Seasonality and El Niño Diversity in the Relationship between ENSO and Western North Pacific Tropical Cyclone Activity

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ABSTRACT

Both the impacts of two types of El Niño on the western North Pacific (WNP) tropical cyclone (TC) activity and the seasonality in the relationship between genesis potential index (GPI) and El Niño–Southern Oscillation (ENSO) are investigated. The ENSO-induced GPI change over the northwestern (southeastern) part of the WNP is mostly attributed to the relative humidity (absolute vorticity) term, revealing a distinct meridional and zonal asymmetry in summer and fall, respectively. The seasonal change in ENSO (background states) from summer to fall is responsible for the seasonal change in GPI anomalies south of 20°N (over the northeastern part of the WNP). The downdraft induced by the strong upper-level convergence in the eastern Pacific (EP)-type El Niño and both the northwestward-shifted relative vorticity and northward-extended convection over the southeastern part of the WNP in the central Pacific (CP)-type El Niño lead to distinct TC impacts over East Asia (EA). The southward movement of genesis location of TCs and increased westward-moving TCs account for the enhanced strong typhoon activity for the EP-type El Niño in summer. In fall the downdraft and anomalous anticyclonic steering flows over the western part of the WNP remarkably decrease TC impacts over EA. The enhanced moist static energy and midlevel upward motion over the eastern part of the WNP under the northern off-equatorial sea surface temperature warming as well as longer passage of TCs toward EA are responsible for the enhanced typhoon activity for the CP-type El Niño. It is thus important to consider the seasonality and El Niño pattern diversity to explore the El Niño-induced TC impacts over EA.

1. Introduction

El Niño–Southern Oscillation (ENSO) affects hydroclimatic events over East Asia (EA) by modulating anomalous low-level circulations over the Philippine Sea

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(PS) (Wang et al. 2000, 2013; Wei Zhang et al. 2016), which is the most fertile region for tropical cyclone (TC) genesis. The variabilities of low-level PS circulations, which are highly linked to those of monsoonal flows, play a primary role in determining TC genesis and motion over the western North Pacific (WNP) (Wang and Chan 2002; Chen et al. 2004). The region favorable for the WNP TC genesis tends to shift southeastward (northwestward) in El Niño (La Niña) years associated with changes in the monsoonal flows (Chen et al. 1998; Wang and Chan 2002). The WNP TCs in fall tend to reveal a northward-recurving motion in strong El Niño years, influencing higher latitudes than those in strong La Niña years (Wang and Chan 2002). ENSO is the most well-known modulator for the WNP TC activity on the interannual time scale.

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Regarding ENSO's intensity, Wang and Chan (2002) argued that the significant changes in the WNP TC genesis associated with ENSO can be only attributed to strong events defined as the Niño-3.4 index greater than one standard deviation in July–September. In the recent decade, however, it has been determined that the maximum sea surface temperature anomalies (SSTA) existing over the central Pacific (CP) can significantly affect the WNP TC genesis (Chen and Tam 2010; Kim et al. 2011; Ha et al. 2012; Jin et al. 2013). The north-westward extension of favorable region for TC genesis is a result of the westward movement of anomalous Walker circulation induced by the CP-type El Niño compared to that of the eastern Pacific (EP)-type El Niño, thus leading to a high probability of EA landfalls (Kim et al. 2011). In addition, Jin et al. (2013) emphasized that northern off-equatorial CP warming moves anomalous cyclonic circulations over the PS farther northward, thereby increasing the TC impacts over EA rather than those of equatorial CP warming. The results indicate that influences of El Niño on the WNP TC activity should be examined considering not only El Niño intensity but also its pattern diversity.

Furthermore, the WNP TC activity is substantially influenced by seasonal variations of large-scale circulations over the WNP (Chen et al. 1998, 2004; Ritchie and Holland 1999; Huang et al. 2011; Choi and Ha 2018). The northeastward movement of monsoon trough leads to the northeastward migration of genesis location of the WNP TC from June to August. The favorable region for TC genesis moves southeastward in fall because an anticyclone over eastern China develops and southwesterly mean flow over the South China Sea (SCS) changes into easterlies from September onward. In addition, the impacts of El Niño on large-scale environments over the WNP become stronger and move eastward from summer to fall. Wu et al. (2017) determined that seasonal changes in meridional gradient of background specific humidity and relative vorticity at low levels play a significant role in the evolution of low-level PS circulations associated with El Niño. Thus, it is required to examine variabilities of the WNP TC activity based on the understanding of the distinct seasonality in summer and fall. Indeed, Chen et al. (1998) insisted that the variabilities of the WNP TC genesis associated with ENSO reveal a meridional (zonal) asymmetry in summer (fall).

A comparison with two types of El Niño revealed that the CP-type El Niño-induced changes in both genesis frequency of TCs in summer and TC tracks in fall are significantly distinct from those of the EP-type El Niño (Chen and Tam 2010; Hong et al. 2011). However, Chen and Tam (2010) focused on boreal summer (June–August) to examine changes in large-scale circulations

associated with two types of El Niño because temporal relationships between genesis frequency of TCs and ENSO indices are more significant in summer. In addition, Hong et al. (2011) compared the changes in TC tracks associated with the EP-type El Niño to those of the CP-type El Niño without a comparison with the climatology. Therefore, we investigated the roles of seasonality and El Niño pattern diversity in the relationship between ENSO and the WNP TC activity in summer [June–August (JJA)] and fall [September–November (SON)]. The next section describes details of data and methods. The seasonality in the relationship between the WNP TC genesis and ENSO is addressed in section 3. Impacts of seasonality and El Niño pattern diversity on the WNP TC activity are presented in section 4. Section 5 contains a summary and discussion.

2. Data and methods

a. Data and oceanic indices

Environmental datasets were used in this study, including the daily and monthly ERA-Interim dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF) (Dee et al. 2011) and Hadley Centre's Global Sea Ice and Sea Surface Temperature dataset (HadISST) 1.1 (Rayner et al. 2003) for the period of 1979–2016. The best-track dataset from the Regional Specialized Meteorological Center (RSMC) Tokyo–Typhoon Center was utilized to investigate the WNP TC activity for the same period (available at <https://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/besttrack.html>). To validate the result, we further used the best track datasets from the Joint Typhoon Warning Center (JTWC) and China Meteorological Administration (CMA). To unify an averaging time interval of maximum sustained wind (MSW) as a 10-min average, the MSW in the JTWC dataset (1-min-averaged MSW) was multiplied by 0.88 (Kruk et al. 2010). We assumed that the 10-min-averaging time interval is used for the CMA (2-min-averaged MSW) (Knapp and Kruk 2010).

To select the EP-type El Niño and CP-type El Niño years, we adopted ENSO indices defined as SSTA averaged over the Niño-4 (5°S–5°N, 160°E–150°W), Niño-3.4 (5°S–5°N, 170°–120°W), and Niño-3 (5°S–5°N, 150°–90°W) regions as well as the El Niño Modoki index (EMI) defined as

$$\begin{aligned} \text{EMI} = & [10^{\circ}\text{S}–10^{\circ}\text{N}, 165^{\circ}\text{E}–140^{\circ}\text{W}]_{\text{CP}} \\ & - 0.5[15^{\circ}\text{S}–5^{\circ}\text{N}, 110^{\circ}–70^{\circ}\text{W}]_{\text{EP}} \\ & - 0.5[10^{\circ}\text{S}–20^{\circ}\text{N}, 125^{\circ}–145^{\circ}\text{E}]_{\text{WP}}, \end{aligned}$$

TABLE 1. Case selections for EP-type El Niño and CP-type El Niño in JJA and SON.

	JJA	SON
EP-type El Niño (Niño-3.4 > 1σ and Niño-3 > 1σ)	1982, 1987, 1997, 2015	1982, 1987, 1997, 2015
CP-type El Niño (EMI > 1σ and Niño-4 > Niño-3)	1991, 1994, 2002, 2004	1990, 1991, 1994, 2004, 2009

where the brackets denote the area-averaged SSTA over the regions (Ashok et al. 2007). The EP-type El Niño years are defined as both Niño-3.4 and Niño-3 indices greater than one standard deviation. The CP-type El Niño years are defined as EMI greater than one standard deviation as well as Niño-4 index greater than Niño-3 index. The selected years are summarized in Table 1.

A bootstrap method was conducted for the significance test regarding the composite analysis. The 95% confidence level is carried out by the outer 2.5% and 97.5% of the bootstrap sampling distribution generated by repeatedly taking random samples from the observation dataset with replacement 10 000 times.

b. Tropical cyclone activity

TCs were classified into three categories using their MSW based on the Saffir–Simpson scale: tropical storm (TS; $17.5 \leq \text{MSW} < 32.9 \text{ m s}^{-1}$), typhoon (TY; $\text{MSW} \geq 32.9 \text{ m s}^{-1}$), and strong typhoon (STY; $\text{MSW} \geq 49.4 \text{ m s}^{-1}$, consisting of typhoon categories 3–5). The TC activity was investigated by using its genesis frequency, genesis location, genesis density, track density, and accumulated cyclone energy (ACE) (Bell et al. 2000). The genesis location of TCs is defined as a track record first reaching TS intensity ($\text{MSW} \geq 17.5 \text{ m s}^{-1}$) in the best track dataset. The location was limited to the WNP region (0° – 50°N , 100°E – 180°). The genesis density was calculated by

counting the number of TCs forming over each $5^\circ \times 5^\circ$ grid. The track density was calculated by counting the number of TCs passing through each $5^\circ \times 5^\circ$ grid. The seasonal ACE of TCs was determined by summing every 6-h MSW records, which are greater than or equal to the TS intensity, during lifetime of TCs for the season.

c. Environmental conditions for TC genesis

The genesis potential index (GPI), representing large-scale conditions for TC genesis, is calculated as

$$\text{GPI} = \underbrace{|10^5 \eta|^{3/2}}_{\text{Term1}} \underbrace{\left(\frac{\text{RH}}{50}\right)^3}_{\text{Term2}} \underbrace{\left(\frac{V_{\text{pot}}}{70}\right)^3}_{\text{Term3}} \underbrace{(1 + 0.1 V_s)^{-2}}_{\text{Term4}} \underbrace{\left(\frac{-\omega + 0.1}{0.1}\right)}_{\text{Term5}}, \quad (1)$$

with absolute vorticity at 850 hPa η (s^{-1}), relative humidity at 700 hPa (RH; %), potential intensity V_{pot} (m s^{-1}), magnitude of vertical wind shear between 200 and 850 hPa V_s (m s^{-1}), and omega at 500 hPa ω (Pa s^{-1}) (Murakami and Wang 2010). We calculated the daily GPI dataset following the method in Camargo et al. (2009), and then made it into a monthly GPI dataset. To quantify the relative contributions of each term to the GPI change, we adopted the quantitative evaluation method (Li et al. 2013). The diagnosed GPI changes are calculated as

$$\begin{aligned} \delta \text{GPI} = & \delta \text{Term1} \times (\overline{\text{Term2} \times \text{Term3} \times \text{Term4} \times \text{Term5}}) + \delta \text{Term2} \times (\overline{\text{Term1} \times \text{Term3} \times \text{Term4} \times \text{Term5}}) \\ & + \delta \text{Term3} \times (\overline{\text{Term1} \times \text{Term2} \times \text{Term4} \times \text{Term5}}) + \delta \text{Term4} \times (\overline{\text{Term1} \times \text{Term2} \times \text{Term3} \times \text{Term5}}) \\ & + \delta \text{Term5} \times (\overline{\text{Term1} \times \text{Term2} \times \text{Term3} \times \text{Term4}}), \end{aligned} \quad (2)$$

where an overbar represents climatology and δ denotes anomaly regressed onto indices, or composite anomaly. To calculate percentages of relative contributions of each term to the diagnosed GPI change, we averaged each diagnosed term over the box regions (delimited by blue and red rectangles) to reveal the significant change associated with ENSO.

Steering flow is defined as the mass-weighted vertical average of the mean flow between 850 and 300 hPa to describe TC motion. The vertically integrated (1000–100 hPa) moisture flux convergence (MFC) and 850-hPa

moisture transport were used to examine large-scale moisture condition. The MFC is calculated as

$$\text{MFC} = -\nabla \cdot (q V_h), \quad (3)$$

with specific humidity q (kg kg^{-1}) and horizontal wind V_h (m s^{-1}). The vertically averaged (1000–500 hPa) moist static energy (MSE), which is highly linked to the ACE and typhoon activity (Chan and Liu 2004; Chan 2007), was utilized to represent the thermodynamic state in the atmosphere. The MSE is defined as

TABLE 2. Summary of the WNP TC activity associated with EP-type El Niño and CP-type El Niño in JJA. Two asterisks (**) and one asterisk (*), where numbers are in boldface, indicate the significance at 95% and 90% confidence levels, respectively, based on the bootstrap method using 10 000 bootstrap samples. Note that $1 \text{ kt} \approx 0.51 \text{ m s}^{-1}$.

		Frequency	ACE (10^4 kt^2)	Genesis longitude ($^{\circ}\text{E}$)	Genesis latitude ($^{\circ}\text{N}$)
Tropical cyclones	Climatology	10.53	94.14	135.02	18.17
	EP-type El Niño	10.5	145.93**	139.08	15.07**
	CP-type El Niño	13.5**	162.97**	137.29	18
Typhoons	Climatology	5.39	80.46	139.88	16.11
	EP-type El Niño	7	136.53**	143.69	13.13**
	CP-type El Niño	8**	147.12**	143.94	16.15
Strong typhoons (above typhoon category 3)	Climatology	1.18	27.25	144.93	13.59
	EP-type El Niño	3.75**	95.36**	—	—
	CP-type El Niño	1.5	44.91	—	—

$$\text{MSE} = C_p T + gz + Lq, \quad (4)$$

with the specific heat at constant pressure C_p ($1004 \text{ J kg}^{-1} \text{ K}^{-1}$), absolute air temperature T (K), gravitational acceleration g (9.81 m s^{-2}), height z (m) the latent heat of evaporation L ($2.5 \times 10^6 \text{ J kg}^{-1}$), and specific humidity q (kg kg^{-1}).

3. Seasonality in TC genesis–ENSO relationship

a. Seasonal characteristics of TC genesis and GPI

The genesis location of TCs can be determined by the monsoonal flows because they include favorable large-scale environments for TC genesis such as the plentiful warm moist air and cyclonic vorticity (Gray 1968; Ritchie and Holland 1999; Harr and Chan 2005; Li et al. 2006; Li 2012). The monsoon trough whose equatorward and poleward sides present westerlies and easterlies respectively exhibits a northwest–southeast axis in JJA (see Fig. S1a in the online supplemental material). The climatological genesis location of TCs (18.17°N , 135.02°E) is located along the northward side of the monsoon trough (Fig. S1a and Table 2). As the easterlies along 20°N dominate from September, the axis of the monsoon trough turns into a west–east axis in SON (Fig. S1b). The climatological genesis location of TCs

(15.95°N , 137.53°E) thus moves southeastward (Fig. S1b and Table 3).

As shown in Figs. 1a and 1b, climatological GPI values are proportional to those of genesis density of TCs, displaying the northeastward extension of GPI in JJA and the zonally elongated GPI pattern shifted southeastward in SON. It indicates that the climatological GPI can successfully represent spatial distributions of climatological seasonal TC genesis because the GPI was developed based on the climatological seasonal variations of TC genesis (Emanuel and Nolan 2004; Camargo et al. 2007; Murakami and Wang 2010). The average of Figs. 1a and 1b, which is the climatological GPI in June–November (JJASON), indicates that the PS is the most favorable region for the WNP TC genesis (Fig. 1c). Half of the difference between Figs. 1b and 1a, which is the seasonal change in climatological GPI from summer to fall, displays a tripolar pattern (Fig. 1d). The suppressions of both TC genesis and GPI north of 15°N from summer to fall are attributed to the decrease in precipitation and MSE as well as the increase in westerly vertical wind shear (Fig. S2). The enhancements of TC genesis and GPI from summer to fall are distinct over the SCS and the southeastern region of the WNP (5° – 15°N , 150°E – 180°), which arise from the increase in precipitation, MSE, and low-level relative vorticity as

TABLE 3. As in Table 2, but for SON.

		Frequency	ACE (10^4 kt^2)	Genesis longitude ($^{\circ}\text{E}$)	Genesis latitude ($^{\circ}\text{N}$)
Tropical cyclones	Climatology	10.71	113.89	137.53	15.95
	EP-type El Niño	9	127.65	145.12**	14.47*
	CP-type El Niño	12.2	170.24**	141.44	14.58*
Typhoons	Climatology	6.5	104.09	141.77	14.57
	EP-type El Niño	6.5	121.92	150.04**	13.25
	CP-type El Niño	8.2*	160.57**	145.43	13.46
Strong typhoons (above typhoon category 3)	Climatology	2.13	49.84	146.06	12.31
	EP-type El Niño	2.75	66.86	—	—
	CP-type El Niño	3.2**	83.02**	—	—

FIG. 1. (a),(b) Spatial distributions of climatological GPI (contours; interval: 2.0) and genesis density (shading; interval: 0.05 yr⁻¹) of TCs ($MSW \geq 17.5 \text{ m s}^{-1}$) calculated by counting the number of them forming over each $5^\circ \times 5^\circ$ grid in June–August (JJA) and September–November (SON) during 1979–2016. (c) Average of climatological GPI in (a) and (b) (shading and contours; interval: 2.0). (d) Half of the difference of climatological GPI between (b) and (a) (shading and contours; interval: 0.5). (e),(f) Variances (shading and contours; interval: 2.0) of GPI in JJA and SON during 1979–2016. The climatologies and variances of GPI were interpolated to a $5^\circ \times 5^\circ$ grid to display with the genesis density of TCs.

well as the decrease in vertical wind shear over the regions (Fig. S2).

b. Seasonality in the GPI–ENSO relationship

The variance of GPI shows the distinct meridional and zonal pattern in JJA and SON, respectively (Figs. 1e,f). The spatial patterns of GPI change associated with Niño-3.4 index (Figs. 2a,b) resemble those of the variance in summer and fall. The influences of ENSO on the

environmental conditions for TC genesis reveal the meridional and zonal asymmetry in summer and fall, respectively (Chen et al. 1998; Wang and Chan 2002). The result supports that the GPI can partially capture the interannual variabilities of the WNP TC genesis associated with ENSO (Camargo et al. 2007; Murakami et al. 2011). Furthermore, it is meaningful to investigate the GPI anomalies regressed onto Niño-3.4 index to evaluate the role of seasonality in the GPI–ENSO linear

FIG. 2. GPI variabilities associated with ENSO (Niño-3.4) during 1979–2016. (a),(b) Spatial patterns of GPI anomalies regressed onto the detrended and normalized Niño-3.4 index in JJA and SON, respectively. (c) Average of (a) and (b). (d) Half of the difference between (b) and (a). (e),(f) As in (c) and (d), but for diagnosed values. Contour intervals are 0.5 in (a)–(c) and (e) and 0.2 in (d) and (f). Shading in (a) and (b) indicates the significant region at the 95% confidence level based on a two-tailed Student's t test.

relationship, even though El Niño and La Niña can be responsible for the asymmetric climate impacts shown in Li and Zhou (2012) and Li et al. (2012). This is because the influences of both El Niño and La Niña on large-scale conditions for TC genesis over the WNP also reveal the prominent meridional and zonal asymmetry in JJA and SON, respectively (not shown). The relative humidity term is the most important factor over the blue boxes in Figs. 2a and 2b, which exhibit the suppressed GPI (Figs. S3a,b). The low-level absolute vorticity term is the primary important factor over the red boxes in Figs. 2a and 2b, which show the

enhanced GPI (Figs. S3c,d). The results imply that a role of the change in thermodynamic factor associated with ENSO in modulating the WNP TC genesis is distinct over the northern (western) part of the WNP in summer (fall). In contrast, a role of the change in dynamic factor associated with ENSO in modulating the WNP TC genesis is distinct over the southeastern part of the WNP in both seasons. From summer to fall, the thermodynamic factor-related region for TC genesis shifts southwestward and the dynamic factor-related region for TC genesis shrinks from east of 140°E to east of 150°E.

The average of Figs. 2a and 2b, which is the GPI change associated with ENSO in JJASON, indicates that influence of ENSO on large-scale conditions for TC genesis reveals a northwest–southeast dipole pattern (Fig. 2c). In contrast, half of the difference between Figs. 2b and 2a, which is the seasonal change in GPI anomalies associated with ENSO, displays a southwest–northeast dipole pattern (Fig. 2d). The diagnosed GPI changes (Figs. 2e,f) substantially represent the typhoon-season average and half of the typhoon-season difference, allowing us to utilize them for investigating relative roles of ENSO and background states in the seasonal change in GPI anomalies from summer to fall. Therefore, Eq. (2) was decomposed into the ENSO-related and background-related terms to evaluate their relative contributions. For

instance, the relative contribution of term1 to the diagnosed GPI change in summer and fall can be written as

$$\delta \text{Term1}_{\text{JJA}} \overline{\alpha 1_{\text{JJA}}}$$

and

$$\delta \text{Term1}_{\text{SON}} \overline{\alpha 1_{\text{SON}}},$$

where $\alpha 1_{\text{JJA}} = \text{Term2}_{\text{JJA}} \times \text{Term3}_{\text{JJA}} \times \text{Term4}_{\text{JJA}} \times \text{Term5}_{\text{JJA}}$ and $\alpha 1_{\text{SON}} = \text{Term2}_{\text{SON}} \times \text{Term3}_{\text{SON}} \times \text{Term4}_{\text{SON}} \times \text{Term5}_{\text{SON}}$.

Also, $\delta \text{Term1}_{\text{JJA}} \overline{\alpha 1_{\text{JJA}}}$ and $\delta \text{Term1}_{\text{SON}} \overline{\alpha 1_{\text{SON}}}$ can be rewritten as

$$\begin{aligned} & \delta \left[\frac{(\text{Term1}_{\text{JJA}} + \text{Term1}_{\text{SON}})}{2} - \frac{(\text{Term1}_{\text{SON}} - \text{Term1}_{\text{JJA}})}{2} \right] \left[\frac{(\alpha 1_{\text{JJA}} + \alpha 1_{\text{SON}})}{2} - \frac{(\alpha 1_{\text{SON}} - \alpha 1_{\text{JJA}})}{2} \right] \\ &= \left[\delta \text{Term1}_{\text{JJASON}} - \frac{1}{2}(\delta \text{Term1}_{\text{SON}} - \delta \text{Term1}_{\text{JJA}}) \right] \left[\overline{\alpha 1_{\text{JJASON}}} - \frac{1}{2}(\overline{\alpha 1_{\text{SON}}} - \overline{\alpha 1_{\text{JJA}}}) \right] \end{aligned} \quad (5)$$

and

$$\begin{aligned} & \delta \left[\frac{(\text{Term1}_{\text{JJA}} + \text{Term1}_{\text{SON}})}{2} + \frac{(\text{Term1}_{\text{SON}} - \text{Term1}_{\text{JJA}})}{2} \right] \left[\frac{(\alpha 1_{\text{JJA}} + \alpha 1_{\text{SON}})}{2} + \frac{(\alpha 1_{\text{SON}} - \alpha 1_{\text{JJA}})}{2} \right] \\ &= \left[\delta \text{Term1}_{\text{JJASON}} + \frac{1}{2}(\delta \text{Term1}_{\text{SON}} - \delta \text{Term1}_{\text{JJA}}) \right] \left[\overline{\alpha 1_{\text{JJASON}}} + \frac{1}{2}(\overline{\alpha 1_{\text{SON}}} - \overline{\alpha 1_{\text{JJA}}}) \right], \end{aligned} \quad (6)$$

respectively.

Adding Eqs. (5) and (6) and then dividing by 2, we have

$$\begin{aligned} & \delta \text{Term1}_{\text{JJASON}} \overline{\alpha 1_{\text{JJASON}}} \\ &+ \frac{1}{4}(\delta \text{Term1}_{\text{SON}} - \delta \text{Term1}_{\text{JJA}})(\overline{\alpha 1_{\text{SON}}} - \overline{\alpha 1_{\text{JJA}}}) \end{aligned}$$

as the typhoon-season average.

Subtracting Eq. (5) from Eq. (6) and then dividing by 2, we have

$$\begin{aligned} & \frac{1}{2}(\delta \text{Term1}_{\text{SON}} - \delta \text{Term1}_{\text{JJA}}) \overline{\alpha 1_{\text{JJASON}}} \\ &+ \frac{1}{2} \delta \text{Term1}_{\text{JJASON}} (\overline{\alpha 1_{\text{SON}}} - \overline{\alpha 1_{\text{JJA}}}) \end{aligned}$$

as half of the typhoon-season difference.

The first and second terms of the expression above can be interpreted as the diagnosed GPI changes due to the seasonal changes in ENSO and background states,

respectively. As shown in Figs. 2f and 3a, the GPI anomalies south of 20°N are attributed to the seasonal change in ENSO. It can be interpreted that the anomalous descending motion of Walker circulation and the suppression from the upper-level convergence induced by El Niño become stronger from summer to fall regarding the peak of El Niño in the late season. Indeed, the relative humidity, omega, and absolute vorticity terms contribute to the suppressed GPI (Fig. 3). The GPI change over the northeastern part of the WNP results from the seasonal change in background states from summer to fall (Figs. 2f and 4a). We can understand the role of seasonal background states ($\alpha 1_{\text{JJA}}$ and $\alpha 1_{\text{SON}}$) in modulating influences of ENSO ($\delta \text{Term1}_{\text{JJASON}}$) on the diagnosed GPI anomalies by comparing $0.5(\delta \text{Term1}_{\text{JJASON}} \overline{\alpha 1_{\text{JJA}}})$ and $0.5(\delta \text{Term1}_{\text{JJASON}} \overline{\alpha 1_{\text{SON}}})$ (Fig. S4). Even though the ENSO-induced anomalies are the same (Figs. S5a,d,g,j,m), the contribution of each anomalous term induced by ENSO to the GPI anomalies could be different depending on the background states (climatological four other terms) between JJA and SON (Fig. S4). The anomalous relative humidity, potential

FIG. 3. (b)–(f) Relative contributions of each term to (a) the diagnosed GPI change due to the seasonal change in ENSO (Niño-3.4). GPI consists of the following five large-scale terms: absolute vorticity at 850 hPa (Avor), relative humidity at 700 hPa (RH), potential intensity (PI), vertical wind shear (VWS), and omega at 500 hPa (Omega). Contour intervals are (a) 0.2 and (b)–(f) 0.1.

intensity (PI), and omega (absolute vorticity and vertical wind shear) terms regressed onto Niño-3.4 index in JJASON associated with four other climatological terms in JJA (SON) reveal stronger impacts north of 15°N (over the southeastern part of the WNP) rather than those in SON (JJA) (Fig. 4 and Fig. S4). The El Niño-induced absolute vorticity term shows the positive contribution over the broad region of the WNP (0°–20°N, 120°E–180°) (Figs. S4a,b). Its contribution decreases over the western part of the WNP and increases over the eastern part of the WNP from summer to fall (Fig. S4c). The result implies that summer background states are conducive to the northwestward

positive contribution of anomalous low-level relative vorticity to the GPI change compared to fall background states. In addition, the El Niño-induced vertical wind shear term contributes to the unfavorable condition for TC genesis over the PS and the favorable condition for TC genesis over the SCS as well as the southeastern part of the WNP. The tripolar pattern is shown south of 20°N because anomalous vertical wind shear induced by El Niño is confined over the region (Fig. S5j). We thus determined that the role of background states in the seasonal change in El Niño-induced GPI anomalies from summer to fall contributes to the positive GPI change over the northeastern part of the WNP.

FIG. 4. As in Fig. 3, but for the seasonal change in background states. Contour intervals are (a) 0.1 and (b)–(f) 0.05.

4. Impacts of seasonality and El Niño pattern diversity on the WNP TC activity

In the next subsections, we examined changes in the WNP TC activity associated with the El Niño pattern diversity according to summer and fall. Since the southeastward retreatments of the climatological high MSE and west–east axis of monsoon trough, the favorable thermodynamic and dynamic conditions for TC genesis move southward from summer to fall. TSs and TYs mainly form over the northwestern and southern parts of the WNP, respectively, implying their regional dependency (Fig. S1). Thus, we examined the relationship between the WNP TC genesis and El Niño pattern diversity regarding not only TCs but also TSs and TYs. The TC impacts over EA were investigated based on the linkage between TC motion and seasonal steering flows.

a. TC activity and El Niño pattern diversity

The composite analysis was conducted regarding genesis frequency, ACE, and genesis location of TCs, TYs, and STY (above typhoon category 3) for the EP-type El Niño and CP-type El Niño years (Table 1) in JJA (Table 2) and SON (Table 3). The statistical significance was calculated based on the difference from the climatological mean. In summer Table 2 reveals the significant southward movement of genesis location of TCs for the EP-type El Niño and the insignificant movement of genesis location of TCs for the CP-type El Niño. The enhanced ACE of TCs is mostly attributed to the increase in genesis frequency of STYs for the EP-type El Niño. The increase in genesis frequency of both TCs and TYs enhances their ACE for the CP-type El Niño. The southward movement of genesis location of TCs and

TABLE 4. Correlation coefficients between genesis frequency of the WNP TC (TCs, TSs, and TYs) and ENSO indices (Niño-3, Niño-3.4, and EMI) in JJA and SON. Two asterisks (**) and one asterisk (*), where numbers are in boldface, indicate the significance at 95% and 90% confidence levels, respectively.

Category	Season	Niño-3	Niño-3.4	EMI
Tropical cyclones (TCs)	JJA	−0.11	0.09	0.37**
	SON	−0.24	−0.22	0.07
Tropical storms (TSs)	JJA	−0.36**	−0.31*	0.01
	SON	−0.4**	−0.44**	−0.35**
Typhoons (TYs)	JJA	0.29*	0.47**	0.45**
	SON	0.08	0.14	0.39**

increase in genesis frequency of STYs for the EP-type El Niño are significantly different from those for the CP-type El Niño, which is statistically significant at the 95% confidence level based on the Student's *t* test. In fall the genesis location of TCs significantly moves southeastward and the genesis frequency of STYs shows an insignificant change for the EP-type El Niño (Table 3). Meanwhile, the increase in genesis frequency of both TYs and STYs contributes to the enhanced ACE of TCs for the CP-type El Niño. In addition, the genesis location of TCs significantly shifts southward. The increase in genesis frequency of TYs for the CP-type El Niño is significantly different from that for the EP-type El Niño at the 95% confidence level based on the Student's *t* test.

Table 4 shows linear relationships between genesis frequency of the WNP TC (TCs consisting of TSs and TYs according to their intensity) and ENSO indices (Niño-3, Niño-3.4, and EMI). The genesis frequency of TCs reveals an insignificant relationship with ENSO indices, except for that with EMI in JJA. However, the genesis frequency of TSs exhibits significant negative correlation coefficients with ENSO indices, except for that with EMI in JJA. In addition, the genesis frequency of TYs reveals significant positive correlation coefficients with ENSO indices in JJA and EMI in SON. The results imply that the relationship between the WNP TC genesis and ENSO show a regional dependency. This is because the genesis location of TSs is marked northwestward compared to that of TYs (Fig. S1). In other words, it is likely that El Niño suppresses (enhances) TC genesis over the northwestern (southeastern) part of the WNP. Indeed, favorable and unfavorable genesis conditions over the WNP cancel out the opposite subregional variabilities of genesis frequency of TCs, thereby revealing the insignificant relationship with the canonical ENSO (Chen and Tam 2010) (Table 4). In contrast, the significant relationship between EMI and genesis frequency of TCs in JJA

might be attributed to the significant relationship with TYs, but not with TSs (Table 4). This is consistent with the result that the genesis frequency of both TCs and TYs significantly increases for the CP-type El Niño in JJA (Table 2). The EMI reveals significant correlation coefficients with genesis frequency of TYs in both JJA and SON, whereas the Niño-3 and Niño-3.4 indices show insignificant correlation coefficients with genesis frequency of TYs in SON. It is likely that the genesis frequency of TYs in SON has a closer relationship with the CP-type ENSO compared to that with the EP-type ENSO (Tables 3 and 4).

b. TC genesis and GPI

As shown in Figs. 5a and 5c, the EP-type El Niño in JJA suppresses (enhances) TC genesis over the northern (southern) part of the WNP, revealing the meridional asymmetry. The GPI change over the blue box in Fig. 5c is primarily attributed to the change in the relative humidity term (Fig. S6a). This is because the upper-level convergence induced by the southward shift of the upper-level trough and enhanced upper-level anticyclone drives the midlevel downward motion (see Figs. S7a and S8a in the online supplemental material) (Wang and Chan 2002), thereby leading to the dry condition over the northeastern part of the WNP. Indeed, the negative MFC anomalies over the northern part of the WNP result in the suppression of TC genesis over the region (Figs. 5a,c and 6a). Thus, the genesis location of TCs significantly shifts southward (Table 2). The GPI change over the red box in Fig. 5c is mostly attributed to the contribution of the absolute vorticity term (Fig. S6c). The enhanced low-level relative vorticity over the southeastern part of the WNP is responsible for the enhancement of TC genesis over the southern part of the WNP (Figs. 5a,c and 6c). The EP-type El Niño in SON remarkably suppresses (enhances) TC genesis over the western (eastern) part of the WNP, which is consistent with the GPI change (Figs. 5b,d). The GPI change over the blue (red) box in Fig. 5d is considerably ascribed to the relative humidity (absolute vorticity) term (Figs. S6b,d). The distinct zonal asymmetry in the GPI change results from the suppression from the upper-level convergence (Figs. S7b and S8b) and the resultant dry condition and low MSE (Figs. 6b,f) over the western part of the WNP. The low-level cyclonic Rossby wave response contributes to the enhanced GPI over the southeastern part of the WNP (Fig. 6d and Fig. S6d). Thus, the genesis location of TCs significantly moves southeastward (Fig. 5b and Table 3).

Unlike the EP-type El Niño, the CP-type El Niño in JJA exhibits a tripolar pattern in the change in genesis density of TCs, revealing the suppression of TC genesis

FIG. 5. Composite maps of (a),(b),(e),(f) genesis density of tropical cyclones (grid and contours; interval: 0.1) calculated by counting the number of TCs forming over each $5^{\circ} \times 5^{\circ}$ grid and (c),(d),(g),(h) GPI (contours; interval: 1.0) anomalies for the EP-type El Niño and CP-type El Niño in JJA and SON, respectively. Shading is shown above the 95% confidence level (90% confidence level for the genesis density) based on the bootstrap method using 10 000 bootstrap samples.

over the PS and the enhancement of TC genesis over the SCS as well as east of 150°E (Fig. 5e). Even though the significant region is only observed over the southeastern part of the WNP, the GPI change also shows the tripolar pattern. The enhanced GPI over the red box in Fig. 5g can elucidate the enhanced TC genesis over the eastern part of the WNP, considerably resulting from the

relative humidity term (Fig. 5e and Fig. S6e). The enhanced MFC and low-level moisture transport over the southeastern part of the WNP result in the prominent contribution of relative humidity term to the GPI change (Fig. 7a). It is noted that, unlike the absolute vorticity term in the EP-type El Niño, the relative humidity term is the most dominant contributor to the

FIG. 6. Composite maps of (a),(b) vertically integrated (1000–100 hPa) moisture flux convergence (MFC; contours; interval: 1.0 mm day^{-1}) and 850-hPa moisture transport (MT; 10^{-3} m s^{-1} ; vectors), (c),(d) 850-hPa relative vorticity (contours interval: $1.5 \times 10^{-6} \text{ s}^{-1}$), (e),(f) vertically averaged (1000–500 hPa) moist static energy (MSE; contours; interval: $0.5 \times 10^3 \text{ J kg}^{-1}$), and (g),(h) vertical wind shear (VWS; contours; interval: 1.0 m s^{-1} for the magnitude of VWS and vectors for the VWS vector) anomalies for the EP-type El Niño in (a),(c),(e),(g) JJA and (b),(d),(f),(h) SON. Shading and vectors (in either zonal or meridional component) are shown above the 95% confidence level based on the bootstrap method using 10 000 bootstrap samples.

enhanced GPI over the southeastern part of the WNP in the CP-type El Niño (Figs. 6a,c and 7a,c; see also Figs. S6c,e). The anomalous low-level relative vorticity is mainly enhanced west of 150°E in the CP-type El Niño

(Fig. 7c), whereas the enhanced relative vorticity anomalies are confined east of 140°E in the EP-type El Niño (Fig. 6c). This is because cyclonic Rossby wave response can extend northwestward under the northern

FIG. 7. As in Fig. 6, but for the CP-type El Niño. Contour intervals are (a),(b) 1.0 mm day^{-1} , (c),(d) $1.5 \times 10^{-6} \text{ s}^{-1}$, (e),(f) $0.5 \times 10^3 \text{ J kg}^{-1}$, and (g),(h) 1.0 m s^{-1} . Shading and vectors (in either zonal or meridional component) are shown above the 95% confidence level based on the bootstrap method using 10 000 bootstrap samples.

off-equatorial SST warming (Jin et al. 2013). The CP-type El Niño in JJA exhibits the northward extension of high MSE and enhanced midlevel upward motion over the eastern part of the WNP (Fig. 7e and Fig. S8c). On the contrary, the much stronger MSE and midlevel

upward motion are confined to the equator (Fig. 6e and Fig. S8a), revealing insignificant contributions to the enhanced GPI over the southeastern part of the WNP (Fig. S6c). Furthermore, the enhanced vertical wind shear cancels out the influence of northwestward-extended

cyclonic anomalies over the PS in the CP-type El Niño (Fig. 7g). Indeed, the negative contributions of both the vertical wind shear and PI terms cancel out the positive contribution of absolute vorticity term over the PS (Fig. S9). Consequently, the relative humidity term is largely responsible for the active TC genesis over the eastern part of the WNP (east of 150°E) for the CP-type El Niño in JJA. The CP-type El Niño in SON suppresses (enhances) TC genesis over the southwestern (southeastern) part of the WNP, revealing the zonal asymmetry, which is consistent with the GPI change (Figs. 5f,h). The enhanced GPI over the red box in Fig. 5h is mainly attributed to the enhanced low-level relative vorticity (Fig. 7d and Fig. S6f). Furthermore, the enhanced moist state, high MSE, and reduced vertical wind shear over the southeastern part of the WNP (Figs. 7b,f,h and Fig. S6f) are responsible for the increase in genesis frequency of TYs (Table 3). Chen and Tam (2010) demonstrated that genesis frequency of TCs between two types of El Niño exhibits an insignificant difference in September–October (SO). However, the genesis frequency of TYs for the CP-type El Niño in SON is significantly different from that for the EP-type El Niño at the 95% confidence level based on the Student's *t* test. It is noted that the enhanced GPI for the CP-type El Niño is confined to east of 140°E, whereas that for the EP-type El Niño shifts toward east of 160°E (Figs. 5d,h). It is determined that the eastward shift of both enhanced vertical wind shear and enhanced suppression west of 160°E for the EP-type El Niño in SON is harmful to TC genesis in situ, thereby extending the unfavorable conditions for TC genesis southeastward compared to other cases (Figs. 5–7).

To understand the role of seasonality in the relationship between GPI and El Niño pattern diversity, the typhoon-season average of GPI anomalies in JJA and SON as well as half of their difference were explored according to two types of El Niño (Figs. 8–11). For the CP-type El Niño, the seasonality was examined utilizing the common years between JJA and SON (1991, 1994, and 2004) in the selected cases (Table 1) for the composite analysis. Half of the typhoon-season difference was decomposed into two parts that are ascribed to the seasonal changes in El Niño and background states, respectively (Figs. 10 and 11). The typhoon-season average of GPI anomalies (GPI change in JJASON) for the EP-type El Niño reveals the northwest-suppression and southeast-enhancement pattern of GPI (Figs. 8c,e). The prevailing change in GPI is the suppression over the northwestern part of the WNP. On the contrary, the average for the CP-type El Niño reveals the west-suppression and east-enhancement pattern of GPI (Figs. 9c,e), exhibiting the prevailing enhancement over the eastern part of the WNP. The result can be

interpreted that the EP-type El Niño might be appropriate to the linkage with the genesis frequency of TSs because it accounts for the suppression over the northwestern part of the WNP where TCs mainly form (Figs. 5 and 6; Table 4). In contrast, the CP-type El Niño might be adequate for the significant relationship with genesis frequency of TYs because it elucidates the moist state and high MSE east of 140°E where has a high probability of TY activity (Chan and Liu 2004; Chan 2007) (Figs. 5 and 7; Tables 2–4).

The seasonal change from JJA to SON exposes a north-enhancement and south-suppression pattern of GPI (Figs. 8d,f). As the EP-type El Niño evolves from JJA to SON, the anomalous descending motion of Walker circulation and the suppression from the upper-level convergence become stronger over the western part of the WNP (Figs. S7a,b, S8a,b). In addition, the enhanced low-level relative vorticity shifts eastward and the enhanced vertical wind shear becomes more harmful to TC genesis (Figs. 6c,d,g,h). Thus, the absolute vorticity, relative humidity, omega (not shown), and vertical wind shear terms mostly contribute to the negative GPI change south of 20°N (Figs. 10a,c,e,g). The prevailing suppression induced by the seasonal change in the EP-type El Niño reduces the favorable region for TC genesis from summer to fall (Figs. 5a–d). A comparison between Figs. 3a and 10a reveals that the EP-type El Niño, which was selected based on the strong intensity, induces the positive GPI change north of 20°N from JJA to SON. This is because the upper-level convergence response to the strong El Niño in JJA become stronger and then leads to the downdraft and dry condition over the northeastern part of the WNP, whereas the suppression disappears in situ in SON (Figs. 6a,b and Figs. S7a,b, S8a,b). Regarding the background states, the related relative humidity, PI, and omega (absolute vorticity and vertical wind shear) terms are responsible for the positive GPI change over the northern (southeastern) part of the WNP from JJA to SON (Figs. 10b,d,f,h). The result implies that summer (fall) background states are conducive to the negative (positive) contributions of anomalous relative humidity, PI, and omega (absolute vorticity and vertical wind shear) terms induced by the EP-type El Niño to the GPI change over the northern (southeastern) part of the WNP compared to fall (summer) background states. The results are consistent with those for the linear relationship with ENSO (Niño-3.4) (Fig. 4). For the CP-type El Niño, the suppression over the western part of the WNP becomes stronger and the enhanced relative vorticity moves eastward from summer to fall (Figs. 7a–f). Thus, the relative humidity, omega, and absolute vorticity terms mostly contribute to the negative GPI change

FIG. 8. As in Fig. 2, but for the EP-type El Niño composite (1982, 1987, 1997, and 2015). Contour intervals are 1.0 in (a)–(c) and (e) and 0.5 in (d) and (f). Shading in (a) and (b) indicates the significant region at the 95% confidence level based on the bootstrap method using 10 000 bootstrap samples.

south of 20°N (Figs. 11a,c,e,g). However, as opposed to the EP-type El Niño, the seasonal change in GPI for the CP-type El Niño reveals a zonal asymmetry with respect to 160°E in the absence of the positive GPI change over the northern part of the WNP (Figs. 8d,f and 9d,f). This is because the northwestward shift of relative vorticity and reduced dry condition over the northern part of the WNP for the CP-type El Niño in JJASON compared to those for the EP-type El Niño (Figs. S5b,c,e,f) contribute to both the negative seasonal change in the absolute vorticity term and reduced positive seasonal change in the relative humidity term over the northern part of the WNP from summer to fall (Figs. 11f,h). In

addition, the more favorable vertical wind shear term over the southeastern part of the WNP enhances the positive GPI change in situ for the CP-type El Niño compared to that for the EP-type El Niño (Figs. 11b,d and Figs. S5k,l).

c. TC track and surrounding environments

The TC impacts over EA were investigated according to the seasonality and El Niño pattern diversity. The TC motion is mainly governed by the large-scale steering flow, which is the deep-layer mean flow. The TC movement reveals the northwestward deviation from the steering flow due to the beta drift (Wang et al. 1998;

FIG. 9. As in Fig. 2, but for the CP-type El Niño composite (1991, 1994, and 2004). Contour intervals are 1.0 in (a)–(c) and (e) and 0.5 in (d) and (f). Shading in (a) and (b) indicates the significant region at the 95% confidence level based on the bootstrap method using 10 000 bootstrap samples.

Chan 2005). The WNP TC motion can be mostly described by the monsoonal flows, subtropical high, and upper-level trough (Harr and Elsberry 1995; Wang et al. 1998; Chan 2005). Thus, the climatological TC impacts could vary according to the seasonal steering flows. The climatological track density of TCs in JJA exhibits that the dominant southwesterly steering flows and the westward extension of subtropical high (5880-m geopotential height) lead to the northeastward-recurving TC motion, thereby heading toward the Korean peninsula and Japan (Fig. S10a). The climatological track density of TCs in SON reveals the prevailing westward-moving TC motion south of 20°N steered by the dominant easterly steering flows (Fig. S10b).

Compared to summer, the reduced TC impacts over northeast Asia in fall is ascribed to the southward deepening upper-level trough in the midlatitude region, the development of the anticyclone over eastern China, and the southeastward retreat of subtropical high (Fig. S10).

The EP-type El Niño in JJA leads to an increase in the number of westward-moving TCs occurred over the southern part of the WNP (Figs. 5a and 12a). The increased westward-moving TCs are attributed to both the anomalous easterly steering flows along 15°–25°N (Fig. 12c) and the suppression over the northern part of the WNP (Figs. S7a, S8a), thus resulting in a high probability of a threat to the Philippines (Fig. 12a). The

FIG. 10. (c)–(h) Relative contributions of three dominant terms to (a), (b) the diagnosed GPI change due to the seasonal change in (a), (c), (e), (g) ENSO and (b), (d), (f), (h) background states for the EP-type El Niño composite (1982, 1987, 1997, and 2015). Contour intervals are 0.4 in (a) and (b), 0.2 in (c), (e), and (g), and 0.1 in (d), (f), and (h).

prevailing westward TC motion causes the increase in genesis frequency of STYs and their ACE (Table 2). This is because TC intensity is partially governed by thermodynamic conditions along its passage. On the contrary, for

the EP-type El Niño in SON, the number of northward-recurring TC increases (Wang and Chan 2002). The anomalous anticyclonic steering flows over the SCS act as a barrier to prevent TCs occurring over the southeastern

FIG. 11. As in Fig. 10, but for the CP-type El Niño composite (1991, 1994, and 2004).

part of the WNP from heading westward, thereby reducing TC impacts over EA (Figs. 5b and 12b,d). Despite the southeastward shift of genesis location of TCs, the increase in the number of northward-recurring TCs east of 135°E contributes to the insignificant change in genesis frequency of STYs and their ACE (Figs. 5b and 12b; Table 3). This is

because they pass over cooler ocean compared to the westward TC motion, thereby missing an opportunity to intensify into STY.

The Korean peninsula and the southern part of Japan would be exposed to a greater threat from TCs for the CP-type El Niño in JJA (Fig. 12e). The increase in

FIG. 12. Composite maps of (a),(b),(e),(f) track density of tropical cyclones (contours; interval: 2.0) and (c),(d),(g),(h) 850-hPa streamfunction (contours; interval: $0.5 \times 10^6 \text{ m}^2 \text{ s}^{-1}$) and steering flow (m s^{-1} ; black vectors) anomalies for the EP-type El Niño and CP-type El Niño in JJA and SON, respectively. Climatological steering flow (red vectors) and 5880-m geopotential height (blue contours) are shown to describe TC motion. Shading and vectors (in either zonal or meridional component) are shown above the 95% confidence level (90% confidence level for the track density) based on the bootstrap method using 10 000 bootstrap samples.

the number of northward-recurving TCs is ascribed to the increase in the number of TCs occurring over the eastern part of the WNP (Fig. 5e) that can be steered by the climatological southeasterly flows (Fig. 12g). Hong et al. (2011) insisted that TC tracks between two types of El Niño show a remarkable difference in fall, but not in summer. However, it is determined that the TC impacts over EA for the CP-type El Niño in JJA are different from those for the EP-type El Niño in JJA (Figs. 12a,e). The CP-type El Niño in SON reveals a high probability of a threat to Japan (Fig. 12f). The increase in the number of northeastward-recurving TCs is caused by both the increase in the number of TCs occurring over the southeastern part of the WNP (Fig. 5f) and the anomalous cyclonic steering flows over the basin (Fig. 12h). This is because the anomalous southeasterly steering flows along 20° – 30° N weaken the climatological northwesterly steering flows, which prevent TCs from heading toward northeast Asia. The anomalous southeasterly steering flows are attributed to both the cyclonic Rossby wave response over the southeastern part of the WNP and the downdraft over the northeastern part of the WNP induced by the local meridional circulation due to the strong upward motion over the southeastern part of the WNP (Fig. 7d and Fig. S8d). Through numerical experiments, Hong et al. (2011) also showed that the local Hadley circulation induced by the local SST warming associated with the CP-type El Niño in SON is responsible for the increase in the number of the WNP TCs making landfall to EA. The prevailing northeastward-recurving TCs from the southeastern part of the WNP lead to the increase in genesis frequency of STYs and their ACE due to their longer passage (Table 3).

To understand the role of seasonality in the relationship between TC tracks and El Niño pattern diversity, the typhoon-season average of large-scale wind anomalies in JJA and SON and half of their difference were examined according to two types of El Niño (Fig. 13). The composites for the common years between JJA and SON (1991, 1994, and 2004) show a good agreement with those for the selected cases for the CP-type El Niño in Table 1 (Figs. 12g,h and 13e,f). The typhoon-season average exhibits that the anomalous southeasterly steering flows along 20° – 35° N allow TCs to move toward EA for the CP-type El Niño, whereas the anomalous northwesterly steering flows along 120° – 140° E prevent TCs from heading toward northeast Asia for the EP-type El Niño (Figs. 13c,g). Half of the typhoon-season difference in the EP-type El Niño reveals that as the season changes from summer to fall, the eastward extension of PS anticyclone prevents TCs from heading toward EA (Fig. 13d). On the contrary,

the anomalous southerly steering flows along 135° – 145° E allow TCs to move toward Japan for the CP-type El Niño (Fig. 13h).

5. Summary and discussion

The GPI–ENSO relationship and impacts of two types of El Niño on the WNP TC activity regarding seasonality are investigated by using the 1979–2016 RSMC best track dataset. We demonstrate that the thermodynamic factor (relative humidity term) is the most important contributor to the GPI change induced by ENSO over the northern and western part of the WNP in JJA and SON, respectively. The ENSO-induced GPI change over the southeastern part of the WNP is mostly attributed to the dynamic factor (absolute vorticity term) regardless of season. The influence of ENSO on large-scale conditions for TC genesis shows a distinct meridional and zonal asymmetry in JJA and SON, respectively. The role of seasonality in the GPI–ENSO relationship is explored by decomposing GPI into the ENSO-related and background-related terms to evaluate their relative contribution. The seasonal change in ENSO from summer to fall is responsible for the seasonal change in GPI anomalies south of 20° N, modulating relative humidity, omega, and absolute vorticity terms. We determine the contribution of each anomalous large-scale factor induced by ENSO to the GPI anomalies could be different depending on the background states (climatological other factors) between JJA and SON. This is because as high MSE retreats southeastward from summer to fall, the favorable thermodynamic and dynamic conditions for TC genesis move southward. Thus, the seasonal change in GPI anomalies over the northeastern part of the WNP results from the seasonal change in background states.

The impacts of seasonality and two types of El Niño on the WNP TC activity are summarized in Table 5 and Fig. 14. The EP-type El Niño in JJA leads to the downdraft from the upper-level convergence over the northeastern part of the WNP and the low-level cyclonic circulation over the southeastern part of the WNP, thereby revealing both the southward movement of genesis location of TCs and increase in the number of westward-moving TCs. The changes in both genesis location and motion of TCs account for the increase in genesis frequency of STYs experiencing high MSE. As the EP-type El Niño–induced upper-level convergence becomes stronger over the western part of the WNP from summer to fall, the resultant downdraft and anomalous anticyclonic circulation over the western part of the WNP remarkably decrease TC impacts over EA exhibiting both the southeastward movement of

FIG. 13. Composite maps of (a),(b),(e),(f) 850-hPa streamfunction (contours; interval: $0.5 \times 10^6 \text{ m}^2 \text{ s}^{-1}$) and steering flow (m s^{-1} ; black vectors) anomalies for the EP-type El Niño (1982, 1987, 1997, and 2015) and CP-type El Niño (1991, 1994, and 2004) in JJA and SON, respectively. Climatological steering flow (red vectors) and 5880-m geopotential height (blue contours) are shown to describe TC motion. Shading and vectors (in either zonal or meridional component) in (a), (b), (e), and (f) are shown above the 95% confidence level based on the bootstrap method using 10 000 bootstrap samples. (c) Average of (a) and (b). (d) Half of the difference between (b) and (a) for the EP-type El Niño. (g),(h) As in (c) and (d), but for the CP-type El Niño. Contour intervals are (c) and (g) $0.5 \times 10^6 \text{ m}^2 \text{ s}^{-1}$ and (d) and (f) $0.3 \times 10^6 \text{ m}^2 \text{ s}^{-1}$.

TABLE 5. Summary of impacts of El Niño pattern diversity on the WNP TC activity in JJA and SON.

	JJA	SON
EP-type	Southward movement of TC genesis	Southeastward movement of TC genesis
El Niño	Increase in ACE	Increase in the number of northward-recurving TC over the eastern part of the WNP
	Enhanced strong typhoon genesis	Reduced typhoon's impact over the South China Sea and East Asia
	Increase in the number of westward-moving TCs	Absolute vorticity (relative humidity) term as the most important factor for the enhanced (suppressed) GPI over the red box (5°–20°N, 160°E–180°) [blue box (5°–30°N, 110°–160°E)]
	Increased typhoon's impact over the Philippine Sea	
	Absolute vorticity (relative humidity) term as the most important factor for the enhanced (suppressed) GPI over the red box (5°–17°N, 140°E–180°) [blue box (17°–30°N, 120°–170°E)]	
CP-type	Increase in genesis frequency of TCs and TYs	Southward movement of TC genesis
El Niño	Increase in ACE	Increase in genesis frequency of TYs
	Increase in the number of northward-recurving TCs	Increase in ACE
	Increased typhoon's impact over the Korean peninsula and Japan	Enhanced strong typhoon genesis
	Relative humidity term as the most important factor for the enhanced GPI over the red box (5°–20°N, 140°E–180°)	Increase in the number of northeastward-recurving TCs
		Increased typhoon's impact over Japan
		Absolute vorticity term as the most important factor for the enhanced GPI over the red box (5°–20°N, 140°E–180°)

genesis location of TCs and the eastward shift of their recurvature point. On the contrary, the CP-type El Niño reveals the northwestward-shifted enhancement of relative vorticity and the enhanced MSE and middle-level upward motion over the southeastern part of the WNP under the northern off-equatorial SST warming. The enhanced MFC and low-level moisture transport over the southeastern part of the WNP lead to the dominant contribution of relative humidity term to the GPI change, especially in JJA. The favorable thermodynamic conditions (high MSE) over the eastern part of the WNP and longer passage of TCs toward EA account for the increase in the genesis frequency of TYs for the CP-type El Niño. The climatological southerly steering flow along 120°–140°E and reduced vertical wind shear around EA for the CP-type El Niño in JJA are responsible for the increased northward-recurving TCs toward EA. In addition, the anomalous southeasterly steering flows along 20°–30°N and reduced vertical wind shear around northeast Asia for the CP-type El Niño in SON result in the increased northeastward-recurving TCs toward Japan. The present results were validated by utilizing the two other best track datasets from the JTWC and CMA (Figs. S11 and S12).

It is noted that the contribution of relative humidity term to the enhanced GPI over the southeastern part of the WNP remarkably increases for the CP-type El Niño in summer in contrast to the absolute vorticity term in the rest of El Niño cases (the EP-type El Niño in JJA and SON, and the CP-type El Niño in SON). This is because the enhanced MSE and MFC over the eastern part of the WNP increase the contribution of relative humidity term to the GPI change in situ. In addition, the enhanced vertical wind shear cancels out the influence of northwestward-extended cyclonic anomalies over the PS revealing the tripolar pattern of anomalous genesis density of TCs. However, the GPI change underestimates the suppression of TC genesis over the PS. The different TC activity between two types of El Niño arises from the suppression induced by the strong upper-level convergence in the EP-type El Niño and both the northwestward-shifted relative vorticity anomalies and the northward-extended convection over the southeastern part the WNP in the CP-type El Niño. The suppression over the northeastern part of the WNP is more significant for the EP-type El Niño in JJA compared to the composite including other El Niño years (not shown). [Jiménez-Esteve and Domeisen \(2019\)](#) determined that the atmospheric response to

FIG. 14. Composite maps of TC tracks and SST anomalies for the (a),(b) EP-type El Niño and (c),(d) CP-type El Niño in (left) JJA and (right) SON. Red and blue dots denote genesis locations of typhoons (TYs) and tropical storms (TSs). Black contours indicate tracks of TCs. The genesis frequencies of TYs, TSs, and strong typhoons (STYs) as well as the selected years are written at the top right of each panel. Two asterisks (**) and one asterisk (*) indicate significance at 95% and 90% confidence levels, respectively (blue and red denote a decrease and an increase in genesis frequency, respectively), and shading indicates the significant region at the 95% confidence level based on the bootstrap method using 10 000 bootstrap samples. The contour intervals are 0.3° and 0.2°C for the EP-type El Niño and CP-type El Niño, respectively. The WNP region (0°–50°N, 100°E–180°) is delimited by the black rectangle.

ENSO considerably depends on the intensity of ENSO revealing distinct nonlinearity, especially for El Niño. In other words, strong El Niño exhibits much stronger atmospheric response compared to the moderate El Niño. This is consistent with the result that TC genesis over the northern part of the WNP in summer is remarkably modulated by the canonical El Niño (Wang and Chan 2002; Chen and Tam 2010). Consequently, the southward movement of genesis location of TCs and increase in genesis frequency of STYs for the EP-type El Niño in JJA are significantly different from those for the CP-type El Niño in JJA (at the 95% confidence level based on the Student's t test). The genesis frequency of TYs for the CP-type El Niño in SON significantly increases compared to that for the EP-type El Niño in SON (at the 95% confidence level based on the Student's t test). The results are different from those in Chen and Tam (2010) and Hong et al. (2011) that the distinct responses to two types of El Niño can be found in the summer TC genesis and fall TC motion.

Even though both the composite analysis for El Niño years (1982, 1987, 1991, 1997, 2002, 2009, and 2015) and La Niña years (1984, 1985, 1988, 1998, 1999, 2000, and 2010) show a good agreement with the result from the linear regression analysis (not shown), the composite for La Niña years reveals the relatively important contributions of PI and omega terms over the northern and

western part of the WNP in JJA and SON, respectively, as well as relative humidity term over the southeastern part of the WNP. The nonlinear relationship regarding the La Niña cases will be further studied in the future. In addition, even though GPI partially performs the interannual variabilities of TC genesis associated with ENSO, the skill for capturing its variability should be further improved. The recent decrease in genesis frequency of TCs over the southeastern part of the WNP (Choi et al. 2015; Hsu et al. 2014, 2017) can be ascribed to the impacts of El Niño diversity (Hu et al. 2018; Zhao and Wang 2019) and SST warming in the North Atlantic (Zhang et al. 2018). The frequent occurrence of CP-type ENSO (Hu et al. 2018; Zhao and Wang 2019) and the enhanced relationship between ENSO and typhoon activity under the negative phase of Pacific decadal oscillation (Zhao and Wang 2016) since the Pacific climate regime shift in 1998 led to the distinct northwestward movement of genesis location of TCs and suppressed typhoon genesis. The 2015/16 El Niño event is the mixture pattern with the Pacific meridional mode (PMM) (Murakami et al. 2017; Wu et al. 2018), exhibiting distinctive monsoon and TC activity during the strong El Niño decaying summer (Wu et al. 2018). The crucial role of the subtropical warming associated with the PMM in modulating TC activity over the WNP

(Zhang et al. 2016) as well as the eastern and central Pacific Ocean (Murakami et al. 2017) has recently been observed. The present results can stimulate the dynamical model community to improve and challenge us to distinguish the ENSO flavors such as its intensity and pattern. The lack of two types of El Niño cases requires further modeling experiments to determine the present results, thus improving the seasonal prediction of the WNP TC activity and contributing to natural hazard mitigation over EA.

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