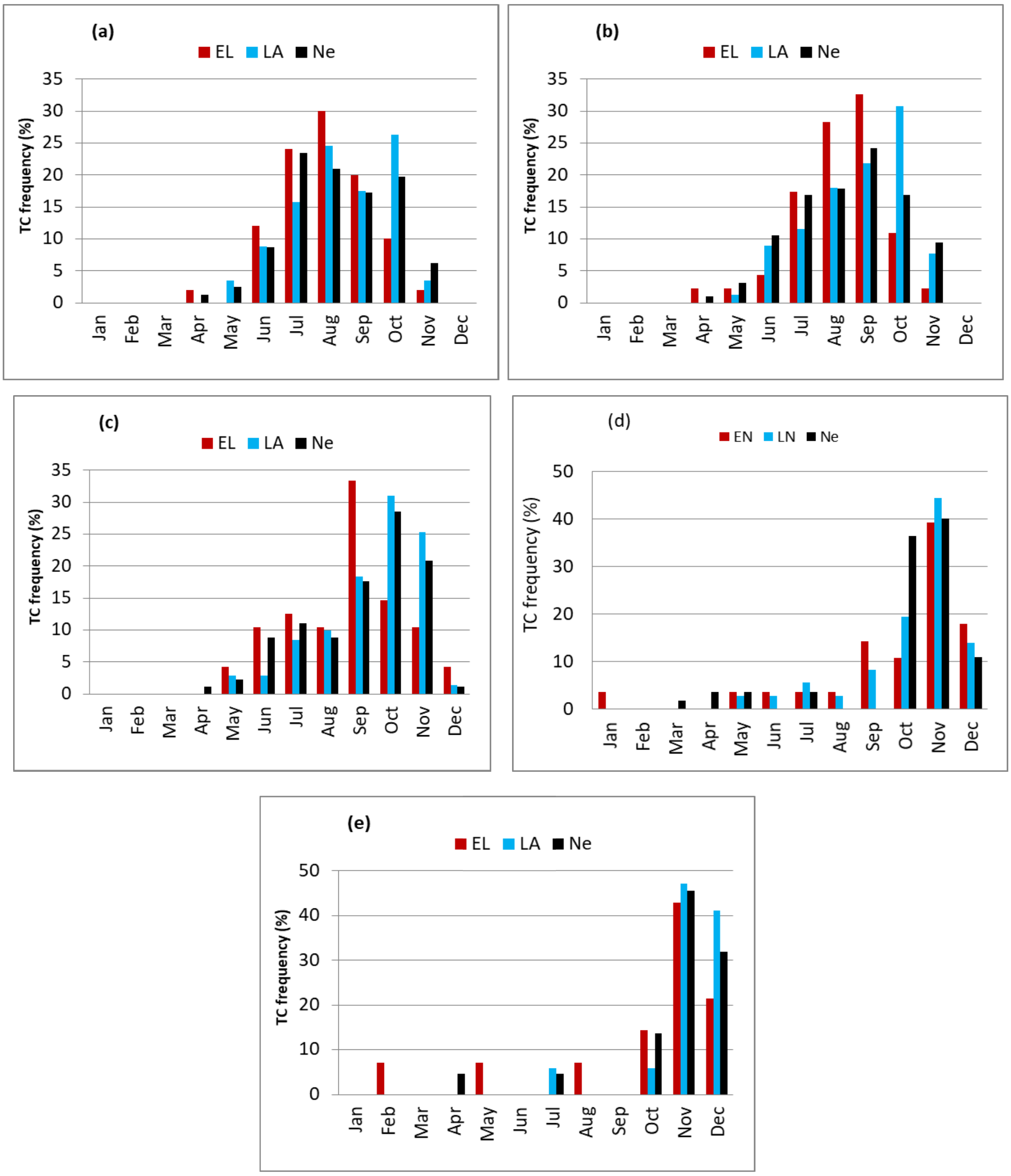


Figure 3. Monthly active TC frequencies over the CZs in the EN, LN and Ne years over (a) CZ1, (b) CZ2, (c) CZ3, (d) CZ4, and (e) CZ5

Regarding CZ5, the average frequency of TC was 0.9 TCs per year, with the highest being 4 TCs per year (1970). There were 25 years without any active TC, accounting for 41.7%, including 6 consecutive years from 1975 to 1980. The average frequencies were 1.5 TCs per year, 2.4 TCs per year, and 2.1 TCs per year for the EN, LN and Ne years, respectively. Compared to the Ne years, the frequency decreased by 13% in the EN years and increased by 34% in the LN years. The storm season in the EN and Ne years was from October to December, whereas in the LN Years, it was one month later and shorter, from November to December. The month with the most TCs in all three ENSO states was November (Fig. 3e).

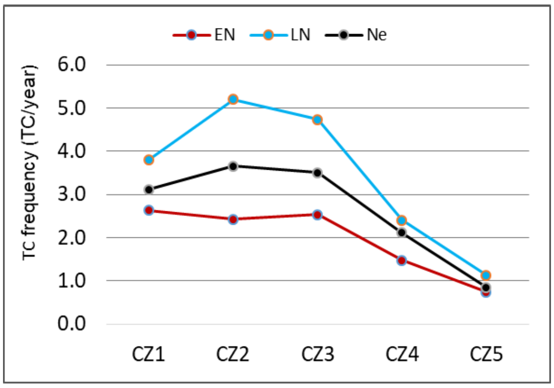


Figure 4. Average frequencies of active TCs over the CZs in the EN, LN, and Ne years

3.2. Effects of EN and LN on tropical cyclone intensity over the coastal zones

Of the total of 392 active TCs over the VCZ during the period 1961-2020, Tropical Storms (ST), including TCs at levels 8 and 9, accounted for the highest frequency (33%), followed by Severe Tropical Storms (STS), including TCs at levels 10 and 11 (27%). Tropical Depressions (TD), including TCs at levels 6 and 7, took up the smallest proportion (16%). Typhoons (Ty) with TCs at levels 12 and above, made up a considerable proportion (24%).

The highest average TC frequency was at level 8 for CZ1 (15.4 %,), CZ3 (20.0%), and CZ4 (22.7%); at level 10 for CZ2 (18.3%); and level 6 for CZ5 (37.7%) (Fig. 5). Overall, the frequencies of strong TCs (STS and Ty) decreased gradually from CZ1 to CZ5 (from North to South). In contrast, the frequencies of weak TCs (TD and ST) increased gradually from CZ1 to CZ5. The Ty frequency was the highest in CZ1 (23%) and lowest in CZ5 (4%); the TD frequency was the highest in CZ5 (57%) and lowest in CZ1 (24%) (Fig. 6).

The highest ($W_{maxCZ-max}$) and mean ($W_{maxCZ-aver}$) values of W_{maxCZ} for TCs, used as representative indicators to evaluate TC intensities over the CZs, indicate that the TC intensity over CZ1 was the strongest, gradually southwards decreasing to CZ5 (Fig. 7). The $W_{maxCZ-max}$ occurred in the Ne years over CZ1, CZ4 and CZ5, in the LN years over CZ2 and CZ3, and did not occur in the EN years (Fig. 8).

The TC numbers in different levels in the EN, LN and Ne years in the CZs varied greatly. During the EN years, TCs at level 12 and above did not occur over CZ4 and CZ5. In the LN years, TCs at level 13 and above did not occur over CZ1 and CZ4. Additionally, over CZ5, TCs at level 10 and above did not occur (Table 4).

Compared with the Ne years, $W_{maxCZ-aver}$ in the EN and LN years decreased by 0.2% and 13% over CZ1,; 5% and 10% over CZ2, 7% and 8% over CZ3, and 5% and 3% over CZ4, respectively. Meanwhile, those over CZ5 increased by 17% in the EN years and decreased by 7% in the LN years. Despite such variation, the values of $W_{maxCZ-aver}$ overall decreased across all the CZs in the LN years. During the EN years, the values of $W_{maxCZ-aver}$ over regions from CZ1 to CZ4 decreased, whereas that over CZ5 increased (Fig. 9).

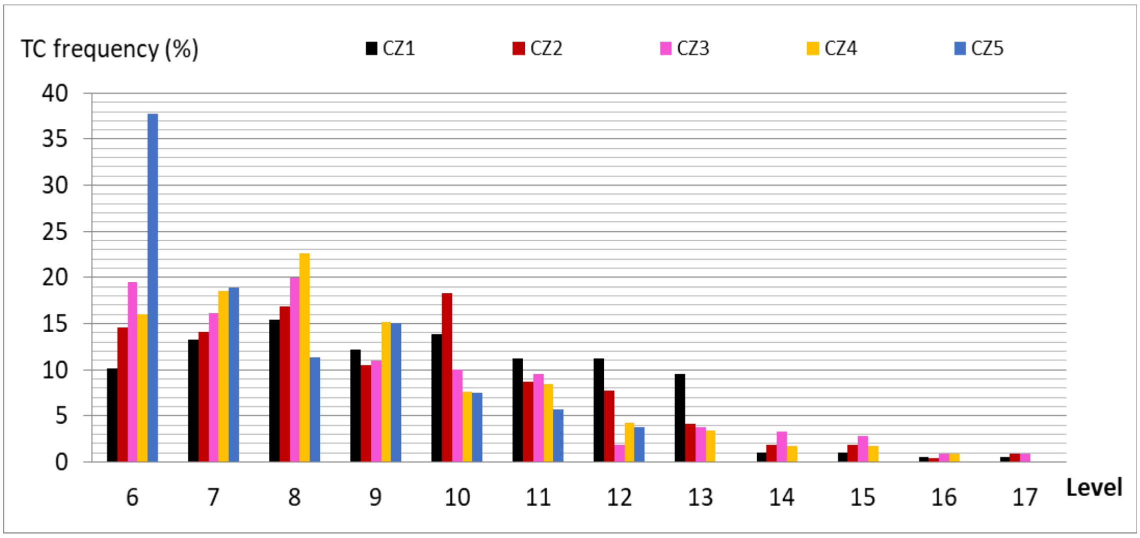


Figure 5. Frequencies of TC levels over the CZs

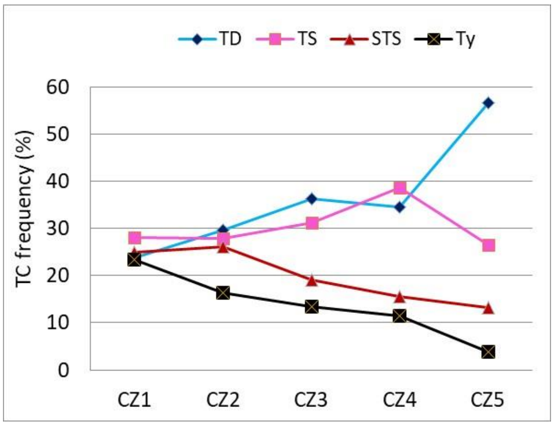


Figure 6. Frequencies of TC categories over the CZs

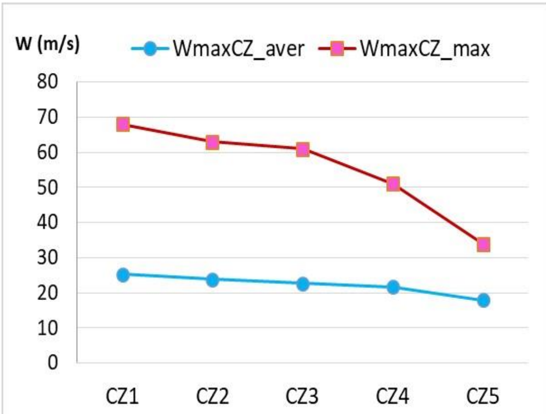


Figure 7. Values of $W_{maxCZ-max}$ and $W_{maxCZ-aver}$ of TCs over the CZs

Table 4. TC numbers at diferente levels in EN, LN and Ne years over the CZs

Level	CZ1			CZ2			CZ3			CZ4			CZ5		
	EN	LN	Ne	EN	LN	Ne	EN	LN	Ne	EN	LN	Ne	EN	LN	Ne
6	6	8	5	4	13	15	12	13	16	3	5	11	4	8	8
7	3	9	13	8	10	13	9	14	11	8	4	10	2	3	5
8	10	8	11	9	19	9	7	15	20	6	10	11	1	2	3
9	4	10	9	6	7	10	4	9	10	3	7	8	2	3	3
10	8	6	12	9	13	18	3	7	11	1	3	5	2	1	1
11	5	7	9	3	6	10	7	7	6	4	5	1	2	0	1
12	3	7	11	2	7	8	1	1	2	3	0	2	1	0	1
13	9	2	7	3	1	5	2	0	6	0	2	2	0	0	0
14	1	0	1	1	0	3	1	1	5	0	0	2	0	0	0
15	0	0	2	0	1	3	1	2	3	0	0	2	0	0	0
16	1	0	0	0	0	1	0	1	1	0	0	1	0	0	0
17	0	0	1	1	1	0	1	1	0	0	0	0	0	0	0

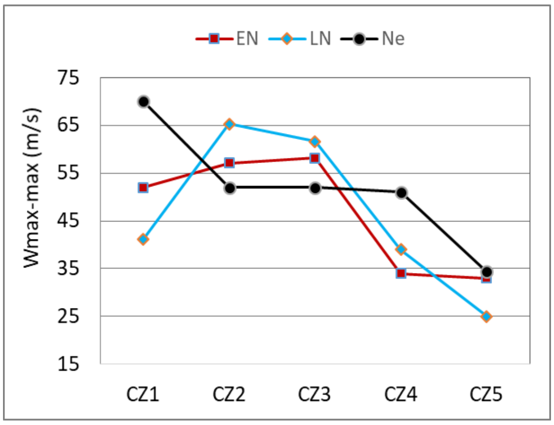


Figure 8. Values of $W_{maxCZ-max}$ in EN, LN and Ne years over the CZs

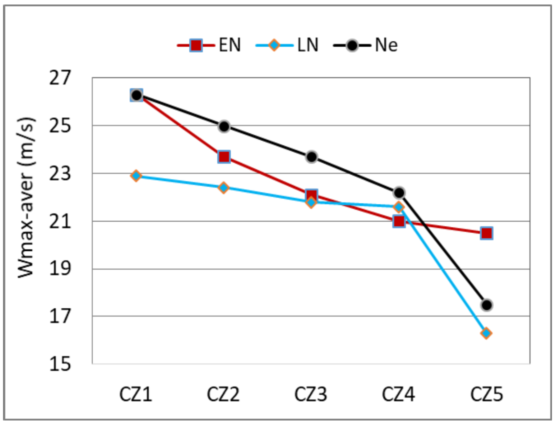
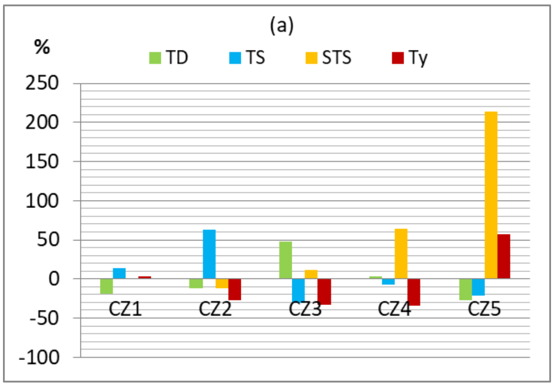


Figure 9. Values of $W_{maxCZ-ever}$ in EN, LN and Ne years over the CZs

For a better evaluation of the ENSO's impacts on TC intensities over the CZs, the changes in the average frequencies of TC categories in the EN and LN years were compared with those in the Ne years.

During the EN years, the frequencies of TC categories over CZ1 showed very little change. Meanwhile, over CZ2, the TS frequency increased significantly by about 63%, whereas those of TD, STS and especially Ty decreased by 28%. Over CZ3, the frequencies of TD and STS increased by 47% and 11%, respectively, while those of TS and Ty decreased by 30% and 33%. Regarding CZ4, the frequencies of TD and TS changed slightly; however, that of STS increased by 63%, and Ty decreased by 34%. Over CZ5, the frequencies of TD and TS decreased by 27% and 21%, respectively, whereas those of STS and Ty increased remarkably (214% and 57%). Thus, the overall TC intensities over CZ2, CZ3, and CZ4 decreased due to the increased frequencies of weak TCs and decreased frequencies of strong TCs. Over CZ5, on the contrary, the TC intensity rose owing to the decrease in the proportions of weak TCs (TD and TS) and a significant increase in strong TCs (STS and Ty) (Fig. 10a).

During the LN years, the frequencies of TD and TS over CZ1 increased by 34% and 27%, respectively, whereas those of STS and Ty decreased by 12% and 41%. Over CZ2, the frequency of TS increased significantly, by about 67%, while those of STS and Ty decreased by 17% and 39%. Over CZ3, the frequencies of TS and STS showed little change, while TD's increased by 28% and Ty's decreased by 54%. Over CZ4, the frequencies of TD and Ty decreased by 34% and 66%, respectively, whereas that of TS increased by 37%, and STS increased remarkably by 104%. Regarding CZ5, the proportions of TD and TS changed slightly, STS decreased by 35%, and especially Ty did not occur (decreased by 100%). Thus, the overall TC intensity over the CZs during the LN years declined due to the decreasing proportions of STS and Ty and increasing frequencies of weak TCs (Fig. 10b).



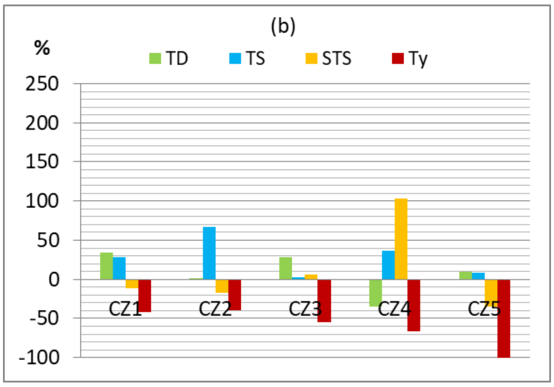


Figure 10. Relative changes in the average frequencies of TC categories over the CZs (a) EN years compared to Ne years, (b) LN years compared to Ne years

4. Discussions

The study examined the impact of EN and LN on the occurrence frequency, intensity, and active time of TCs over the CZs. The frequency and intensity of TCs were determined by calculating the wind speed fields of active TCs in the ES, using the best tracks and empirical model. The results showed a gradual decrease in TC frequency from CZ2 to CZ5, with a higher frequency observed in the LN years compared to the EN years (Fig. 4). Conversely, TC intensity in the regions decreased gradually from CZ1 to CZ5, with greater intensity in the EN years than in the LN years (Fig. 7 and Fig. 9). These findings are consistent with previous studies by Toan et al. (2014), Hang et al. (2010), and Phong and Chinh (2017). However, the TC frequencies over the CZs in this study are higher than in previous studies, possibly because they were determined from the spatial distribution of TC wind speed fields.

TC activity depends significantly on meteorological and oceanographic conditions, such as SST and monsoon in the region (Chan, 1995; Landsea, 2000, Wang et al., 2002). SST in the ES is higher in EN years than in LN years (Wang et al., 2006). An SST trend analysis in Haiphong CZ by Vinh et al. (2022) also indicates a similar result. Compared to LN years, TC intensity in the ES during EN years is stronger, but the frequency is lower (Duy et al., 2016). During late Autumn and early Winter months (October, November, December), the northeast monsoon is prevalent in the VCZ, and TC activity tends to shift southward (CZ4 and CZ5). Thus, TC activity in the VCZ can be closely related to TC activity in ES, SST and the northeast monsoon.

Despite the study’s limitations, it provides insights into the impacts of EN and LN on the frequency, intensity, and active time of TCs in the CZs. These findings have important implications for forecasting TC activity over the CZs based on climate and ENSO activity predictions. To enhance the application of the results, the impact levels of EN and LN events and their long-term trends on TC characteristics in the CZs need to be estimated. Additionally, reducing the calculation time step to 1 hour or 2 hours, instead of the curent 6 hours in this study, is needed.

5. Conclusions

Both EN and LN significantly influence the frequencies, active time and intensities of TCs in all the CZs, with these influences varying widely among 232iferente CZs.

The main active time of the TCs, known as the storm season, gradually decreases and occurs later in a southerly direction from CZ1 to CZ5: over CZ1 and CZ2, it spans 5 months, from June to October; over CZ3, it covers 5 months, from July to November; and over CZ4 and CZ5, it only spans to 3 months, from October to December. Compared to the Ne years, there is little shift in storm seasons in the EN years in the CZs (except CZ2). In the LN years, storm seasons in CZ3, CZ4, and CZ5 occur later and are about a month shorter.

The TC frequencies in the CZs are greater in the LN years than in the EN years and gradually decrease from CZ1 to CZ5. Compared to the Ne years, the frequencies of TCs over all five CZs decrease significantly (24% on average) in the EN years, with the most substantial decline being recorded over CZ2 at about 34%, and the least over CZ5 at roughly 13%. In contrast, during the LN years, the TC frequencies over the CZs increase considerably (29% on average), with the most significant increase observed in CZ2 at approximately 42%, and the least in CZ4 at about 13% (Fig. 4). The TC frequencies in CZ1, CZ2, and CZ3 are higher in the last month of the storm season. The frequencies of STS and Ty in the LN years are significantly lower than those in the Ne years, especially in the CZ1, CZ4, and CZ5 regions. Notably, the Ty frequencies in the CZ2, CZ3, and CZ4 in both EN and LN years are much lower.

The TC intensities in the CZs gradually decrease from CZ1 to CZ5. CZ1, CZ2, and CZ5 exhibit significant differences in TC intensities between EN, LN, and Ne years. Compared to the Ne years, the average TC intensities in CZ2, CZ3, and CZ4 decrease by 5-7%, while that of CZ5 increases substantially (approximately 17%) in the EN years. Conversely, in the LN years, the average TC intensities decrease in all the CZs, with the most remarkable decline of about 13% in CZ1 and the least, roughly 3% in CZ4.

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