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ABSTRACT

Tropical cyclone (TC) is one of the destructive natural phenomena which cause huge damage to society and economy. There are a variety of factors modulating TC activity over the western North Pacific (WNP). Large-scale environment, such as sea surface temperature (SST) and vertical wind shear, directly affects formation, development, and track of TCs. The El Niño–Southern Oscillation (ENSO) indirectly controls TC activity by modifying the large-scale environment. Effect of large-scale environment on ENSO-related TC activity was investigated by many previous studies. However, the physical mechanisms linking environmental factors and TC features were mainly explained in terms of anomalous large-scale environmental conditions. In recent decades, many studies have employed full dynamical models to understand the TC activity associated with ENSO. However, the role of individual large-scale environmental variables to ENSO-related TC features is limitedly understood although the importance of large-scale environmental fields was pointed out by many studies. Therefore, this study aims to reveal key environmental fields regulating ENSO-related TC activity by using an axisymmetric model. The design of the model allows to investigate the contribution of each environmental variable to TC features. For instance, to examine the role of humidity in TC genesis, we can discard the contributions of other input environmental variables.

To investigate how TC genesis anomaly is modulated by anomalous large-scale environment induced by ENSO, numerical experiments were conducted. Four monthly-mean variables, namely 600-hPa level relative humidity (RH600), SST, 850-hPa level relative vorticity (RV850), and vertical wind shear (VWS) derived from the reanalysis data were used to drive the model. The model run was performed for the storm season (June to October) of 16 conventional ENSO (i.e., El Niño or La Niña) years defined by Niño-3.4 SST anomaly during 1970–2015. The control experiment, in which realistic interannual variations of all four environmental variables were used, demonstrated that the model was able to replicate the spatial distributions and TC genesis anomalies corresponding to the conventional ENSO, particularly in the northwest (NW; 17°N–30°N, 120°E–140°E) and southeast (SE; 0°N–17°N, 140°E–180°E) sectors of the WNP. In addition, the model was

able to reproduce anomalous TC genesis patterns for other types of ENSO which are the eastern Pacific warming (EPW) and central Pacific warming (CPW).

To elucidate individual contributions of four input variables, RH600, SST, RV850, and VWS, to ENSO-related TC genesis frequency, sensitivity experiments were conducted. The experiment with the real interannual variation of RH600 can produce less TC geneses in the NW sector corresponding to lower RH600 in El Niño (EN) years, compared to La Niña (LN) years. The result indicated that relative humidity at mid-tropospheric layer plays a key role in regulating ENSO-related TC genesis. In the SE sector, the sensitivity experiment with real interannual variation of RV850 can reproduce more TC geneses corresponding to stronger RV850 in EN years, compared to LN years, which suggested that relative vorticity at lower tropospheric layer is the dominant factor in modulating ENSO-related TC genesis. In reality, the low-level convergence associated with stronger RV850 in EN years than LN years increases the water vapor transport toward the SE. This presumably sustains cumulus convection in the TC warm core. Although this effect was not explicitly included in the model, RV850 indirectly increased TC genesis through TC seeding process. Thus, more TC seeds were placed in the SE sector in EN years than LN years. In addition, it was revealed that the effects of ENSO-induced VWS and SST anomalies on TC genesis are negligible. The results of sensitivity experiments, thus, pointed out the importance of mid-tropospheric relative humidity and low-level relative vorticity to ENSO-related TC genesis anomaly over the WNP.

To examine the TC genesis, track and landfall anomalies in relation to ENSO-induced large-scale environmental anomalies, the simulated results were analyzed in monthly timescale. It was revealed that the model was capable of replicating monthly evolution of ENSO-related TC genesis anomaly during storm season. In addition, it can reproduce the contrast in TC landfalls between EN and LN years, especially in September to November (SON). In particular, TC landfall counts around China and Philippines dramatically decreased in EN years during SON, compared to LN years. The significant decrease in TC landfall counts during SON in EN years was attributed to the effect of both shift in TC genesis position and steering flow. In EN (LN) years, the mean TC genesis position moved eastward (westward), which might lead to less (more) chances of TC

landfall during June to November. However, the simulated TC landfalls significantly decreased in only SON of EN years. Also, in the late storm season (SON), the occurrence of anomalous westerly in mid-latitudes can be an important factor to prevent TC landfalls around China and Philippines. Therefore, the model was sensitive to both the shifts in simulated TC genesis position and large-scale steering flow. However, the model also showed the limitation in predicting tracks of TCs generated over east WNP (140°E–180°E).

This study confirmed the dominant effects of environmental factors on ENSO-related TC genesis and landfall. In particular, it demonstrated that mid-tropospheric relative humidity and low-level relative vorticity play a key role in modulating ENSO-related TC genesis. In addition, both TC genesis position and large-scale steering flow are found to be important in controlling ENSO-related TC landfall. Furthermore, mid-tropospheric relative humidity, low-level relative vorticity, and large-scale steering flow can serve as the potential predictors of TC activity in seasonal timescale. Finally, the results suggested that ENSO-related TC features over the WNP are predictable by using a monthly-averaged status of large-scale environment. Therefore, having appropriate large-scale mean state is essential in predicting TC activity anomalies in the WNP corresponding to ENSO.

ABBREVIATION

AGCMs	Atmospheric General Circulation Models
CCCR	The sensitivity experiment in which VWS set as real value, while RH600, SST and RV850 set as climatology
CCRC	The sensitivity experiment in which RV850 set as real value, while RH600, SST and VWS set as climatology
CRCC	The sensitivity experiment in which SST set as real value, while RH600, RV850 and VWS set as climatology
CRCR	The sensitivity experiment in which SST and RV850 set as climatology, while RH600 and VWS set as real values
CRRR	The sensitivity experiment in which RH600 set as climatology, while SST, RV850 and VWS set as real values
RCCC	The sensitivity experiment in which RH600 set as real value, while SST, RV850 and VWS set as climatology
RCRC	The sensitivity experiment in which RH600 and VWS set as climatology, while SST and RV850 set as real values
RCRR	The sensitivity experiment in which SST set as climatology, while RH600, RV850 and VWS set as real values
RRCR	The sensitivity experiment in which RV850 set as climatology, while SST, RH600 and VWS set as real values
RRRC	The sensitivity experiment in which VWS set as climatology, while SST, RH600 and RV850 set as real values
RRRR	Control Experiment (all variables include RH600, SST, RV850, and VWS set as real values)
CHI	Coastal areas belonging to China where TCs possibly landfall
CPC	Central Pacific cold, which is defined by SST anomaly (smaller than -1 standard deviation) at Niño-4
CPW	Central Pacific warming, which is defined by SST anomaly (larger than 1 standard deviation) at Niño-4
DIV200	Divergence at 200-hPa level
EN	El Niño, which is defined by SST anomaly (larger than 1 standard deviation) at Niño-3.4

ENSO	The El Niño–Southern Oscillation
EPW	Eastern Pacific warming, which is defined by SST anomaly (larger than 1 standard deviation) at Niño-3
EPC	Eastern Pacific cold, which is defined by SST anomaly (smaller than -1 standard deviation) at Niño-3
GCM	Global Circulation Model
GPI	Genesis Potential Index
ICP	Indochina Peninsula
ITCZ	Inter Tropical Convergence Zone
JKP	Japan and Korea Peninsula
JRA55	The Japanese 55-year Reanalysis
LN	La Niña, which is defined by SST anomaly (smaller than -1 standard deviation) at Niño-3.4
NCEP	National Centers for Environmental Prediction
NW	Northwest sector of the WNP (17°N–30°N, 120°E–140°E)
PHI	Philippines
RCM	Regional Climate Model
RH600	Relative Humidity at 600-hPa level
RV850	Relative Vorticity at 850-hPa level
SST	Sea Surface Temperature
SE	Southeast sector of the WNP (0°N–17°N, 140°E–180°E)
TC	Tropical Cyclone
VWS	Vertical Wind Shear (Difference in horizontal wind at 200 and 850-hPa levels)
WNP	Western North Pacific
ω_{600}	Pressure Velocity at 600-hPa level

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Chapter 1. Introduction

1.1. TC activity over the WNP and large-scale environment

Tropical cyclone (TC) is most active in the western North Pacific (WNP) where nearly one-third of total TC numbers over the world is generated (Figure 1.1). The WNP is the ocean basin with the largest number of intense TCs (yellow and red colors of tracks in Figure 1.1). In average, there are around 20 typhoons and 10 tropical storms in the WNP every year (Gray, 1967). Figure 1.2a,b,c,d shows the geographical distribution of TC genesis in the WNP in different seasons of year. In the peak storm season (JAS), more TCs generated and the TC genesis positions extended northward, compared with other seasons. Most of TCs (approximately 85%; Wu et al., 2012) occur in the WNP during June to November (Figure 1.3). During the storm season, many TCs possibly threaten countries in the East Asia and Southeast Asia, which can cause people losses and property damages. For instance, the typhoon Haiyan attacked Philippines, Vietnam, and China in November 2013. Estimated damages were around 4.55 billion USD, and 6300 people were killed. Therefore, more studies are expectantly conducted to enhance understandings of TC activity, which might help improve prediction of TC activity.

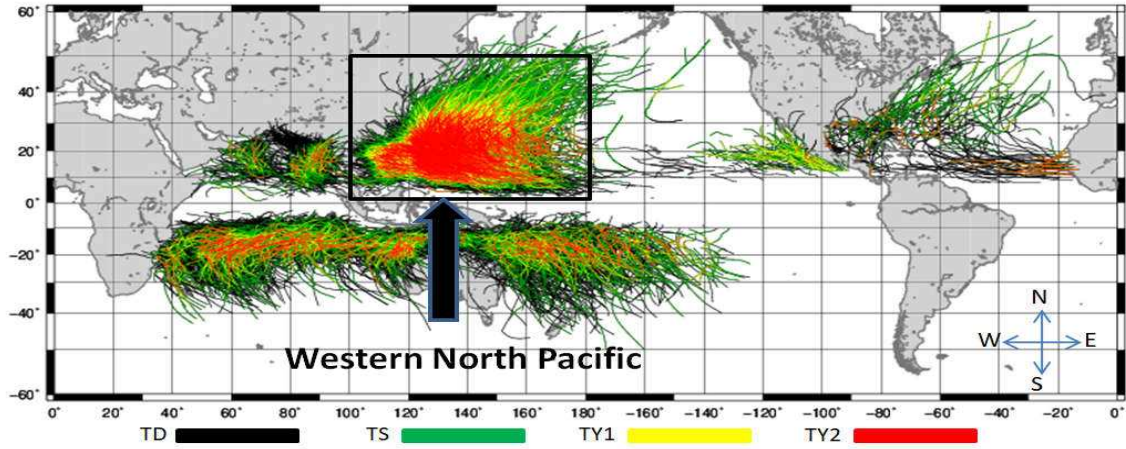


Figure 1.1 TC Tracks over the world during the period of 1951–2015. The black, green, yellow and red colors indicate Tropical Depression (TD; maximum wind speed is less than 17 m s^{-1}), Tropical Storm (TS; maximum wind speed is in a range of $17\text{--}32 \text{ m s}^{-1}$), Typhoon 1 (TY1; maximum wind speed is in a range of $33\text{--}42 \text{ m s}^{-1}$), Typhoon 2 (TY2; maximum wind speed is more than or equal to 43 m s^{-1}), respectively. The best track data provided by the Joint Typhoon Warning Center (JTWC) was used.

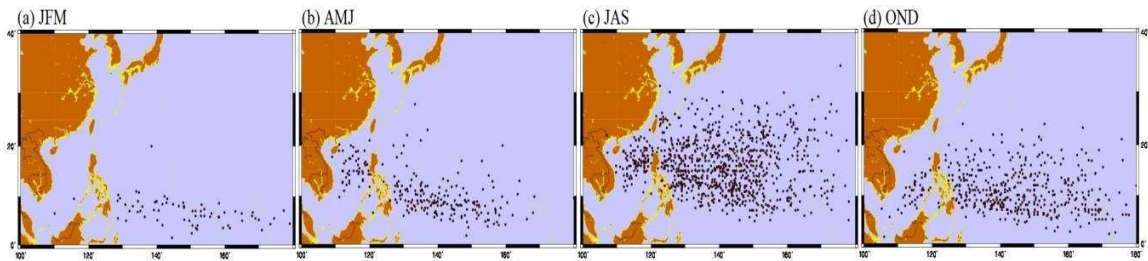


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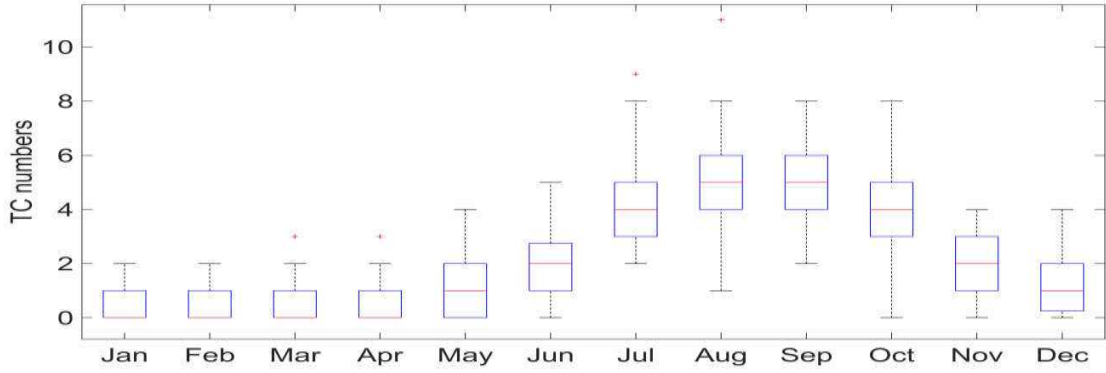


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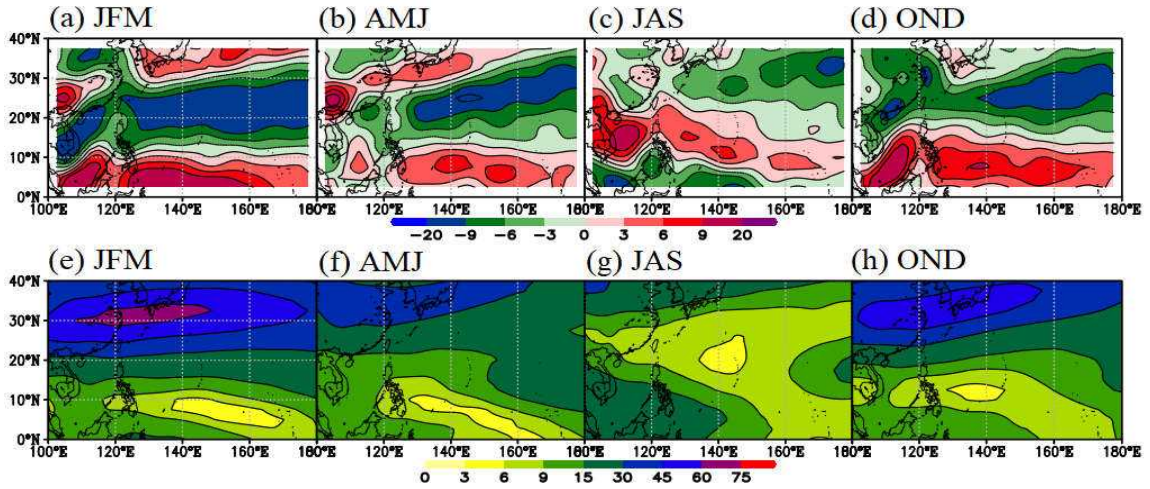


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Previous studies suggested that TC genesis directly relates to some environmental parameters (variables) such as low-level relative vorticity, vertical wind shear (VWS; i.e., the difference of horizontal wind vectors at certain vertical levels), sea surface temperature (SST), mid-tropospheric relative humidity (e.g., Gray, 1967; Malkus and Riehl, 1960; Miller, 1964; Leipper, 1967; Perlroth, 1967, 1969). SST and low-level relative vorticity are considered to be important factors to initiate development of TCs or tropical disturbances in atmospheric boundary layer. Gray (1977, 1967) mentioned that a slight enhancement in SST may cause a substantial increase in the equivalent potential temperature gradient between surface and middle troposphere, which has a strong influence on cumulus convection. Palmen (1948) also pointed out that TCs are unable to form over oceans where SST is below 26.5°C. Meanwhile, low-level cyclonic circulation represented by positive value of 850 or 925-hPa level relative vorticity helps converge mass and momentum from ambient environment into inner TC (Gray, 1977). Around 80–85% of TCs in the WNP are formed in Intertropical Convergence Zone (ITCZ) or monsoon trough where low-level relative vorticity is positive and large (Wu et al., 2012). Mid-tropospheric relative humidity can be related to the development of cumulus convection cells in TC warm core. A wetter mid-tropospheric layer (700 to 500-hPa) accumulates more energy in terms of enthalpy (Gray, 1977), in particular, when air mass is lifted in mid-tropospheric layer. A wet mid-tropospheric layer allows more condensation heat to be released, which heats the air mass and enhances deep cumulus convection. Inversely, vertical wind shear hinders development of TCs because strong wind shear prevents accumulation of enthalpy in TC warm core. Gray (1967) evidenced that most of TCs generated in environment with weak wind shear. Figure 1.4 indicates climatology of the large-scale environmental variables. In the peak storm season (JAS), area with high positive RV850 (red color; Figure 1.4c) and low VWS (yellow color; Figure 1.4g) extends northward, which supports more TC geneses between 5°N–30°N of the WNP (Figure 1.2c). Meanwhile, in other seasons (JFM and AMJ), area with high positive RV850 and low VWS retreats southward (Figure 1.4a,b,e,f). Consequently, the TC genesis positions are closer to the equator (Figure 1.2a,b). The results in Figure 1.4 illustrate that the large-scale environmental fields are changed season-by-season, followed by shift in distribution of TC genesis (Figure 1.2).

1.2. ENSO and its effects on large-scale environment

The El Niño–Southern Oscillation (ENSO) is a tropical atmosphere–ocean interaction mode consisting of three phases (El Niño, La Niña, and Neutral). El Niño (EN) and La Niña (LN) phases are identified by the warming and cooling of sea surface temperature (SST), respectively, compared to climatology, at the Niño-3.4 (5°S–5°N; 170°W–120°W) region of the Pacific. Recently, another type of ENSO has been found. The warm phase was separated into two types: the eastern Pacific warming (EPW) and central Pacific warming (CPW). Similarly, the cold phase was divided into the eastern and central Pacific cold (EPC and CPC). According to this classification, EPW (CPW) and EPC (CPC) were determined by the warming and cooling state of SST at the Niño-3 (Niño-4) of the Pacific.

Effects of ENSO on large-scale environment around tropics and subtropics were revealed in previous studies (e.g., Bjerknes, 1969; Wang et al., 2000; Wu et al., 2003; Wu et al., 2012). In fact, ENSO links with the Walker circulation (Bjerknes, 1969). In EN years, the warming of SST in the Niño-3.4 stimulates ascending motion in the atmosphere at the equatorial central Pacific, accompanied by the strengthening of Walker circulation-related low-level westerly over equatorial WNP. Inversely, LN years are characterized by the cooling of SST at equatorial central Pacific but with the warming at the west of the equatorial WNP (near Indonesia). Ascending motion in the atmosphere, thus, occurs around Indonesia, corresponding to the strengthening of Walker circulation-related low-level easterly over the equatorial WNP. ENSO also modulates the subtropical high and East Asian trough. EN years accompany an eastward withdrawal of subtropical high (Wang et al., 2000; Wu et al., 2003), and the deepening of the East Asian trough (He et al., 2013). Wu et al. (2012) showed EN years are accompanied by an eastward extension of monsoon trough. Therefore, ENSO modulates some environmental factors in tropics and subtropics such as low-level wind and vertical velocity, which might importantly affect TC activity.

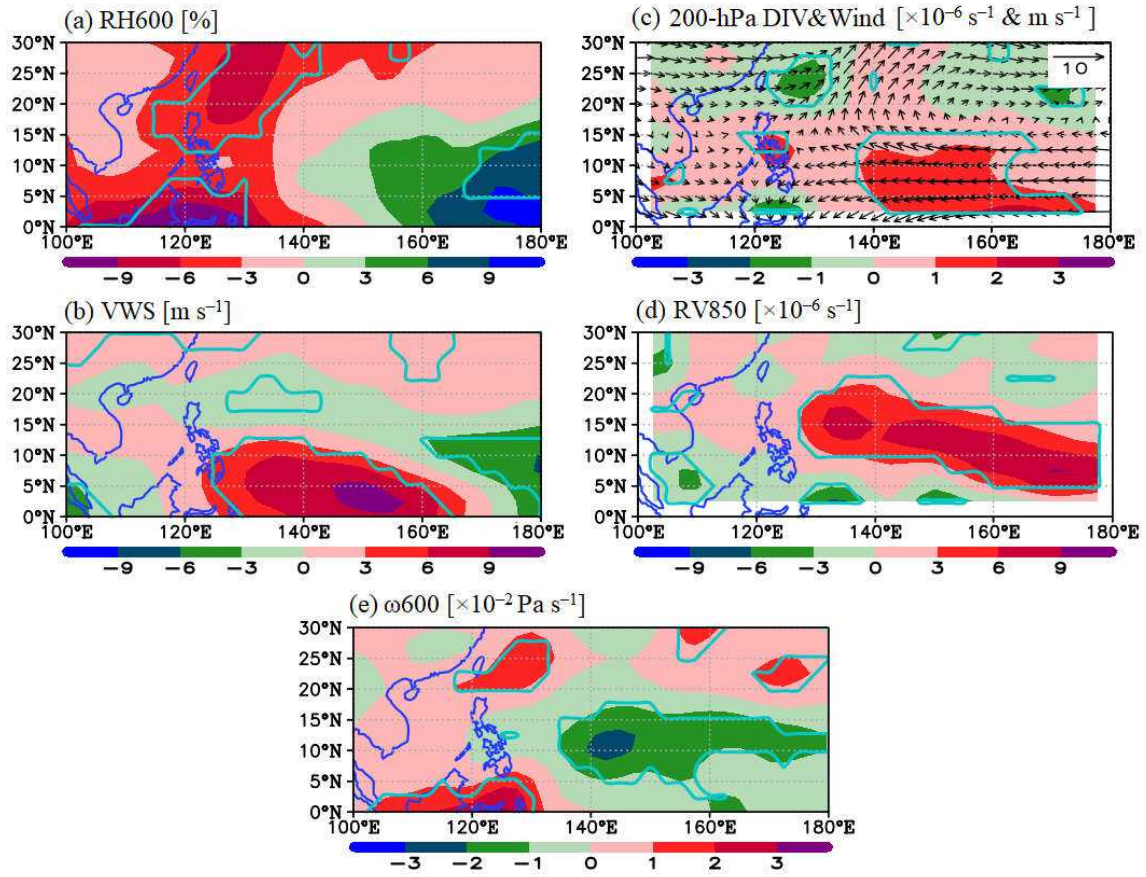


Figure 1.5 Difference in averaged environmental variables (June to October) between eight EN and eight LN years during 1970–2015. (a) RH600 (%), (b) VWS (m s^{-1}), (c) Divergence (DIV200; $\times 10^{-6} \text{ s}^{-1}$) and horizontal wind at 200-hPa (m s^{-1}), (d) RV850 ($\times 10^{-6} \text{ s}^{-1}$), and (e) pressure velocity at 600-hPa (ω_{600} ; $\times 10^{-2} \text{ Pa s}^{-1}$). Thick contours indicate the areas where the difference is statistically significant ($p = 0.05$). The JRA55 data was used. See more in Section 3.4.

Figure 1.5 indicates difference in five selected large-scale environmental variables between EN and LN years. In EN years, 850-hPa level relative vorticity (RV850) dramatically increases in the southeast of the WNP (Figure 1.5d), compared to LN years, implying the eastward extension of monsoon trough. Also, there is a significant increase in 600-hPa level relative humidity (RH600) and decrease in vertical wind shear at the equatorial central Pacific near 180°E. Meanwhile, in the west of 140°E, in EN years,

RH600 significantly decreases and vertical velocity significantly increases, particularly in the northwest of the WNP (Figure 1.5a,e). The reason can be attributed to an association between the East Asian trough and subtropical high, leading to a convergence at 200-hPa level in EN years (Figure 1.5c).

1.3. Impact of ENSO on TC activity

1.3.1. TC genesis

Figure 1.6a,b exhibits that the climatology of TC genesis extends eastward in EN years while it retreats westward in LN years. The significant difference in TC genesis between EN and LN years (Figure 1.6c) implies that there are more TC geneses in the southeast sector and less TC geneses in the northwest sector of the WNP in EN years, compared to LN years, which is consistent with the finding of Wang and Chan (2002). More specifically, Table 1.1 quantitatively measures the changes in the mean TC genesis positions between conventional ENSO years. The mean TC genesis positions in JAS, compared between strong EN and strong LN years, dramatically shift in the north-south direction (approximately 6 degree latitudes; Table 1.1). In other words, in JAS of strong EN years, the mean positions move southward, compared to strong LN years. Meanwhile those in OND, compared between strong EN and strong LN years, significantly change in the west-east direction (approximately 18 degree longitudes; Table 1.1). In other words, in OND of strong EN years, the mean TC genesis positions shift eastward, compared to strong LN years. Inversely, changes in the mean TC genesis positions, compared between moderate EN and moderate LN years, are not really apparent. Thus, it is implicated that strong ENSO years have stronger impact on the TC genesis position than moderate ENSO years.

Table 1.1 Deviations of mean TC genesis locations in ENSO years relative to normal years. Positive (negative) values in latitudes and longitudes indicate northward (southward) and eastward (westward) shifts of TC genesis, respectively. The bold numbers indicate that the difference is statistically significant ($p = 0.05$). The calculation was done for July to September (JAS), October to December (OND), and July to December (JASON) in 1965–1999. Source: Wang and Chan (2002).

Years	JAS		OND		JASON	
	Lat	Lon	Lat	Lon	Lat	Lon
Strong EN	-2.5	5.8	-1.5	9.4	-2.7	6.7
Moderate EN	-0.1	3.7	-0.7	0.9	-1.1	2.4
Moderate LN	2.2	-0.2	0.5	-4.6	0.1	-1.1
Strong LN	3.8	-2.6	0.5	-8.5	2.4	-4.5

From physical perspective, in the southeast of the WNP, the enhanced TC genesis counts in EN years are attributed to an increase in the relative vorticity at 850-hPa level, compared to LN years (Chen et al., 1998; Chan, 2000; Wang and Chan, 2002). Note that, the enhancement in low-level relative vorticity strongly links with eastward extension of monsoon trough (Wu et al., 2012). Meanwhile, in the northwest of the WNP, upper tropospheric convergence is intensified during EN years as a result of interaction between the East Asian trough and the subtropical ridge, which significantly decreases TC numbers compared to LN years (Wang and Chan, 2002). Recent studies revealed that the difference in mid-tropospheric humidity between the ENSO years also contributes to the difference in the pattern of TC genesis in the western part of the WNP near the Philippine Sea (Camargo et al., 2007; Kim et al., 2011; Chen and Tam, 2010; Lyon and Camargo, 2009).

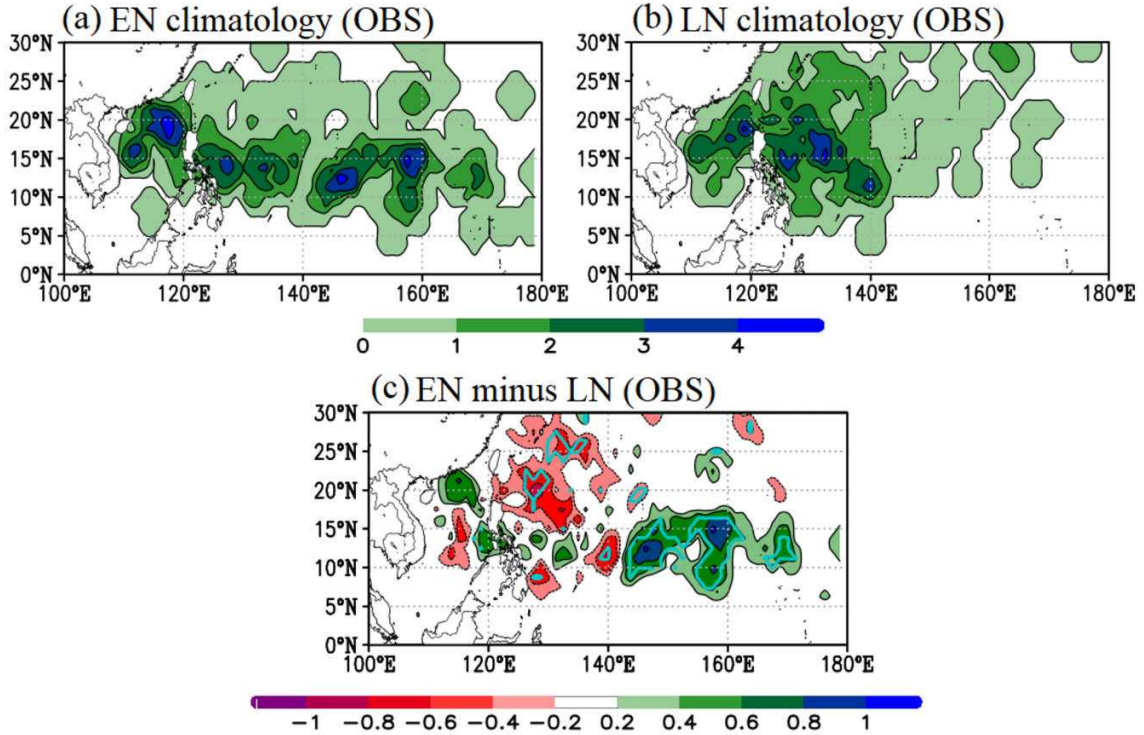


Figure 1.6 TC genesis climatology (shading; counts per year per $5^\circ \times 5^\circ$ box) in the storm season (June to October) for (a) eight EN years and for (b) eight LN years during 1970–2015. (c) Difference in TC genesis frequency (shading; counts per year per $5^\circ \times 5^\circ$ box) between eight EN and eight LN years. Thick contours represent the area where the difference is statistically significant ($p = 0.1$). For the drawing, TC genesis counts were interpolated onto a $1.25^\circ \times 1.25^\circ$ mesh grid. The JTWC best track data was used.

1.3.2. Track and landfall

The difference in TC tracks and landfall between EN and LN years mainly occurs in the late storm season (September to November). Specifically, there are 2.5 times more TCs recurving from southeastward to northeastward across 35°N (Wang and Chan, 2002). Wu et al. (2004) found less TC landfalls on China, Indochina peninsula, and Philippines in EN years in SON, compared to LN years (Table 1.2). The reason was attributed to the eastward (westward) displacement of TC genesis position in EN (LN) years, which tended to decrease (increase) the chance for TC landfalls in EN (LN) years (Wu et al., 2004). In

addition, anomalous westerly wind at high level in mid-latitude (around 30°N) pushes TCs northwestward and prevents TC landfall to East Asia (China, Korea and Japan) in EN years (Chan, 2000). Therefore, ENSO modulates TC track and landfall by modifying genesis location and large-scale steering flow.

Table 1.2 Mean TC landfall counts (unit: counts per year) in EN, LN, and Neutral (N) years in the period 1961–2000. Source: Wu et al. (2004).

Area	June - August			September - November		
	EN	LN	N	EN	LN	N
Korea-Japan	3	2.8	2.8	1.2	0.8	1.4
China	5.1	4.8	4.9	1.7	4	2.8
Indochina	1.8	1.3	1.5	1.7	3.8	2.9
Philippines	1.4	2	1.9	1.3	4.3	3.2

1.4. Impact of CPW and EPW on TC activity

Recently, some researches discussed the influences of the CPW and the EPW on TC activity (Kim et al., 2011) in addition to the conventional ENSO. In EPW years, the genesis and track density of TCs are enhanced over the southeast and suppressed in the northwest of the WNP (Kim et al., 2011). The extension of the monsoon trough and the weak wind shear over the central Pacific can be reason to increase TC activity in the southeast of the WNP (Kim et al., 2011). Meanwhile, in CPW years, more TCs formed nearly the south of Japan compared to climatology, which greatly threatens the southern part of Japan (Kim et al., 2011; Xu and Huang, 2015; Li and Wang, 2014; Wang et al., 2013). Kim et al. (2011) attributed a higher rate (not significant) of TC genesis near the south of Japan to a decrease of VWS in the CPW years. In Chapter 3, the axisymmetric model's ability in simulating TC genesis in EPW and CPW years was examined.

1.5. Unsolved issues

As addressed in Section 1.3, although many studies discussed TC activity in association with ENSO (e.g., Wang and Chan, 2002, Chen et al., 1998; Chan, 1985, 2000; Chan et al., 1998, 2001; Pudov and Petrichenko, 1998, 2001; Chia and Ropelewski, 2002; Wu et al., 2004; Camargo and Sobel, 2005; Kim et al., 2015; Villafuerte et al., 2015), physical mechanisms linking between environmental factors and TC features were mainly explained in terms of anomalous large-scale environmental conditions. For instance, strengthening of low-level relative vorticity controls increased TC genesis counts in southeast sector while lower mid-tropospheric relative humidity accounts for decreased TC genesis counts in northwest sector of the WNP in EN years, compared to LN years. However, aforementioned studies did not argue interaction effects between environmental variables to TC genesis in association with ENSO (ENSO-related TC genesis). In reality, large-scale variables interact each other. It means that the variation of a particular environmental variable also affects other variables. For example, reduction of low-level relative vorticity induces weakening of low-level cyclonic circulation which might lead to the decrease in relative humidity in middle troposphere. Therefore, it is difficult to isolate the contribution of individual variable to ENSO-related TC genesis. Camargo et al. (2007, 2009) adopted Genesis Potential Index (GPI) to examine the contribution of environmental variables to ENSO-related TC genesis. In this regard, the study demonstrated the statistical relationship denoting the important role of mid-tropospheric relative humidity for TC formation in the northwest sector; however, the dynamical processes behind this were not elucidated. Thus, studies that use dynamical models are required to enhance the understandings.

In recent decades, many studies have employed full dynamical models (i.e., GCMs and RCMs) to study the TC activity in association with ENSO (e.g., Bell et al., 2014; Li and Wang, 2014; Shaevitz et al., 2014; Wu and Lau, 1992; Yu et al., 2016; Zhang et al., 2016). The advantage of this kind of model is the capability of describing physical processes and interaction processes between large-scale environment and TC activity. Many studies examined future change in TC activity as a response to large-scale

environment in global warming condition (e.g., Wang and Wu, 2012; Wehner et al., 2018; Murakami et al., 2012; Knutson et al., 2015). It was revealed that TC genesis frequency reduces but TC intensity increases in the global warming condition (Wehner et al., 2018; Bengtsson et al., 1996; Knutson et al., 2015; Zhang and Wang, 2017; Gualdi et al., 2008; Emanuel, 2013). The reasons were attributed to changes in large-scale atmospheric conditions, such as convective instabilities, vertical wind shear, low-level vorticity, mid-tropospheric vertical velocity. Krishnamurthy et al. (2016) investigated the behavior of TCs to the strength of ENSO events. Some other studies pointed out the remote effects of SST-related modes on TC activity, such as the Pacific Meridional Mode (PMM; Zhang et al., 2016), the tropical North Atlantic SST variability (Yu et al., 2016; Huo et al., 2015; Zhang et al., 2017; Gao et al., 2018), the Indian Ocean variability (Du et al., 2011), North Atlantic Gyre Oscillation (Zhang et al., 2013), and the Pacific Decadal Oscillation (PDO; Lee et al., 2012; Liu and Chan, 2003; Girishkumar et al., 2015). As mentioned above, although effects of large-scale environment on ENSO-related TC activity have been discussed by many studies, individual contribution of each large-scale environmental variable to ENSO-related TC genesis has not yet been examined. Thus, present study aims to focus on this issue. Note that, Zhao et al. (2011) and Wang and Wu (2012) used an axisymmetric model to isolate individual contribution of SST and vertical wind shear on TC activity. However, this work was done for interannual variation of TC intensity. In addition, TC genesis and tracks used in these studies were derived from the best track dataset. Shen et al. (2018) used a multi-member ensemble simulation performed by GCMs to analyze the sensitivity of TC activity to sea surface temperature (SST), large-scale steering flow, and vertical wind shear. It was revealed that both SST and large-scale steering flow influence TC tracks. However, the individual contribution of SST and steering flow to TC tracks was not separated. It is difficult to assess this with full dynamical models because SST and steering flow are interacting each other in the model. Even if artificially modified SST is prescribed in the model, the SST will modulate the steering flow as well so that it becomes impossible for us to distinguish the effects of SST and steering flow on TC track. Thus, present study proposes an axisymmetric model that enables to examine the role of individual

environmental variables to TC activity. More details of this model will be discussed in Section 1.6.

1.6. The axisymmetric model

The axisymmetric model was assumed that a storm has axisymmetric structure and airflow is in hydrostatic and gradient wind balance (Emanuel et al., 2004). Since primitive equation system of this model did not include vertical wind shear, Emanuel (1995) setup an additional term as effects of wind shear on TC intensity in middle-layer moist entropy equation. Schubert and Hack (1983) transformed the model's equations into angular momentum coordinate, permitting a very high radial resolution of the critical inner-core region using only a limited number of radial nodes. Note that, this model had just been used to predict the intensity of TC. Emanuel et al. (2008) proposed a new downscaling framework in which the simple axisymmetric model is used to diagnose future change of TC activity in the global warming condition. In this framework, TC tracks were determined by the large-scale steering flow and β -effect. TC intensity, then, was evaluated by putting the environmental variables along the TC track into the axisymmetric model. The benefit of this framework is to assess the potential of synoptic environment (i.e., relative vorticity and humidity) in generating and developing TCs. Emanuel et al. (2004) and Emanuel (2006) employed this model to examine effects of environmental factors such as potential intensity, storm track, wind shear, and upper-ocean thermal structure on TC intensity. The results demonstrated that the model is capable of reproducing the intensity evolution of TCs. Emanuel et al. (2008) showed that the model can replicate interannual variation of TC activity in different ocean basins over the world. However, the model's skill in simulating TC activity was lower in the WNP than in the Atlantic. Sato et al. (2011) improved the model's skill in simulating the interannual variation of TC activity in the WNP by incorporating the empirical weighting of 850-hPa relative vorticity. Zhao et al. (2011) and Wang and Wu (2012) used the axisymmetric model to examine interannual variations of ENSO-related TC intensity and changes in TC intensity in the global warming condition, respectively. Note that, in Zhao et al. (2011) and Wang and Wu (2012), the genesis

positions and TC tracks were based on the best track; thus, their model did not predict the genesis and track. The present study attempted to evaluate the effects of ENSO on TC genesis and track. Therefore, all TC features were predicted by the method described in Section 2.2. The results will prove that the axisymmetric model has a potential in predicting TC activity based only on the large-scale environment. Another benefit of this model is that it can be used to investigate the individual contribution of each environmental variable to TC features. For utilizing this benefit, this study proposed a methodology of sensitivity experiment which will be summarized in Section 1.7.

1.7. The purpose of the study

As addressed in Section 1.5, the role of individual environmental variables to ENSO-related TC genesis anomaly has not been examined yet although many studies pointed out the effect of ENSO on TC activity over the WNP. Thus, this study aims to reveal key environmental fields regulating ENSO-related TC activity over WNP. Since it is difficult to evaluate the effect of each environmental variable to the TC activity by using a full dynamic model, this study adopted the axisymmetric model. Through the analysis of TC activity in response to the anomalous synoptic environment, this study also examines the potential of large-scale environment in predicting TC activity. The success of this study helps enhance the understandings of role of individual environmental variable to ENSO-related TC activity and provide useful information for the prediction of TC activity in seasonal timescale. Main objectives of this research are summarized as the followings.

- To reveal key environmental factors controlling TC genesis in association with ENSO over the WNP.
- To examine the potential of large-scale environment in predicting TC activity in association with ENSO over the WNP.

Chapter 2. Data and Methodology

2.1. Data

The monthly mean atmospheric variables including air temperature (T_a), wind (U and V), and relative humidity (RH) were used. The data of all variables was derived from the Japanese 55-year reanalysis (JRA55; Ebita et al., 2011; Kobayashi et al., 2015) with a horizontal resolution of $1.25^\circ \times 1.25^\circ$. Monthly mean SST from the Extended Reconstructed SST dataset with horizontal resolution of $1^\circ \times 1^\circ$ (ERSSTv2; Smith and Reynolds, 2004) was used after re-gridding to $1.25^\circ \times 1.25^\circ$. The TC best track datasets provided by the Joint Typhoon Warning Center (JTWC), Japan Meteorological Agency (JMA) and China Meteorological Administration (CMA) were used to verify simulations. All datasets were used for the period 1970–2015.

The detrended SST anomaly (SSTA) over the Niño-3.4 region (5°S – 5°N ; 170°W – 120°W) averaged during June to October for each year in the period 1970–2015 was used to identify conventional El Niño (EN) and La Niña (LN) years (conventional ENSO). EN (LN) years were assigned if SSTA were larger than +1 (smaller than -1) standard deviation of SST at the Niño-3.4 region (Figure 2.1), following the criteria by Wang and Chan (2002). I selected eight strongest EN and eight strongest LN years as the targeted years of this study (Table 2.1). I also examined the response of TC activity to conventional EN/LN and other SST modes including the Eastern Pacific warming (EPW) and Central Pacific warming (CPW) years. Selections of EPW and CPW years were similar with those of EN years but based on SSTA averaged over the Niño-3 (5°S – 5°N ; 150°W – 90°W) and Niño-4 (5°S – 5°N ; 160°E – 150°W) regions, respectively (Kim et al., 2011). The selected years were summarized in Table 2.1.

Table 2.1 Lists of EN, LN, EPW, and CPW years.

ENSO type	YEAR							
EN	1972	1982	1987	1991	1997	2002	2009	2015
LN	1970	1971	1973	1975	1988	1998	1999	2010
EPW	1972	1976	1982	1987	1997	2009	2015	
CPW	1991	1994	2002	2004				

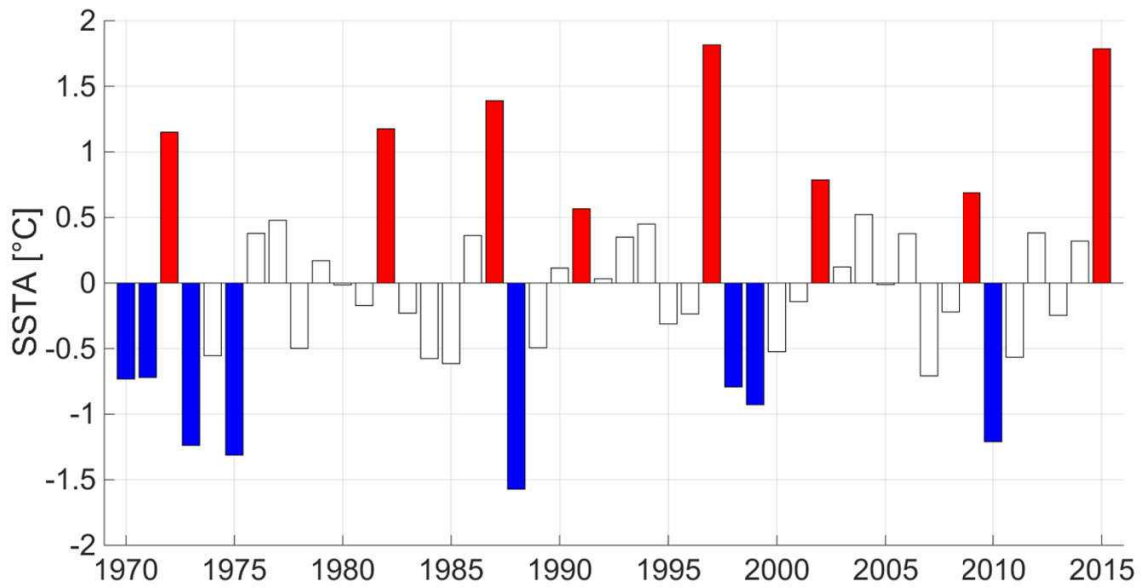


Figure 2.1 Interannual variation of detrended Niño-3.4 SST anomaly (SSTA) averaged over June to October. Red and blue bars represent EN and LN years.

2.2. Model

The axisymmetric model was designed to assess the potential of synoptic environment in generating and developing TCs. The monthly mean environmental variables, such as mid-tropospheric relative humidity at 600-hPa level (RH600), SST, relative vorticity at 850-hPa level (RV850), vertical wind shear (VWS; difference in horizontal wind between 200 and 850-hPa levels), and large-scale steering flow, were used as the model forcing. The model "run" was conducted by monthly basis. In each run, there

were many "simulations" conducted by the axisymmetric model using monthly mean atmospheric and oceanic variables. As mentioned later, the number of axisymmetric model simulations (i.e., the number of simulated TCs for each month) is usually larger than the real TCs that were observed in each month. Each simulation predicts the evolution (position, track, and intensity) of each TC.

The simulation of each TC was subdivided into three steps: TC seeding, tracks, and development. The TC seeding process was intended to determine the genesis distribution and genesis probability of TC at each grid box as described in Section 2.2.1. The track of each TC was identified by large-scale steering flow and β -effect as described in Section 2.2.2. Development of TC was calculated by an axisymmetric model as described in Section 2.2.3. To predict TC intensity, the large-scale environmental variables surrounding the TC are updated every six hour as the locations of the modeled TC changes along the TC track. Note that, monthly mean environmental variables are used to constrain axisymmetric model. Figure 2.2 illustrates the model experiment procedures described in Sections 2.2.1, 2.2.2, and 2.2.3.

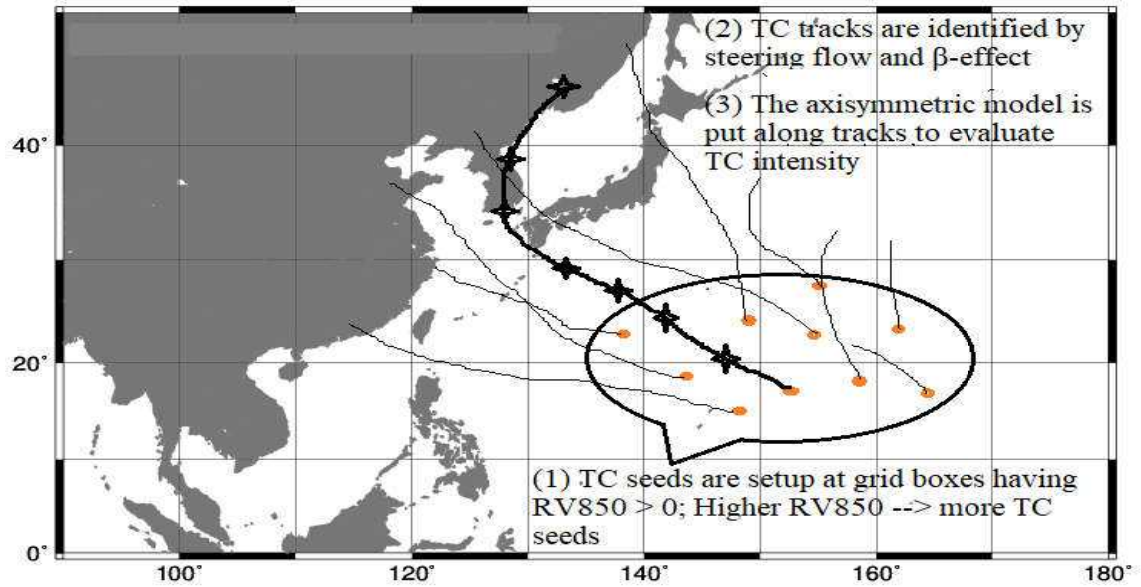


Figure 2.2 Three processes of the model run: (1) TC seeding process (as Section 2.2.1), (2) TC tracks (as Section 2.2.2), and (3) TC intensity evaluation (as Section 2.2.3). Yellow dots display TC seeds setup at grid boxes based on $RV850$ magnitude. Black bold line shows TC tracks identified by large-scale steering flow and β -effect. Asterisks on the bold black contour show the locations where the axisymmetric model was placed to evaluate TC intensity. Time interval between two asterisks along the track (i.e., the interval of updating track) was six hours. Note that, monthly mean environmental fields (e.g., $RH600$ and VWS) were used for all TCs in each month.

Figure 2.3 illustrates a result of particular run for October 1970. Monthly mean fields of $RH600$, $RV850$, VWS , and SST were used to simulate all TCs in Figure 2.3.

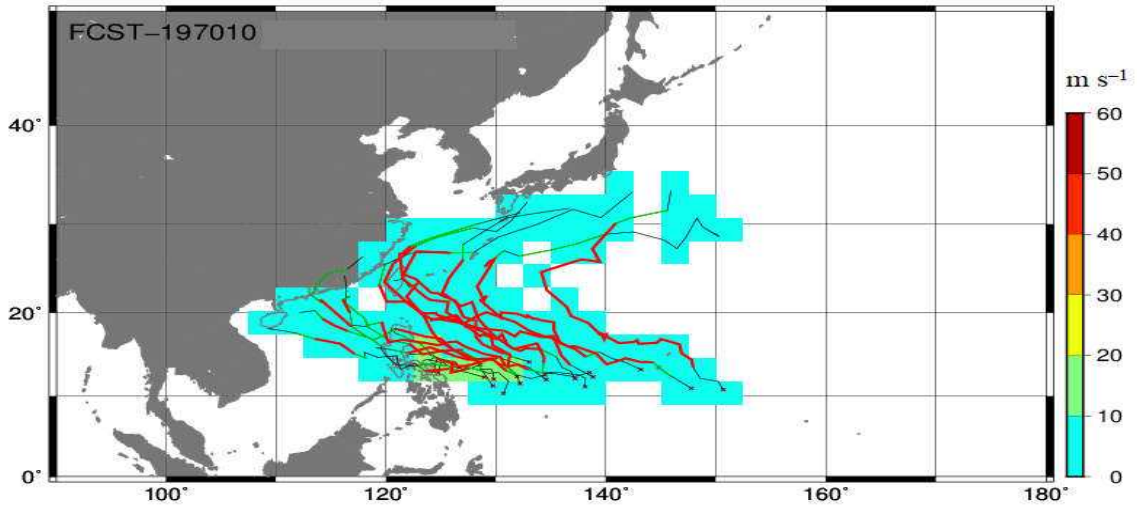


Figure 2.3 An example of the model run for 1970 October. Mean TC intensity (average of maximum wind speed) is displayed by color (unit: m s^{-1}). Cross marks represent TC seed positions.

As Saffir-Simpson scale, the classification of TCs is based on their intensity. A TC is assigned as a tropical depression or tropical storm if its maximum wind speed is below or above/equal to 17.2 m s^{-1} , respectively. In this study, only tropical storms were analyzed. Thus, hereafter, tropical storms are called as TCs, and TC seeds can be considered as tropical depressions. In the simulation, TC seeds were setup at grid box with initial maximum wind speed of 12 m s^{-1} (see Section 2.2.1). A TC was assigned when the intensity of TC seed reached 17.2 m s^{-1} . Genesis location was defined as the first position where the TC was assigned. Then, the evolution of the TC was calculated further until its intensity dropped below 17.2 m s^{-1} (i.e., tropical depression). Life span of the TC was defined as the duration since the TC seed was assigned as the TC until the TC returned tropical depression. During the life span of TC, maximum wind speed must be above or equal to 17.2 m s^{-1} . In this study, only TCs with life span longer than 48 hours were analyzed. The reason for applying life span threshold of 48 hours is to remove short-lived and weak tropical disturbances. The simulations with the threshold of 48 hours performed the highest correlation with the best track in respect to the geographical distribution of genesis frequency.

There are some points that need attention. Firstly, the axisymmetric model was designed to simulate the genesis and track of potential TCs, rather than accurately producing TC features in a given month/year. The TC numbers produced by the model were much larger than those observed. Thus, relative variation of TC features was analyzed instead of the absolute number. Secondly, although it is possible for the axisymmetric model to simulate TCs under more realistic conditions using high temporal resolution fields (e.g., daily data) as a forcing, this study employed the monthly mean fields as input data. Because the main objective of this study is to examine TC features in seasonal timescale in association with ENSO. The ENSO is a low frequency oscillation, which persists, at least, timescale of some months or season. Meanwhile, the daily data might consist of high frequency modes of oceanic and atmospheric variability. To investigate the synoptic scale anomaly that was generated by ENSO forcing, thus, monthly data is more appropriate than the daily data.

2.2.1. TC seeding process

To evaluate the effects of environmental conditions for generating TCs in the WNP, TC seeds having initial maximum wind speed of 12 m s^{-1} were setup at each grid box. The TC seeds are imposed at all grid boxes where RV850 is greater than zero. The number of TC seeds, which represents the potential of genesis, was determined by the method proposed in Sato et al. (2011). The number of TC seeds at each grid box (N) was decided by the following equation.

$$N = \min \{1 + 2.5 \times \text{RV850} \times 10^5, 5\} \quad (2.1)$$

This implies that monthly TC genesis number at each grid box increases with monthly mean RV850 at corresponding grid box. TC seeds were randomly distributed in the grid box. Whether these TC seeds reach the intensity of TC or not depends on other environmental variables (i.e., RH600, SST, and VWS) which are used to evaluate TC intensity in an axisymmetric model (Section 2.2.3).

2.2.2. TC tracks

At every six hour, tracks for each TC were computed by the large-scale steering flow and β -effect. The large-scale steering flow was determined by the weighting average of monthly mean 850, 700, 500, and 200-hPa wind field with weighting coefficients of 0.1, 0.2, 0.5, 0.2 as the equation 2.3, respectively (Sato et al., 2011). The daily-scale wind fluctuation effect was added to the monthly mean wind fields at four levels as the following equation (Emanuel et al., 2006).

$$U = \bar{U} + F \times \sqrt{\overline{U'^2}} \quad (2.2)$$

where U (zonal and meridional components) is the wind field at four levels after added daily-scale fluctuation, $\bar{U}$ is monthly mean wind field, $\overline{U'^2}$ is variance of daily wind over the month, and F is a random number ranging from -1 to 1. The β -effect was simply incorporated as a linear function of latitude following Wu and Wang (2004). Then, the steering flow was combined by of horizontal wind field at four levels (850, 700, 500, 200-hPa) computed by the equation 2.2 and β -effect as the following.

$$\text{Steering flow} = 0.1U(850) + 0.2U(700) + 0.5U(500) + 0.2U(200) + \beta\text{-effect} \quad (2.3)$$

2.2.3. Axisymmetric model

The axisymmetric model used in this study was described in detail in Emanuel (1995). The model assumes that the storm is in axisymmetric structure, and the airflow is in hydrostatic and gradient wind balance (Emanuel et al., 2004). The model variables are phrased in potential radius coordinates (Schubert and Hack, 1983). Potential radius (R) is proportional to the square root of the absolute angular momentum per unit mass about the storm center (Emanuel et al., 2004) and is defined by

$$fR^2 = 2rV + fr^2 \quad (2.4)$$

where V is the azimuthal velocity, f is the Coriolis parameter, and r is the physical radius from the storm center. The vertical structure of the model consists of two layers

(boundary and middle troposphere layers). Processes of deep and shallow cloud for development of TC warm core are performed in middle troposphere layer. Relative humidity at 600-hPa was used for this layer. SST was used for surface (boundary) layer. The effect of vertical shear in middle troposphere is parameterized in the prognostic equation for middle level entropy (Sato et al., 2011).

$$\frac{\partial \chi_m}{\partial t} = \dots - \alpha V_{\text{shear}}^2 V_{\text{max}}^2 (\chi_m - \chi_{m0}) \quad (2.5)$$

where α is a coefficient of shear influence, V_{shear} is the wind shear between the 850 and 200-hPa, V_{max} is maximum horizontal wind speed, χ_m is the middle layer moist entropy variable, and χ_{m0} is its ambient environmental value. In this study, α is equal to 0.005 as the control experiment in Sato et al. (2011). The time step for the model's integral in predicting TC intensity is 20 seconds.

2.2.4. How environmental variables affect development of TC in the model

a. Low-level relative vorticity (850-hPa relative vorticity - RV850)

From a physical perspective, low-level cyclonic circulation (represented by positive RV850) ensures a supply of mass, momentum and water vapor, which sustains cumulus convection in the TC warm core (Gray, 1977). High positive RV850 condition in association with synoptic disturbances such as monsoon trough, intraseasonal variation, and easterly wave contains cumulus convective systems which play an important role in initiating development of TCs. Thus, higher positive RV850 implies more cumulus convective systems that might result in more TC geneses. Sato et al. (2011) improved the framework of axisymmetric model experiment in simulating interannual variation of TC activity in the WNP by setting up the empirical function of RV850 as the equation 2.1. It implicates that the number of simulated TC seeds strongly links with that of cumulus convective systems in monsoon trough and intraseasonal variation (equation 2.1). Therefore, although the effect of RV850 is not explicitly included in the axisymmetric model, it indirectly controls TC genesis counts through the number of TC seeds as described in the equation 2.1 (Section 2.2.1).

b. Vertical wind shear (VWS)

Vertical wind shear (VWS), which is defined as difference in horizontal wind velocity between 200 and 850-hPa levels, plays an important role in hindering accumulation of humidity in mid-tropospheric layer (Gray, 1967). Thus, high VWS prevents the development of convection cells in TC warm core. The effect of VWS is parameterized in middle level moist entropy equation (Section 2.2.3). Emanuel et al. (2004) examined the effect of vertical wind shear on evolution of TC intensity in the axisymmetric model for some TCs. The results showed that, in the experiments with the effect of wind shear, the simulated evolution of TC intensity was close to realistic condition. While in the experiments without the effect of wind shear, the simulated TC intensity developed quickly and was far from the observation.

c. Mid-tropospheric relative humidity (600-hPa relative humidity - RH600)

In reality, high mid-tropospheric relative humidity encourages development of deep convection by increasing enthalpy and precipitation efficiency (Gray, 1977). In contrast, low mid-level relative humidity acts to suppress deep convection because cumulus-induced condensation is likely to be re-evaporated, which cools the mid-tropospheric layer (Gray, 1977). This effect is included in the convective scheme based on subcloud-layer entropy equilibrium (Emanuel, 1989) in the model which is

$$\varepsilon_p = \frac{\chi_m - \chi_{m0}}{\chi_b - \chi_{m0}} \quad (2.6)$$

where ε_p is precipitation efficiency, χ_{m0} is the initial entropy deficit of the mid-troposphere, χ_m is entropy of the mid-troposphere, and χ_b is entropy in the boundary layer. Precipitation efficiency variable characterizes for deep convection. Higher ε_p implies deep convection is more active, and vice versa. Higher (lower) RH600 increases (decreases) χ_m , which results in more (less) ε_p .

$$M_u(\chi_b - \chi_m)[\lambda_{max}(1 - \varepsilon_p) + \lambda_{min}\varepsilon_p] \quad (2.7)$$

The term in (2.7) indicates the detrainment of entropy into the lower troposphere. M_u is the convective updraft mass flux at the boundary layer top. λ_{max} and λ_{min} are parameters that govern the rate of detrainment of cloud air in the lower troposphere (Emanuel, 1995). When $\varepsilon_p = 0$, a greater fraction of detrainment occurs in the lower troposphere, which implies occurrence of shallow clouds (Figure 2.4; Emanuel, 1995). While high ε_p , most of the detrainment happens in the upper troposphere, which implies deep clouds (Figure 2.4; Emanuel, 1995).

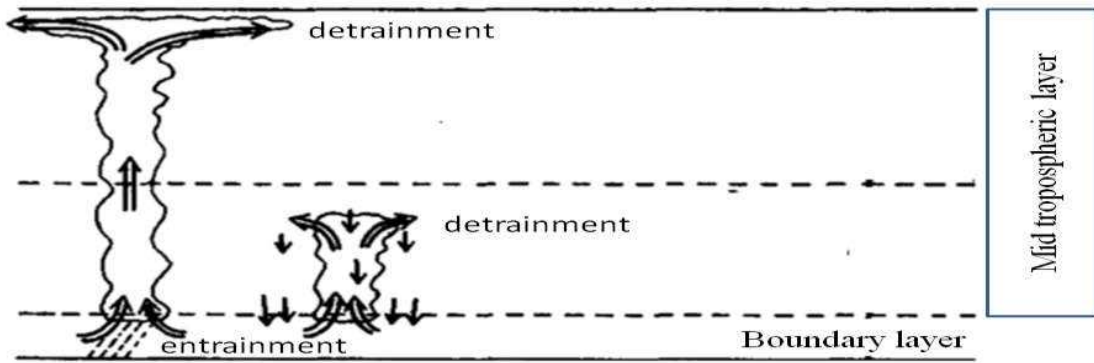


Figure 2.4 Vertical structure of the model includes two layers (boundary and mid-tropospheric layers). Shallow and deep clouds are calculated in mid-tropospheric layer. Source: Emanuel, 1989.

Note that, in the axisymmetric model, the instability state of atmosphere, which is related to cumulus cloud formation, is examined in two vertical layers (boundary and mid-tropospheric layers). Meanwhile, in full dynamical model, the instability state of atmosphere is identified in multiple vertical layers. Thus, in full dynamical model, an abrupt artificial increase (decrease) in relative humidity at 600-hPa level (RH600) as performed in the sensitivity experiments in Chapter 3 might stop the numerical integration because of computational instability. However, the sensitivity experiments in Chapter 3 can be done in the axisymmetric model. The sudden decrease of RH600 in the axisymmetric model simulation resembles the situation that the TC tends to be weakened when it is migrating into the region where middle tropospheric humidity is low.

Chapter 3. Effect of ENSO phase on the contribution of environmental variables to tropical cyclone genesis over the WNP

3.1. Introduction

The influences of the shift in TC genesis position on other features (life span, intensity, tracks and landfall) were introduced in Section 1.3 (Chapter 1). The mechanisms of ENSO-related changes in TC genesis position have been explained in terms of anomalous large-scale environmental conditions. In the southeast sector of the WNP, the relative vorticity at 850-hPa strengthens (weakens) during EN (LN) years compared with normal years as the monsoon trough extends eastward (retreats westward), which is associated with an increase (a decrease) in TC genesis numbers (Chen et al., 1998; Chan, 2000; Wang and Chan, 2002). In the northwest sector, upper tropospheric convergence is intensified during EN years as a result of interaction between the East Asian trough and the subtropical ridge, which significantly decreases TC numbers compared to LN years (Wang and Chan, 2002). Recently, many researches using full dynamical models studied TC activity in relation to ENSO. However, most of them focused on examining the model's skills in simulating TC activity, and the response of TC activity to various SST-related modes (i.e., IOD and PDO). A few studies pointed out the role of individual environmental variables on ENSO-related TC genesis. Thus, this part is expectantly examined contribution of each synoptic variable to ENSO-related TC genesis in the WNP by using a dynamical model.

To consider the complex response of TC activity to ENSO-related environmental anomalies, a dynamical model that can represent the statistical features of TCs is required. The axisymmetric model as described in Chapter 3 can replicate TC intensity under prescribed large-scale environmental variables, such as vertical shear, sea surface temperature (SST), and potential intensity (Emanuel, 1995; Emanuel et al., 2004). Since, this model enables to investigate effect of each input parameter to TC development, it is relevant to the goal of examining the role of individual environmental variable to ENSO-related TC genesis. For instance, to examine the role of humidity in TC genesis, it can discard the contributions of other input environmental variables by using climatological

values while retaining real values for the humidity field. Meanwhile, it is hard to do that work with a full dynamical model.

The objective of this Chapter is to reveal key environmental factors to the interannual variation of ENSO-related TC genesis anomalies. The rest of the Chapter is organized as follows. Section 3.2 describes experimental design. Section 3.3 presents the results of control and sensitivity experiments. Section 3.4 discusses results and summary.

3.2. Experimental designs

In this study, the contributions to TC genesis of four environmental variables, 600-hPa level relative humidity (RH600), SST, RV850, and vertical wind shear between 200 and 850-hPa levels (VWS), were examined for 16 conventional ENSO (EN and LN; Table 2.1) years. Each run was conducted for each month from June to October in 16 selected ENSO years (i.e., 80 runs in total) in the period 1970–2015. In each run, many TCs (see Figure 3 in Sato et al., 2011) were generated as described in Section 2.2. To evaluate the effects of ENSO-related anomalies in each variable on TC genesis, a series of experiments was conducted.

In the control experiment, all four input environmental variables were set to real monthly mean fields to confirm the ability of the model to simulate ENSO-related TC features. The control experiment is also referred to as RRRR, which indicates that all four variables, in the order RH600, SST, RV850 and VWS, were set to real fields of the targeted year. In the sensitivity experiments, some input environmental variables were replaced by the climatological mean fields so that the effect of year-to-year variation in the replaced variables was discarded. The replaced variables are indicated by the “C” flag; e.g. the experiment is referred to as RCRR if the SST field is replaced by the climatological mean while other variables vary interannually. The sensitivity experiments were divided into three groups: The 1R3C experiments in which only one variable was set to the real value while the other three variables were set to the climatology so that the contribution of the single variable can be highlighted: The 3R1C experiments in which only one variable was

set to climatology while the other three variables were set to real values: The 2R2C experiments in which two variables were set to real values and the other two to the climatology. Table 3.1 gives details of the experiments.

Table 3.1 Lists of sensitivity experiments together with the input parameter settings. R indicates the variable having realistic interannual variation while C indicates the variable set to climatology.

Run name	RH600	SST	RV850	VWS
CONTROL (CTL)				
RRRR	R	R	R	R
1R3C				
RCCC	R	C	C	C
CRCC	C	R	C	C
CCRC	C	C	R	C
CCCR	C	C	C	R
3R1C				
CRRR	C	R	R	R
RCRR	R	C	R	R
RRCR	R	R	C	R
RRRC	R	R	R	C
2R2C				
RCRC	R	C	R	C
CRCR	C	R	C	R

3.3. Results

3.3.1. Control experiment (RRRR)

To compare the pattern of TC genesis between observations and simulations, both observed and simulated TC genesis were re-gridded to $1.25^\circ \times 1.25^\circ$ mesh grids in the WNP (0°N – 30°N , 100°E – 180°E). Note that, TC genesis numbers in each grid box of $1.25^\circ \times 1.25^\circ$ were defined as TC genesis numbers within a surrounding $5^\circ \times 5^\circ$ grid box. Since the model assesses the potential of TC genesis, the simulated TC genesis numbers were much larger than the observed TC genesis numbers. Therefore, the simulated TC genesis numbers were multiplied by a factor of one-third to compare with the observation.

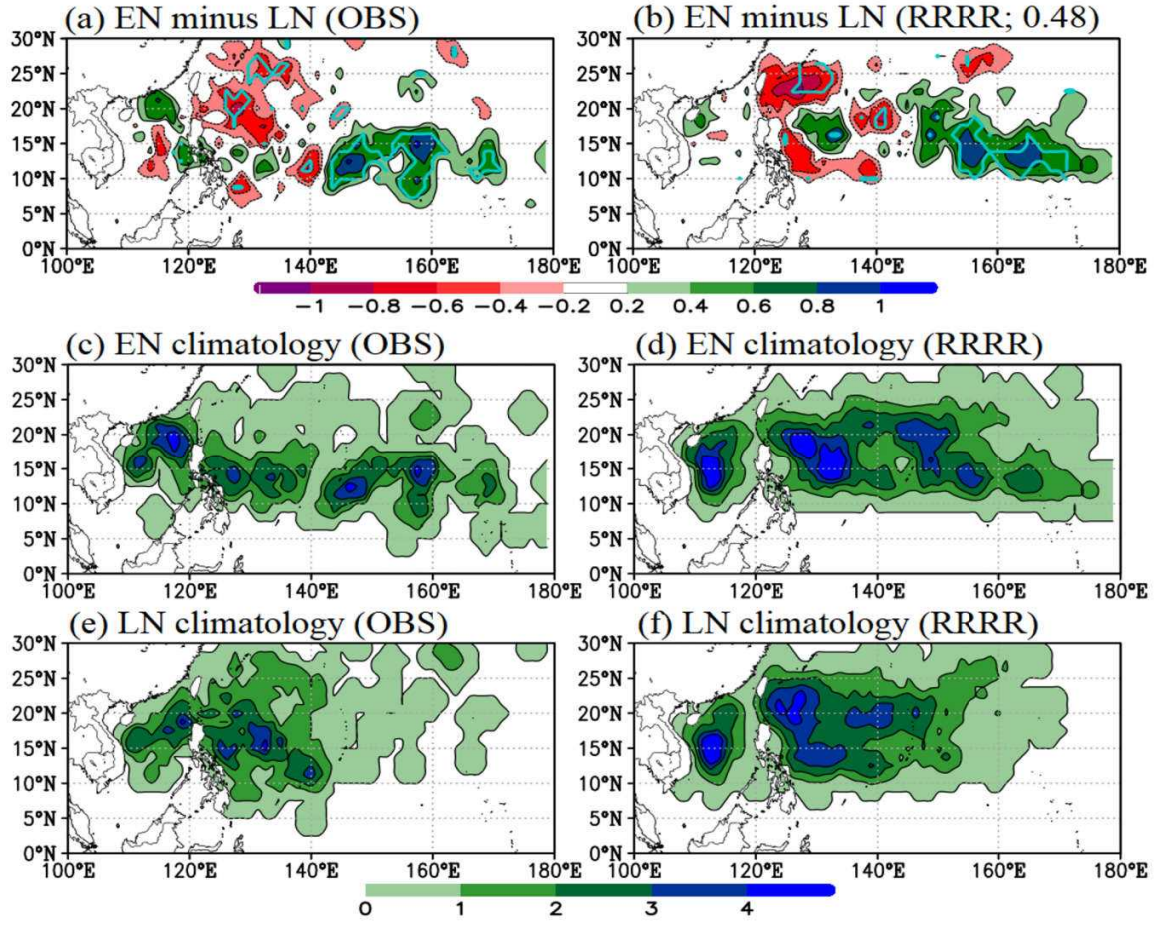


Figure 3.1 Difference in TC genesis frequency (shading; counts per year per $5^\circ \times 5^\circ$ box) between EN and LN years analyzed from (a) observations and (b) the RRRR experiment. For the drawing, TC genesis counts were interpolated onto a $1.25^\circ \times 1.25^\circ$ mesh grid. The TC frequency in simulation was multiplied by a factor of one-third. Thick contours represent the area where the difference is statistically significant ($p = 0.1$). The number in brackets at the top of the figure panel shows the spatial correlation of the anomalous TC genesis patterns (difference in genesis between EN and LN years) between the observation and simulation. TC genesis climatology for observation in (c) EN and (e) LN, and for RRRR in (d) EN and (f) LN are also shown.

Climatological genesis patterns of TC in EN and LN years for the observation and RRRR are shown in Figure 3.1c,e,d,f. In EN years, TC genesis position extends eastward over 140°E while in LN years it lies in the western side of 140°E . TC genesis patterns in RRRR are similar with those in the observation. Figure 3.1a,b illustrates the difference in

TC genesis pattern between EN and LN years. In the observations (Figure 3.1a), there is a significant decrease (increase) in TC genesis frequency in the northwest (NW; 17°N–30°N, 120°E–140°E) sector and a significant increase (decrease) in TC genesis frequency in the southeast (SE; 0°N–17°N, 140°E–180°E) sector of the WNP during EN (LN) years. The difference in TC genesis frequency between EN and LN is small in other areas of the WNP. These results are consistent with the findings of Wang and Chan (2002). Hereafter, it will be focused on the NW and SE sectors. The RRRR experiment (Figure 3.1b) shows a similar spatial distribution to the observations (spatial correlation is 0.48). This suggests that the model can capture a contrasting pattern of ENSO-related TC genesis anomalies in the NW and SE sectors. However, RRRR fails to simulate a significant increase in TC genesis frequency during EN years around 140°E–150°E. Because of the simplified model dynamics, it is clear that the model has some shortcomings in this ocean subdomain. However, it is suggested that the anomalies in TC genesis frequency over the NW and SE sectors are generated as a response to the anomalous environmental fields prescribed in the model. To confirm whether this result is not affected by the selection of years, the same analysis was performed by using randomly selected 14 years out of total 16 years (i.e., 7 EN and 7 LN years by excluding 1 EN and 1 LN years). After repetitions of 64 times, t-test was applied to determine the area satisfying 90% confidence level. This procedure was also applied for other analyses (Figures 3.2, 3.3, 3.4, 3.5).

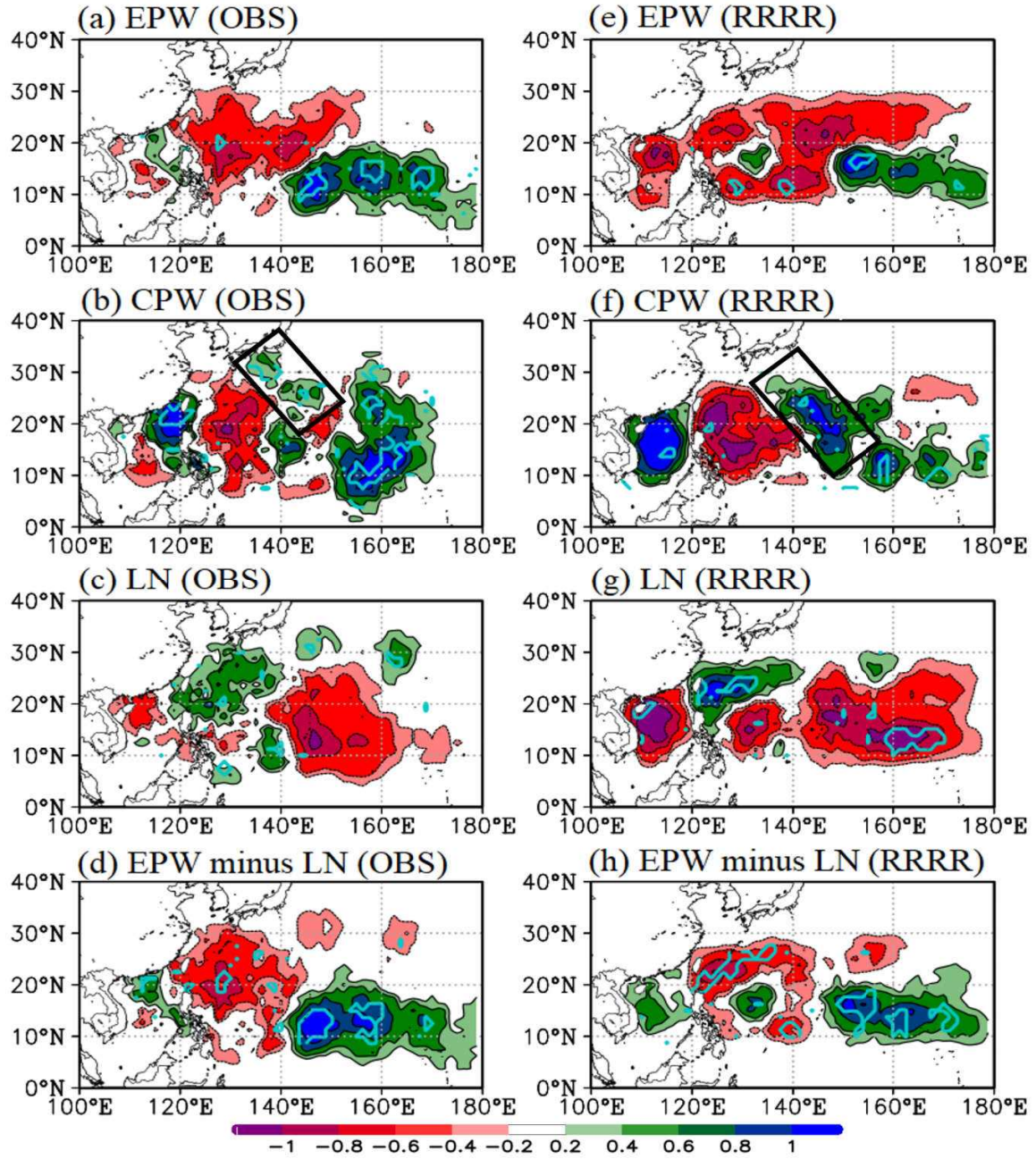


Figure 3.2 Anomalous TC genesis patterns in EPW years relative to climatology in (a) observation and in (e) RRRR. (b) and (f) Same as (a) and (e) but in CPW years. (c) and (g) Same as (a) and (e) but in the LN years. TC genesis difference between EPW and LN years in (d) observation and in (h) RRRR. Thick contours indicate significant difference ($p = 0.1$). Rectangle boxes in (b) and (f) indicate the area with increased TC genesis in CPW years.

Here, the performance of the model for CPW and EPW years was also examined, because in CPW years, there are positive TCs anomaly near the south of Japan compared with the climatology, which greatly threaten the southern part of Japan (Kim et al., 2011; Xu and Huang, 2015; Li and Wang, 2014). Figure 3.2 compares the anomalies (relative to climatology) of TC genesis patterns between observation and RRRR for EPW, CPW, and LN years. In CPW years, there are positive TC genesis anomalies to the east of 150°E in both observation (Figure 3.2b) and RRRR (Figure 3.2f). Especially, a northwest-to-southeast sector with positive TC genesis anomalies (rectangle boxes in Figure 3.2b,f) indicates more TCs formed near the south of Japan (not significant), compared to EPW years (Figure 3.2a,e). These results are consistent with the finding of Kim et al. (2011). In EPW years, there are less TC genesis counts in the west of 140°E, and more TC genesis counts in the east of 140°E (Figure 3.2a,e) while the opposite is true for LN years (Figure 3.2c,g). The anomalous TC genesis pattern in EPW years is similar to that in EN years in Wang and Chan (2002). It is also clear that difference in TC genesis counts between EPW and LN years (Figure 3.2d,h) resembles that between conventional ENSO years (EN and LN; Figure 3.1a,b). Overall, the results show that the model can distinguish TC genesis characteristics between EPW and CPW years. Through the sensitivity experiments in the following sections, I will pursue key environmental variables determining TC genesis anomalies.

3.3.2. Sensitivity experiments

Figure 3.3 displays the difference in TC genesis pattern between two ENSO phases obtained by 1R3C-type sensitivity experiments in which only one out of four environmental variables has year-to-year variation corresponding to ENSO. In the NW sector, only the RCCC experiment (real field for RH600) simulated a significant lower count of TC genesis in EN years than in LN years (Figure 3.3a). In the SE sector, only CCRC (real field for RV850) indicates that TC genesis counts in EN years surpass those in LN years (Figure 3.3c). The anomalous TC genesis pattern of RCCC in the NW and that of CCRC in the SE are, thus, consistent with those of RRRR (Figure 3.1b) and the

observations (Figure 3.1a). In contrast, CRCC (Figure 3.3b) and CCCR (Figure 3.3d) failed to capture the anomalous TC genesis pattern in the NW and SE sectors. These results suggest a crucial role of RH600 and RV850 in determining anomalous TC genesis in the NW and SE sectors, respectively.

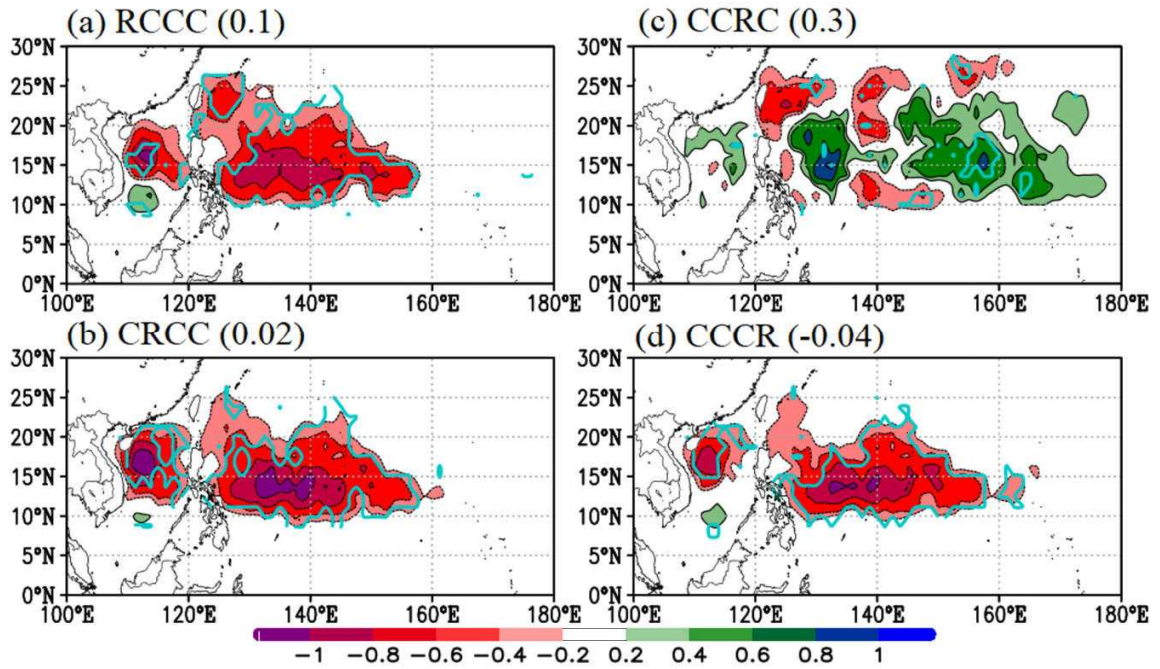


Figure 3.3 As Figure 3.1a,b but for (a) RCCC (real RH600), (b) CRCC (real SST), (c) CCRC (real RV850) and (d) CCCR (real VWS).

Figure 3.4 displays the anomalous TC genesis patterns obtained by 3R1C-type and 2R2C-type sensitivity experiments to examine the combined contributions of environmental variables to TC genesis. The experiments RCRR, RRRC, RRRC, RCRC (Figure 3.4b,c,d,e; real field for RH600) and CRRR, RCRR, RRRC, RCRC (Figure 3.4a,b,d,e; real field for RV850) reproduce anomalous negative and positive TC genesis patterns in the NW and SE sectors, respectively, consistently with those observed. Surprisingly, the simulated TC genesis anomalies resemble observed anomaly fields in the NW (SE) if RH600 (RV850) varies realistically, irrespective of the status of the other variables. High spatial correlations occur in the experiments RRRC (0.47), RCRR (0.46),

RCRC (0.45) in which both RH600 and RV850 retain real values. A slightly lower spatial correlation of RCRC compared with those of RRRC and RCRR reflects the discarded interannual variation of SST and VWS. These results support the finding in the 1R3C-type experiments (Figure 3.3) that RH600 (RV850) is a crucial factor in regulating ENSO-related TC genesis frequency in the NW (SE) sector. Since wetter mid-troposphere is preferable to sustain the updraft and inhibit the downdraft development in convective clouds (Gray, 1998; Cheung, 2004), the lower RH600 in the NW sector is likely to be associated with the middle tropospheric descending motion. In the SE sector, the RV850 is a limiting factor for the TC genesis in LN years. Since the SE sector is located around the confluence zone between monsoon-induced westerly and trade easterly (Yoshida and Ishikawa, 2013), the interaction between two circulation systems may regulate the ENSO-related interannual variation of TC genesis.

Table 3.2 shows the temporal correlations between observed and simulated genesis counts calculated for 16 ENSO years. The RRRR shows significant correlations at 90% confident level in both the NW (0.43) and SE (0.46) sectors. It means that RRRR can capture year-to-year variations of TC genesis in both sectors. In the NW sector, RCCC, RCRR, RRCR and RRRC experiments (i.e., real field for RH600) have significant positive correlations, whereas the correlations for others are not significant. In the SE sector, CCRC, CRRR, RCRR and RRRC experiments (i.e., real field for RV850) have significant positive correlations. This again suggests that RH600 and RV850 play a key role in regulating ENSO-related interannual variation of TC genesis in the NW and SE sectors, respectively. However, in the SE sector, significant negative correlations are found in the experiments RCCC, CRCC, CCCR and RRCR (i.e., real field for RH600, SST or VWS but climatological field for RV850). A possible reason for the negative correlation will be discussed in Section 3.4.

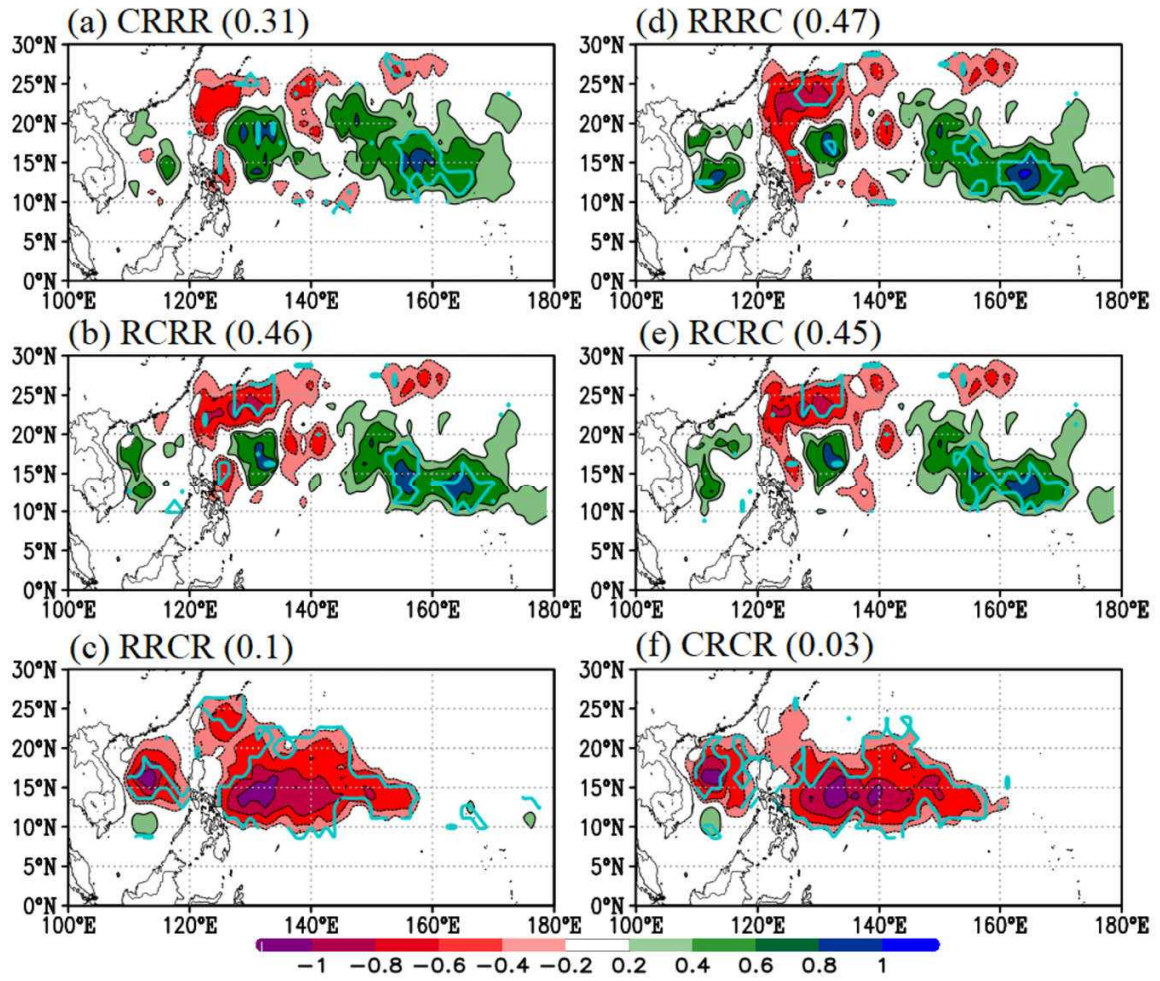


Figure 3.4 As Figure 3.1a,b but for (a) CRRR (climatological RH600), (b) RCRR (climatological SST), (c) RRRC (climatological RV850), (d) RRRC (climatological VWS), (e) RCRC (climatological SST and VWS), and (f) CRCR (climatological RH600 and RV850).

Table 3.2 Temporal correlation between year-to-year variations of observed and simulated genesis counts during June to October, calculated for 16 ENSO years in the NW and SE sectors. Correlations significant at $p = 0.10$ and $p = 0.05$, and $p = 0.01$ are indicated by * and **, and ***, respectively.

RRRR	1R3C						3R1C	
	RCCC	CRCC	CCRC	CCCR	CRRR	RCRR	RRCR	RRRC
NW								
	0.43*	0.44*	0.16	0.11	0.13	0.05	0.51**	0.45*
SE								
	0.46*	-0.77***	-0.67***	0.51**	-0.73***	0.49*	0.54**	-0.77***

Since TC genesis features in CPW years differs from those in EPW years, the 1R3C-type sensitivity experiments were also conducted to examine key environmental variables, particularly focusing on TC genesis near the south of Japan where VWS is expected to be a regulating factor (Kim et al., 2011). However, the significant effect of VWS (Figures not shown) cannot be revealed. This perhaps is due to the limitation of the model or too weak control of CPW to anomalous TC genesis. In the following section, only TC genesis response to environmental variables related with conventional ENSO was discussed.

3.4. Discussion and summary

In the NW sector, there is a decrease (an increase) in RH600 and DIV200 (divergence at 200-hPa), and an increase (a decrease) in pressure velocity at 600-hPa level (ω_{600}) during EN (LN) years (Figure 3.5a,c,f). This can be explained in terms of upper tropospheric convergence (divergence) during EN (LN) years intensifying the downdrafts (updrafts), so that the mid-troposphere becomes dry (wet). Although it is difficult to clarify the cause and effect relationship, these processes maintain a favorable environment that collaboratively suppresses (enhances) TC formation in EN (LN) years over the NW sector. Wang and Chan (2002) also pointed out that significant lower DIV200 and higher ω_{600}

over this region are intensified due to the confluence between the upper tropospheric East Asian trough and subtropical ridge during EN years. To examine the role of RH600 in ENSO-related TC genesis, further statistical analysis was performed. There is a high correlation between TC counts and RH600 ($r = 0.64$) and between TC counts and DIV200 ($r = 0.63$) as summarized in Table 3.3. Note that, the correlation between DIV200 and RH600 is also high ($r = 0.62$, $p = 0.003$), which indicates a possible link between these variables. In fact, the upper tropospheric convergence (divergence) may cause a lower-tropospheric divergence (convergence) that also leads to a dry (wet) mid-troposphere during EN (LN) years. The axisymmetric model adopted in this study succeeded in simulating the TC genesis anomaly in the NW sector as a response to the input RH600 anomaly, which also indirectly reflects the anomalies in DIV200 and ω_{600} .

Table 3.3 Temporal correlation of year-to-year variations calculated for 16 selected ENSO years between total observed genesis counts (June to October) and averaged environmental variables (June to October) in the NW and SE sectors. Correlations significant at $p = 0.05$ and $p = 0.01$ are indicated by ** and ***, respectively.

	RH600	SST	RV850	VWS	DIV200
NW	0.64***	0.09	-0.2	-0.01	0.63***
SE	0.3	0.17	0.89***	0.56**	

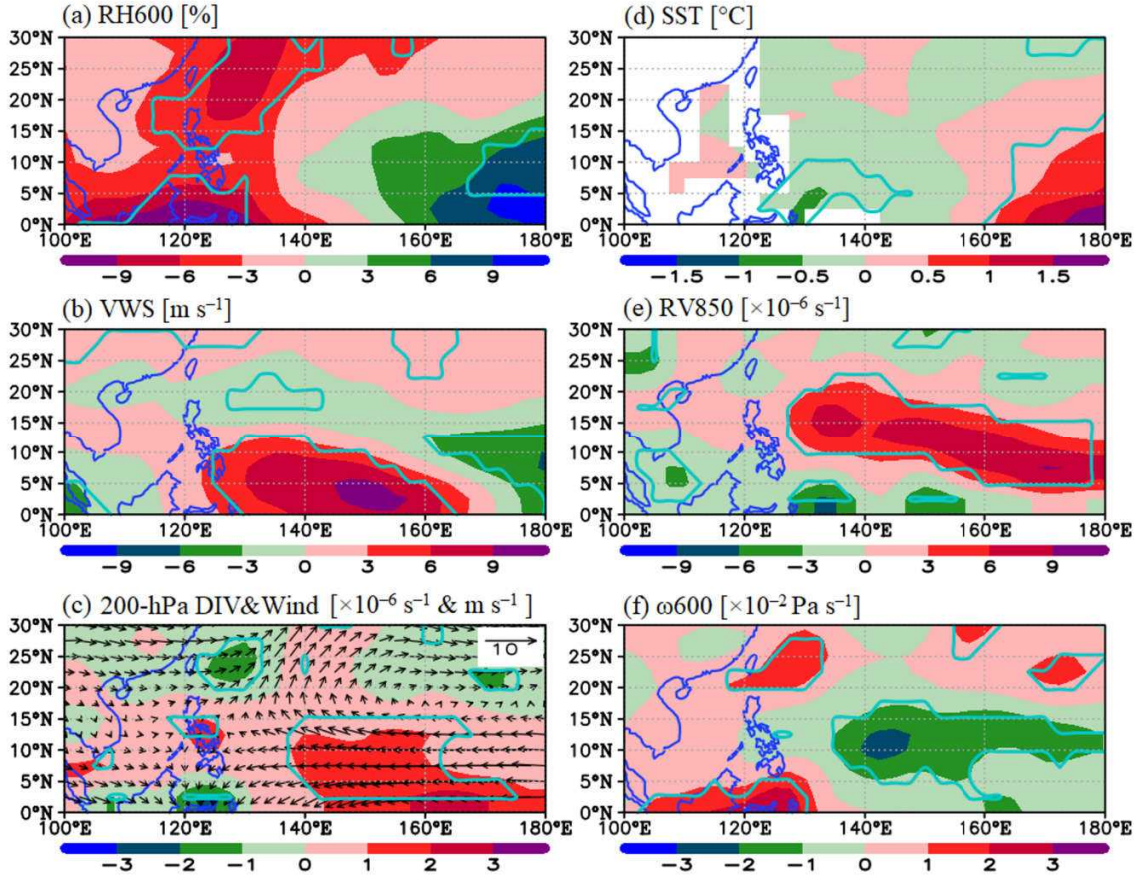


Figure 3.5 Difference in averaged environmental variables (June to October) between EN and LN years. (a) RH600 (%), (b) VWS (m s^{-1}), (c) DIV200 ($\times 10^{-6} \text{ s}^{-1}$) and horizontal wind at 200-hPa (m s^{-1}), (d) SST ($^{\circ}\text{C}$), (e) RV850 ($\times 10^{-6} \text{ s}^{-1}$), and (f) pressure velocity at 600-hPa (ω_{600} ; $\times 10^{-2} \text{ Pa s}^{-1}$). Thick contours indicate significant differences ($p = 0.05$).

As mentioned in Section 3.3.2, high mid-tropospheric relative humidity encourages development of deep convection by increasing enthalpy and precipitation efficiency (Gray, 1977). In contrast, low mid-level relative humidity acts to suppress deep convection because cumulus-induced condensation is likely to be re-evaporated, which cools the mid-tropospheric layer (Gray, 1977). Figure 3.6a shows evidence that more TC geneses occur with higher relative humidity at 600-hPa, and vice versa. However, some exceptional cases remain in strong ENSO years such as 1982 and 2015. In these years, it is speculated that other oceanic variability modes, such as PMM (Zhang et al., 2016), dominantly modify TC

genesis pattern. In fact, Hong et al. (2018) found that mean TC genesis location in 2015 has an unprecedented eastward shift, attributed to the subtropical SSTA or PMM. This means that the TC genesis in these years cannot be explained solely by the interannual variation of RH600. More studies are needed to identify additional factors that influence TC genesis by taking account of dynamical processes that initiate TC genesis (Yoshida and Ishikawa, 2013).

In the SE sector, significant higher (lower) RV850 (Figure 3.5e) agrees with more (less) TC genesis in EN (LN) years. A high correlation between TC counts and RV850 ($r = 0.89$; Table 3.3) supports a strong linkage between TC genesis counts and RV850 during ENSO years. From a physical perspective, as mentioned in Section 3.3.2, an increase in RV850 in EN years ensures a supply of mass, momentum and water vapor, which sustains cumulus convection in the TC warm core (Gray, 1977). According to the vorticity weighting method adopted by Sato et al. (2011), the number of TC seeds increases in the simulations as RV850 becomes higher. Therefore, in EN years more TC seeds are placed in the SE sector than LN years because of the higher RV850 in EN years (Figure 3.6b). This explains why the CCRC, CRRR, RCRR, RRRC and RCRC experiments, which all include the interannual variation of RV850, were able to capture ENSO-related TC genesis anomalies in the SE sector.

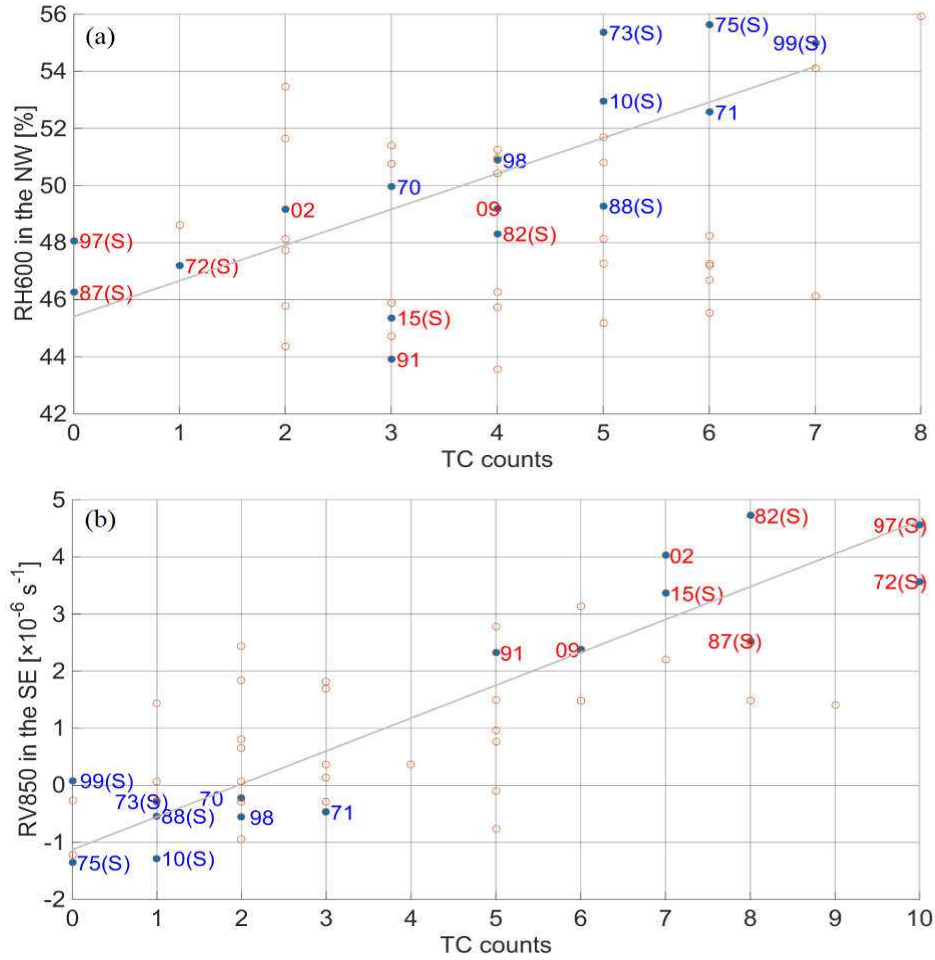


Figure 3.6 Scatter plot (a) between observed TC counts (June to October) and RH600 (averaged over June to October) in the NW sector, and (b) between TC counts (June to October) and RV850 (averaged over June to October) in the SE sector. Red circles show years between 1970 and 2015. The 16 ENSO years are indicated with numbers. Red (blue) shows EN (LN) years. An S in brackets indicates a strong ENSO year. The solid line is the linear regression for the 16 ENSO years.

In addition, it is speculated that, in the SE and NW sectors, RV850 and RH600 relates to the formation and development of TCs, respectively. In EN years, an eastward extension of monsoon trough toward the SE sector enhances the occurrence of tropical disturbances. Therefore, TC genesis number is larger in EN years in the SE sector than LN

years. In NW sector, RH600 appeared to be a limiting factor for TC genesis. There might be some tropical disturbances that moved into the NW sector from other sectors (i.e., the SE). During EN, however, the low RH600 in the NW sector inhibits the further development of tropical disturbance. Therefore, TC genesis number is less in EN years in the NW.

In the southwest sector (SW; 0°N–17°N, 120°E–150°E) of the WNP, the experiments with climatological RV850 (RCCC, CRCC, CCCR, RRCR, CRRC; Figures 3.3a,b,d and 3.4c,f) show significant negative anomalies in TC genesis while the best track does not have a significant anomaly. This implies that anomalies in other parameters (RH600, SST, and VWS) tend to reduce TC genesis in EN years. It also explains why the experiments RCCC, CRCC, CCCR and RRCR (climatological field for RV850) show significant negative correlations (Table 3.2). In contrast, the CCRC, CRRR, RCRR, RRRR, and RCRC experiments (Figures 3.3c and 3.4a,b,d,e), in which RV850 retained its real value and some of the other parameters were fixed to climatology, show positive anomalies in TC genesis although they are not statistically significant. In reality, the negative impacts induced by lower RH600, lower SST, and stronger VWS in EN years and the positive impact of stronger RV850 compensate each other, resulting in a negligible TC genesis anomaly in RRRR (Figure 3.1b) which is consistent with that in the observations (Figure 3.1a).

As shown in Table 3.3, there is a positive correlation (0.56) between observed TC genesis counts and VWS in the SE sector. It is different from our earlier speculation because strong VWS inhibits the TC development. During EN years, stronger low-level westerly and stronger upper-level easterly strengthen VWS over the southwest part (140°E–165°E) of the SE sector, which tends to inhibit the TC genesis. Note that, zonal wind component predominantly modulates the intensity of VWS in comparison to the meridional wind component. In the same time, however, RV850 is intensified during EN years. As revealed in Section 3.2.2, RV850 has strong influence on TC genesis in the SE sector, enhancing the TC genesis number irrespectively from strong VWS in EN years. In Table 3.2, there is a negative correlation (-0.73) between observed TC genesis counts and that

simulated in CCCR (real value for VWS). Since in the SE sector VWS is stronger in EN years than LN years (Figure 3.5b), the CCCR simulated less TCs in EN years than LN years (Figure 3.3d), although this is an opposite tendency with observation ($r = -0.73$ for CCCR in Table 3.2). In the real atmosphere, dynamic (i.e., VWS, RV850) and thermodynamical (i.e., SST, RH600) parameters vary interactively. It means that the interannual variation of VWS accompanies the changes in other parameters (i.e., RV850, RH600, SST). Therefore, the positive correlation between VWS and TC genesis number in the SE sector ($r = 0.56$ in Table 3.3) denotes that the positive effect induced by other variables (RV850, RH600, and SST) is more dominant than the negative effect induced by VWS in controlling the TC genesis number. More realistic TC variation in RRRC ($r = 0.47$ in Table 3.2) than CCCR ($r = -0.73$ in Table 3.2) supports this speculation.

The overall model results imply that the direct impact of ENSO-induced SST and VWS anomalies on TC genesis is weak in the WNP. This is consistent with previous studies. Chan (2007) suggested that the role of ENSO-related SST anomaly on TC genesis in the WNP acts indirectly through the modification of the planetary-scale atmospheric circulation. This also agrees with the fact that local SST does not affect TC formation (Wang and Chan, 2002). Moreover, Yu et al. (2016) demonstrated remote effects of tropical Indian ocean, north Atlantic, and subtropical Pacific on TC genesis in the WNP. The VWS is a key factor controlling the number of super typhoons; however, it does not modulate TC counts if weak intensity TCs are included (Li and Zhou, 2012). Wang and Chan (2002) also revealed that the ENSO-related interannual variation of TC counts is not explained by VWS in the WNP. Therefore, it is very reasonable that our sensitivity experiments were less sensitive to SST and VWS variations during ENSO years.

In this study, some shortcomings of the axisymmetric model are also discussed. The model is not able to simulate two-way interactions between the environment and TC activity while previous studies demonstrated that the TCs can modify the large-scale environment. In particular, TCs may alter SST (Zhang et al., 2015) through the change in tropical ocean mixing process and meridional heat transport (Emanuel, 2001; Srivier and Huber, 2007; Hu and Meehl, 2009; Fedorov et al., 2010). The cooling of SST resulting

from a TC can decrease likelihood of formation of other following TCs. In this regard, the absence of atmosphere to ocean feedback may cause overestimation of the TC genesis counts, particularly in the year when genesis number is high. The model used in this study is not suitable for simulating TCs that has non-axisymmetric structure. It will be interesting to examine the roles of specific environmental parameters to modify TC activities by using a mesoscale meteorological model (e.g., Yoshida et al., 2017). Analyzing a GCM ensemble experiments (Ueda et al., 2018) may have benefits in investigating the robust effect of ENSO on TC activity.

Nevertheless, the results of the sensitivity experiments demonstrated a contribution of key environmental conditions to the anomalous TC genesis in the WNP associated with the ENSO phases. Therefore, the axisymmetric model is useful for the diagnosis of TC activity related to ENSO phase, such as paleoclimate studies and climate prediction beyond the seasonal timescale in which a probabilistic representation of TC activity based on a large number of experiments is desired.

Chapter 4. The potential of large-scale environment in predicting TC activity in relation to ENSO

4.1. Introduction

ENSO is one of the important factors regulating TC activity over the WNP through modifying the large-scale environment. The effects of ENSO on the large-scale environment discussed in Chapter 1 are briefly summarized as the followings. During EN years, an eastward extension of monsoon trough resulting from strengthening of ENSO-induced low-level westerly enhances low-level relative vorticity. In the fall of EN years, deepening of the East Asian trough strengthens anomalous westerly in upper tropospheric layer. These effects of ENSO on the large-scale environment modulate TC features. Specifically, in EN (LN) years, the mean TC genesis position shifts eastward (westward) and more TCs formed in the southeast (northwest) sector of WNP. In EN years, there are approximately 2.5 times more TCs recurving from northwestward to northeastward across 35°N. In the spring and summer of the post-EN years, TC numbers are less than climatology. Since ENSO impacts on TC activity through modifying the synoptic environment, it is necessary to assess the potential of the synoptic environment in predicting TC activity in relation to ENSO.

As mentioned in Chapter 2, the axisymmetric model is designed to assess the potential of synoptic environment in generating and developing TCs. Some previous researchers (e.g., Emanuel, 2006; Emanuel et al., 2008; Sato et al., 2011) examined this model's capability in simulating TC activity. However, its capability in predicting TC activity in relation to ENSO phases was not studied yet. Zhao et al. (2011) also used the axisymmetric model to examine interannual variations of TC intensity related to ENSO, but they used best track data; therefore, TC number and track were not predicted. In this study, all TC features including tracks, genesis frequency, and genesis location are predicted. As mentioned in Section 1.3, ENSO has an influence on all TC features such as genesis, intensity, life span, track, and landfall. A scientific question raised here is that whether there is any approach to predict TC activity based on the synoptic environment. Thus, the objective of this Chapter is to examine the potential of the large-scale environment in

predicting TC features with monthly timescale in relation to ENSO. The remainder of this Chapter is structured as the followings. Section 4.2 and 4.3 present the experiments and simulated results, respectively. Discussion and summary are mentioned in Section 4.4.

4.2. Experimental designs

The axisymmetric model was employed to simulate TC activity. The JRA55 reanalysis data was used as input for running model while JTWC and JMA (best track data) were used to verify the simulation. Details of datasets, the model, and classification of ENSO years were same as those represented in Chapter 2. Monthly mean atmospheric and oceanic fields of 16 conventional ENSO years were used as the model forcing to examine the model's capability in predicting TC activity in association with ENSO over the WNP. Each run was conducted for each month from June to November in 16 selected conventional ENSO years in the period 1970–2015 (i.e., 96 runs in total). In each run, many TCs were generated as described in Section 2.2. Difference in simulated TC features such as TC genesis, track, and landfall between ENSO years were compared with those in the observation. TC features (genesis distribution and passage frequency) were displayed for June to August (JJA), July to September (JAS), August to October (ASO), and September to November (SON).

4.3. Results

4.3.1. Genesis and passage frequency

Difference in TC genesis patterns between EN and LN years (Figure 4.1) was averaged for June to August (JJA), July to September (JAS), August to October (ASO), and September to November (SON) to evaluate monthly evolution of TC genesis pattern. In the observation, there are less TCs in the west of 140°E and more TCs in the east of 140°E in EN years during the storm season (Figure 4.1a,b,c,d), compared with LN years. However, significant TC genesis anomalies mainly occur in the southeast (SE) and northwest (NW) sectors of the WNP during the peak storm season (JAS and ASO; Figure 4.1b,c), which is

consistent with Wang and Chan (2002). The simulation also indicates similar anomalous TC genesis patterns as observed during the storm season. Significant TC genesis anomalies also focus on the SE and NW sectors. In general, the model can, thus, replicate the geographical distribution of ENSO-related TC genesis in monthly timescale.

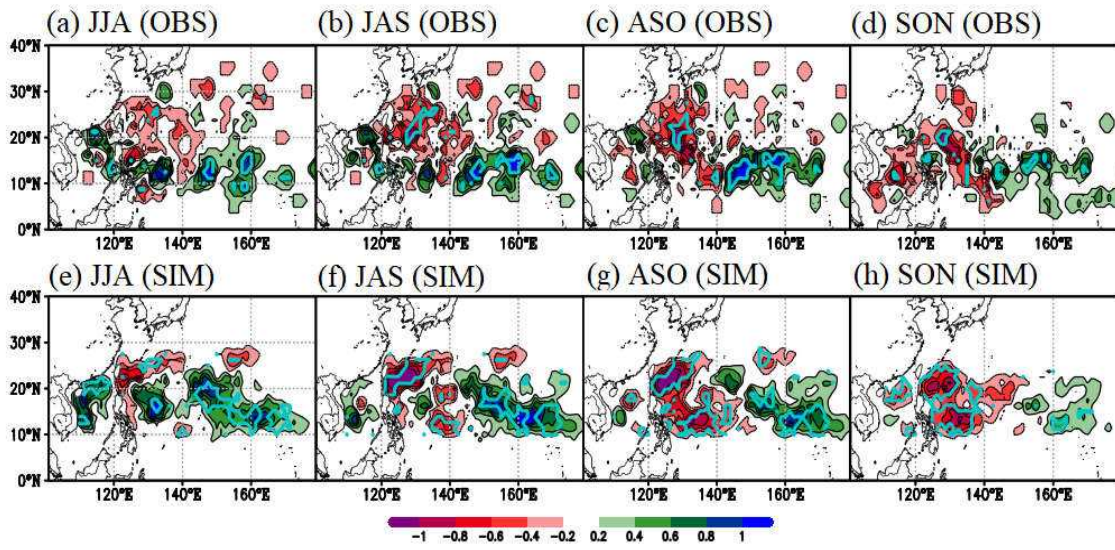


Figure 4.1 The difference in TC genesis frequency (shading; counts per year per $5^\circ \times 5^\circ$ box) between EN and LN years was averaged for (a) June to August (JJA), (b) July to September (JAS), (c) August to October (ASO), and (d) September to November (SON) of the observation. (e), (f), (g), and (h) Same as (a), (b), (c), and (d) but for the simulation. For the drawing, TC genesis counts were interpolated onto a $1.25^\circ \times 1.25^\circ$ mesh grid. Bold contours indicate significant difference at $p = 0.1$.

To more understand the simulated TC genesis feature, the mean TC genesis positions of observation and simulation were examined (Table 4.1). The mean genesis positions (latitude and longitude) of eight selected EN years were compared with that of eight selected LN years. Note that, since shift in TC genesis positions in the SCS is not sensitive to ENSO years, TC genesis positions were averaged in only domain 120°E – 180°E of the WNP (except for the SCS). The significant negative difference in the mean latitude (JJA and SON) illustrates that, TCs tend to form more nearly the equator in EN years than

LN years. In other words, in EN (LN) years, the mean TC genesis position shifts southward (northward). Meanwhile significant positive difference in the mean longitude (JJA and SON) implies that genesis positions tend to moves eastward in EN years, compared with LN years. Interestingly, these characteristics were present in simulated TCs. It implies that the model can capture the displacement of the mean TC genesis positions between ENSO years, which is consistent with the results in Figure 4.1.

Table 4.1 Three-month mean TC genesis positions were indicated by latitude (Lat) and longitude (Lon) for EN and LN years. The calculation was performed over the domain 120°E–180°E for the observation and simulation during June to August (JJA) and September to November (SON). The significant differences in mean TC genesis position between EN and LN years at $p = 0.1$, 0.05, and 0.01 are indicated by *, **, and ***, respectively. The analysis was done for eight EN and eight LN years during 1970–2015.

Years	June to August (JJA)				September to November (SON)			
	OBS		SIM		OBS		SIM	
	Lat	Lon	Lat	Lon	Lat	Lon	Lat	Lon
EN	15.59	144.58	17.65	141.66	14.42	150.01	16.03	148.81
LN	19.77	135.27	19.43	137.25	16.62	136.46	17.12	137.76
EN-LN	-4.18***	9.31***	-1.78**	4.40*	-2.19**	13.54***	-1.09*	11.04**

Figure 4.2 shows difference in TC passage frequency between EN and LN years. TC passage frequency at each grid box ($1.25^\circ \times 1.25^\circ$) was counted by all tracks moving across that grid box. In the observation, in JJA (Figure 4.2a), positive anomalous TC passage frequencies dominate in whole WNP. While in the late storm season (ASO and SON; Figure 4.2c,d), negative and positive anomalous TC passage frequencies occur in the west and east of 140°E , respectively. The simulation shows similar TC passage frequencies as observed. However, in SON, in the east of 140°E , anomalous TC passage frequencies are significant in the observation but insignificant in the simulation. These points show deficiency in the model's skill. Nevertheless, in general, the model can replicate anomalous TC passage frequencies between EN and LN years over the WNP.

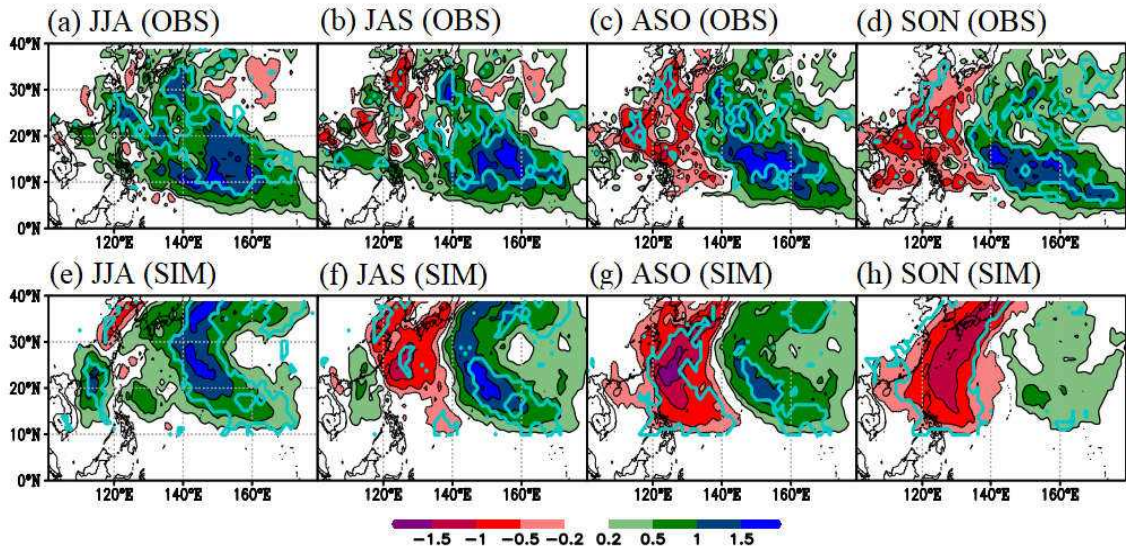


Figure 4.2 As Figure 4.1 but for TC passage frequencies.

4.3.2. TC landfall

To examine TC landfall feature in association with ENSO years, the East Asia and South East Asia were subdivided into four areas: Japan and Korea peninsula (JKP), China (CHI), Indochina Peninsula (ICP), Philippines (PHI) as displayed in Figure 4.3. The number of TC landfalls on each area in EN years was compared with that in LN years.

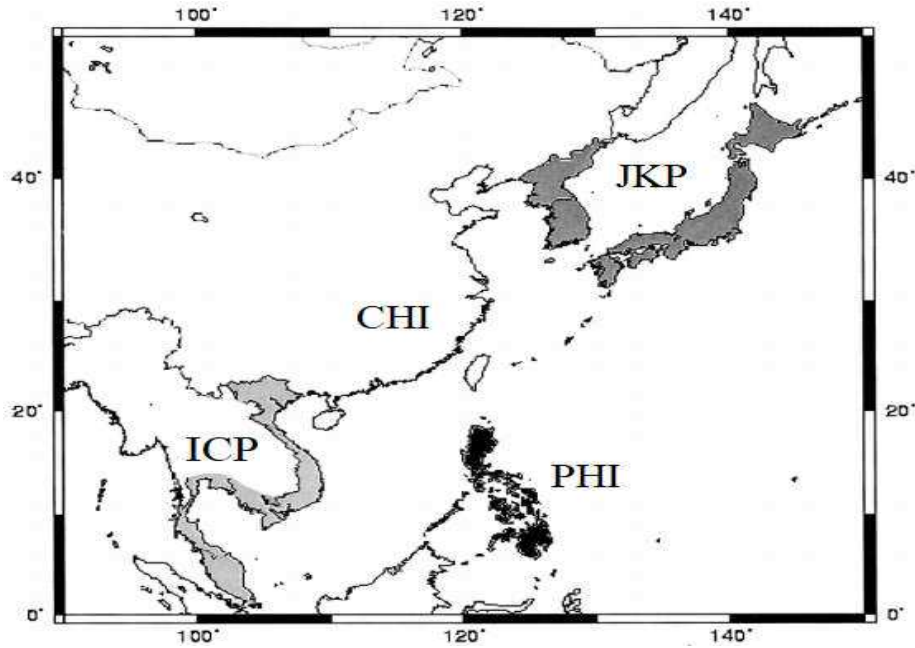


Figure 4.3 Four areas for analyzing TC landfall: Japan and Korea peninsula (JKP), China (CHI), Indochina peninsula (ICP), Philippines (PHI).

Table 4.2 shows the mean TC landfall feature in four areas for EN and LN years. As mentioned in Section 2.2, the TC numbers produced by the model were much larger than those observed. Thus, in here, it needs to be paid attention on relative comparison in TC landfalls between EN and LN years instead of absolute numbers of TC landfall. In ASO, both observations and the simulation show that mean TC landfall counts are less in EN years than in LN years in four areas. The simulation also indicates negative anomalies of TC landfall in four areas but significant negative anomalies only occur in JKP and PHI. Note that, negative anomaly, which is a difference in TC landfall counts between EN and LN years, implicates that less TC landfall counts in EN year than LN years, and vice versa. In SON, four areas in both the observations and simulation also show negative anomalies of TC landfall counts. However, in JMA best track dataset, significant negative anomalies were in CHI, ICP, and PHI while, in JTWC dataset, those occur in only CHI. The simulation exhibits significant negative anomalies in JKP, CHI, PHI (except for ICP). The TC landfall in earlier season (JJA and JAS; Table 4.3) were also examined. In JJA, the results of both the observation and simulation indicate that more TCs landfall in EN years

than LN years in four areas, which is consistent with anomalous TC passage frequencies in Figure 4.2e. In JAS, positive and negative landfall anomalies are mixed in both the observation and simulation. In both JJA and JAS, landfall anomalies are not statistically significant. Thus, in general, the model can distinguish TC landfall feature in two stages of the storm season. In particular, in earlier stage (June to August), there were more TC landfalls in EN years than LN years. The opposite was true for late stage (September to November). These results are consistent with the findings of Wu et al. (2004) as introduced in Section 1.3.2. It is speculated that the simulation showed anomalous TC landfalls in relation to ENSO because the model can replicate anomalous TC genesis and track (controlled by the steering flow). This point will be more discussed in Section 4.4.

Table 4.2 Mean TC landfall numbers in EN and LN years for ASO and SON. The calculation was performed for two kind of the observation (JTCW and JMA) and the simulation in four areas (JKP, CHI, ICP, PHI). The significant differences in mean TC landfall counts between EN and LN years at $p = 0.1$, 0.05 , and 0.01 are indicated by *, **, and ***, respectively. EN and LN years were selected in 1970–2015.

Area	Data	August - October (ASO)			September - November (SON)		
		EN	LN	EN-LN	EN	LN	EN-LN
JKP	JTCW	2.12	2.37	-0.25	1.12	1.25	-0.13
	JMA	2.87	3.50	-0.62	1.50	1.62	-0.12
	SIM	19.25	29.62	-10.37*	3	16.62	-13.60***
CHI	JTCW	2.37	4	-1.62	1.25	2.50	-1.25*
	JMA	2.75	4	-1.25	1.25	2.37	-1.12*
	SIM	10.62	18.37	-7.7	2	8.75	-6.75***
ICP	JTCW	2.25	2	0.25	2	2.62	-0.62
	JMA	1.75	2	-0.25	1.62	2.87	-1.25*
	SIM	3.87	4.75	-0.87	2	3.75	-1.75
PHI	JTCW	2.62	3.75	-1.12	2.87	3.87	-1
	JMA	2	3.62	-1.62**	2.25	4.12	-1.87**
	SIM	1.87	6	-4.10***	0.75	6.12	-5.37***

Table 4.3 As Table 4.2 but for JJA and JAS.

Area	Data	June - August (JJA)			July - September (JAS)		
		EN	LN	EN-LN	EN	LN	EN-LN
JKP	JTWC	3.37	2.25	1.12	3.62	3.25	0.37
	JMA	4	2.87	1.12	4.25	4.25	0
	SIM	31.62	25	6.62	30.87	38.75	-7.87
CHI	JTWC	3.50	3.12	0.37	3.62	4.25	-0.62
	JMA	3.75	3.25	0.5	3.87	4.12	-0.25
	SIM	24.87	21.5	3.37	21.25	25	-3.75
ICP	JTWC	1.25	0.87	0.37	2	1.50	0.50
	JMA	1.12	1	0.12	1.87	1.62	0.25
	SIM	4.75	5	-0.25	4.75	5.75	-1
PHI	JTWC	2	2	0	2.37	2.37	0
	JMA	1.62	2	-0.37	1.75	2.37	-0.62
	SIM	4.62	4.10	0.50	4	3.62	0.37

The ratio of TCs originated from three subsectors, namely South China Sea (SCS; 100°E–120°E), west WNP (120°E–140°E), and east WNP (140°E–180°E), to total TC landfalls on each areas (JKP, CHI, ICP, and PHI; Figure 4.4) was examined (hereafter referred to as contribution ratio). A sum of the contribution ratio is equal to 100%. The calculation was carried out individually for both EN and LN years.

In EN years, in the simulation, the contribution ratio of TCs generated over east WNP is 30% for landfall in JKP and nearly zero for landfalls in CHI, ICP, and PHI (Figure 4.4c), which is far different from the observation (Figure 4.4a). It means that, most of the simulated TCs generated over east WNP cannot make landfall on CHI, ICP, and PHI. In the simulation, TCs generated over SCS mainly contribute to total TC landfalls on ICP with the ratio of nearly 100% while in the observation, the ratio of TCs generated over SCS, west WNP and east WNP is in similar magnitude. It implies that, most of simulated TCs generated over east and west WNP cannot reach ICP. In addition, in the simulation, TC landfalls on CHI is attributed to TCs generated over SCS (approximately 60%) which are more dominant than those generated over west WNP (approximately 40%), but the opposite

is true for the observation. These results, thus, illustrate that the model fails to predict the contribution ratio of TCs generated over east WNP to TC landfall on CHI, ICP, PHI, and TCs generated over west WNP to TC landfall on ICP. In other words, the model fails to predict tracks of TCs generated over east WNP.

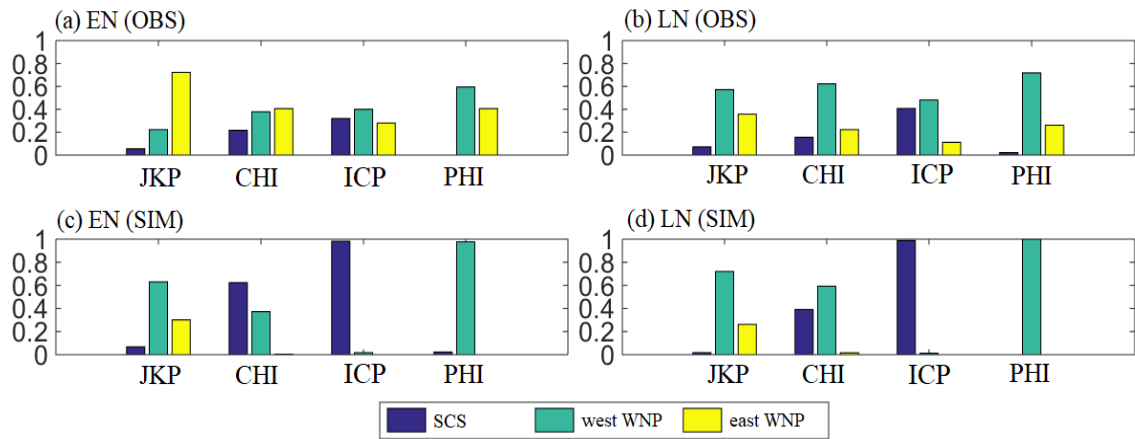


Figure 4.4 The contribution ratio (%) of TCs originated from three subsectors over the WNP, namely the South China Sea (SCS; 100°E–120°E), west WNP (120°E–140°E), and east WNP (140°E–180°E) to total TC landfalls on four areas: Japan and Korea peninsula (JKP), China (CHI), Indochina peninsula (ICP) and Philippines (PHI). Note that, a sum of the contribution ratio to total TC landfalls is equal to 100%. The calculation was performed for (a) EN years and (b) LN years of the observation. (c) and (d) Same as (a) and (b) but for the simulation. The analysis was done in the storm season (June to November) during 1970–2015.

In LN years, in the simulation (Figure 4.4d), the contribution of TCs generated over west WNP to TC landfalls on JKP, CHI, and PHI is more predominant than that of others, which is consistent with the observation (Figure 4.4b). However, in ICP, the contribution of TCs generated over SCS is nearly 100% (Similar to EN years; Figure 4.4c), surpassing the observed number (approximately 40%). It means that, most of simulated TCs generated over west and east WNP cannot landfall on ICP. Especially, similar to EN years, TCs generated over east WNP in the simulation almost do not contribute to landfalls on CHI,

ICP, and PHI while those in the observation still fluctuate from 10% to 30%. The results in LN years suggest that the model can simulate the contribution of TCs generated over west WNP to landfalls on JKP, CHI, and PHI (except ICP). However, it fails to simulate that of TCs generated over east WNP to landfalls on CHI, ICP, and PHI, which is similar to the results in EN years. In other words, the model fails to predict tracks of TCs generated over east WNP.

There are several possible reasons causing the failure in predicting tracks of TCs generated over east WNP. First, the monthly mean steering flow used in the model might not be valid to simulate TC tracks. Second, only northward component of β -effect was considered in the model, ignoring westward component. It is speculated that strong impact of northward β -effect can steer TCs northward.

4.4. Discussion and summary

The dominant roles of RV850 and RH600 in modulating ENSO-related TC genesis were elaborated in Chapter 3, focusing on the peak storm season (June to October). Figure 4.5a–h shows difference in RV850 and RH600 between EN and LN years for JJA, JAS, ASO, and SON to exhibit monthly evolution of these environmental variables during the storm season (June to November). RV850 in JJA, JAS, ASO, and SON is higher in EN years than LN years (positive anomalous RV850; Figure 4.5a–d) in the SE sector, which is favorable condition for TC genesis during EN years (Figure 4.1e–h). As demonstrated in Chapter 3, RV850 mainly controls ENSO-related TC genesis in the SE sector. Therefore, it suggests that anomalies of TC over this sector were generated in the simulation as a response to the anomalous RV850.

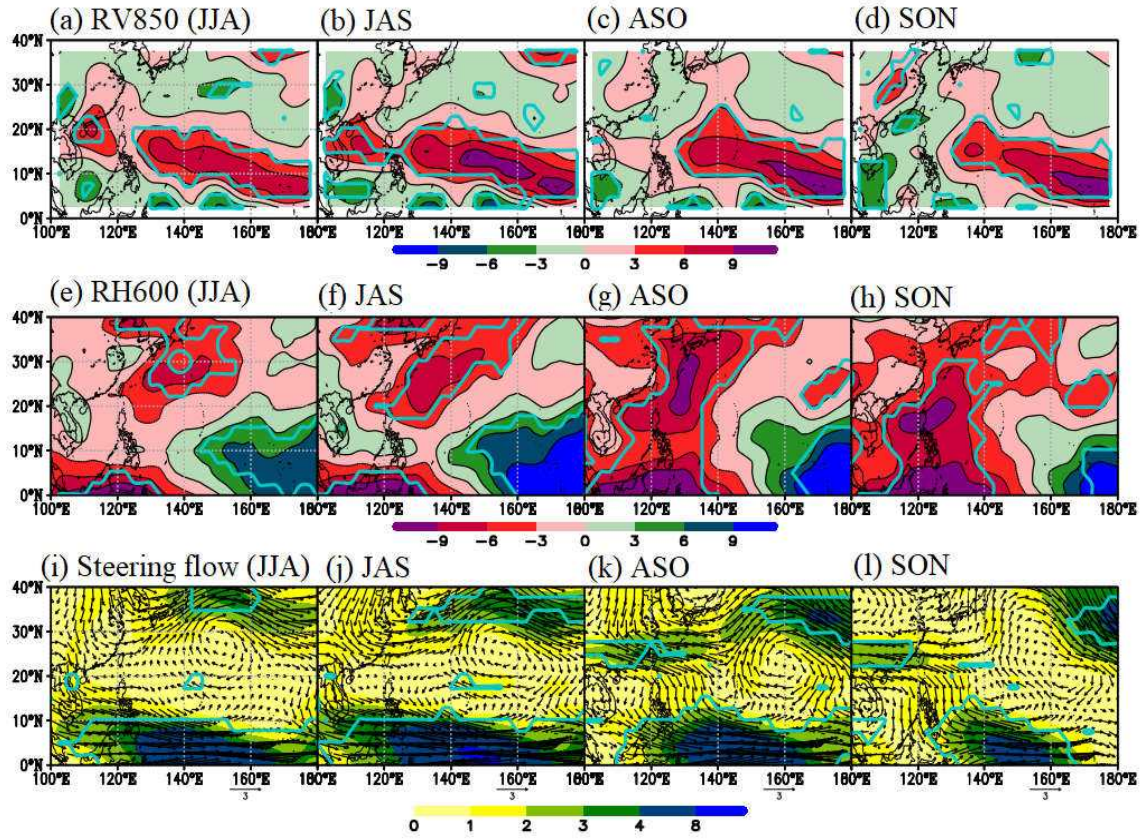


Figure 4.5 Difference in RV850 ($\times 10^{-6} \text{ s}^{-1}$) between EN and LN years averaged for (a) JJA, (b) JAS, (c) ASO, and (d) SON. (e), (f), (g), and (h) Same as (a), (b), (c), and (d) but for RH600 (%). (i), (j), (k), and (l) Same as (a), (b), (c), and (d) but for the steering flow (shading in i–l: wind speed; m s^{-1}). Bold contours denote difference is statistically significant at $p = 0.05$.

Lower RH600 in EN years is predominant in the NW sector (Figure 4.5e–h), which suppresses TC genes during EN years (Figure 4.1e–h). However, negative anomalous RH600 tends to extend southeastward in ASO and SON, which reduces the simulated TC genesis to the west of 150°E (Figure 4.1g–h). While negative TC genesis anomalies in the observation is just extended to the west of 140°E . In this case, the model seems to be too sensitive to changes of RH600 in ASO and SON. As mentioned in Chapter 3, RH600 mainly controls ENSO-related TC genesis in the NW sector. Therefore, it suggests that

anomalies of TC genesis over the NW sector were generated in the simulation as a response to the anomalous RH600.

The difference in TC landfall counts between EN and LN years can be attributed to effects of both the TC genesis position and large-scale steering flow (Zhang et al., 2012; Chan, 2000). In fact, the model can replicate the difference in the TC genesis position between EN and LN years (Figure 4.1 and Table 4.1) during JJA, JAS, ASO, and SON. The eastward (westward) displacement of TC genesis positions in EN (LN) years can lead to less (more) landfalls in EN (LN) years. However, positive anomalous landfalls (more landfalls in EN than LN years) just occur in JJA. It implies that the genesis position does not alone control the landfall feature. In ASO and SON (especially in SON), significant anomalous westerly exists between 20°N–30°N and 100°E–130°E (Figure 4.5k,l), which can prevent landfalls on CHI and PHI during EN years. At the same time, landfalls also present significant negative anomalies. Significant negative anomalies of landfall on CHI and PHI, thus, are produced as a response to the anomalous large-scale steering flow. This result suggests an essential role of the large-scale steering flow in controlling the landfall feature. Nevertheless, the deficiency of the model in predicting TC tracks became obvious. The low contribution ratio of TCs generated over east WNP to landfalls on CHI, ICP, and PHI (far different from the observation) indicates that the model cannot predict TC tracks which originated over east WNP.

Chapter 5. Conclusions

This study focuses on two objectives. The first objective is to examine the role of individual large-scale environment variables to ENSO-related TC genesis in the WNP. It is also expected to reveal key environmental variables in controlling ENSO-related TC genesis in the NW and SE sectors of WNP. Second objective is to examine the potential of the large-scale environment in predicting TC activity. In other words, the analysis was intended to answer the question whether it is possible to predict ENSO-related TC activity based on the synoptic environment. Since the axisymmetric model was designed to assess the potential of the synoptic environment in predicting TC activity, it was employed as the main tool for analysis in this study.

To investigate the impact of the large-scale environmental conditions on TC genesis in the WNP, numerical experiments using the axisymmetric model were conducted for the storm season during 16 conventional ENSO years during 1970–2015. Monthly mean atmospheric and oceanic fields were used for running the model. The control experiment, in which realistic interannual variations in four environmental variables were used, demonstrated that the model was able to replicate the spatial distributions of TC genesis anomalies corresponding to conventional ENSO, particularly in the NW and SE sectors of the WNP. In addition, the model was also able to reproduce more TC genesis in CPW years in the WNP where is near the south of Japan.

Individual contribution of four input variables RH600, SST, RV850, and VWS, to ENSO-related TC genesis frequency were examined by the sensitivity experiments. In the NW sector, the experiment with the real interannual variation of RH600 can produce less TC geneses corresponding to lower RH600 in EN years, compared to LN years. The result indicated that relative humidity at mid-tropospheric layer plays a key role in regulating ENSO-related TC genesis. In the SE sector, the sensitivity experiment with real interannual variation of RV850 can reproduce more TC geneses corresponding to stronger RV850 in EN years, compared to LN years, which suggested that relative vorticity at lower tropospheric layer is the dominant factor in modulating ENSO-related TC genesis. In reality, the low-level convergence associated with stronger RV850 in EN years than LN

years increases the water vapor transport toward the SE. This presumably sustains cumulus convection in the TC warm core. Although this effect was not explicitly included in the model, RV850 indirectly increased TC genesis through TC seeding process. Thus, more TC seeds were placed in the SE sector in EN years than LN years. In addition, it was also revealed that the effects of ENSO-induced VWS and SST anomalies on TC genesis in the WNP are negligible.

To examine the TC genesis, track and landfall anomalies in relation to ENSO-induced large-scale environmental anomalies, the simulated results were analyzed in monthly timescale. It was revealed that the model was capable of replicating monthly evolution of ENSO-related TC genesis anomaly as a response to anomalous RV850 and RH600 in the WNP during storm season. Anomalous TC landfalls in association with ENSO were examined in four areas, namely Japan and Korea peninsula (JKP), China (CHI), Indochina peninsula (ICP), and Philippines (PHI). The results showed that the model can reproduce ENSO-related anomalous TC landfalls during storm season. In general, the simulated positive and negative anomalies of TC landfall tended to occur in early season (JJA) and late season (SON), respectively, which is in agreement with the observation. Especially, negative anomalies of TC landfall were statistically significant in CHI and PHI in SON. In other words, TC landfall counts around CHI and PHI dramatically decreased in EN years during SON, compared to LN years. The significant decrease in TC landfall counts during SON in EN years was attributed to the effect of both shift in TC genesis position and steering flow. In EN (LN) years, the mean TC genesis position moved eastward (westward), which might lead to less (more) chances of TC landfall during June to November. However, the simulated TC landfalls significantly decreased in only SON of EN years. Also, in the late storm season (SON), the occurrence of anomalous westerly in mid-latitudes can be an important factor to prevent TC landfalls around China and Philippines. Therefore, the model was sensitive to both the shifts in simulated TC genesis position and large-scale steering flow. However, the model also showed the limitation in predicting tracks of TCs generated over east WNP (140°E–180°E).

This study confirmed the dominant effects of environmental factors on ENSO-related TC genesis and landfall. In particular, it demonstrated that mid-tropospheric relative humidity and low-level relative vorticity play a key role in modulating ENSO-related TC genesis. In addition, both TC genesis position and large-scale steering flow are found to be important in controlling ENSO-related TC landfall. Furthermore, mid-tropospheric relative humidity, low-level relative vorticity, and large-scale steering flow can serve as the potential predictors of TC activity in seasonal timescale. Finally, the results suggested that ENSO-related TC features over the WNP are predictable by using a monthly-averaged status of large-scale environment. Therefore, having appropriate large-scale mean state is essential in predicting TC activity anomalies in the WNP corresponding to ENSO.

There are some benefits gained from this research. The key factors controlling ENSO-related TC activity, such as, mid-tropospheric relative humidity, low-level relative vorticity, and large-scale steering flow, can be used to build a statistical relationship (i.e., regression equations) serving for seasonal TC forecasts. The results of the research also suggested the potential of the axisymmetric model for seasonal TC forecast by using the large-scale environment from the output of GCMs. It is worth examining the model's predictability with output of GCMs for the WNP. It is expected that this work partly contributes to enhance the operational forecast in Asian countries.

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