Modulation processes of El Niño-Southern Oscillation on summer tropical cyclone activity in the northwestern North Pacific

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Abstract

Interannual variability of summer (June-August) tropical cyclones (TCs) in the northwestern North Pacific (NP) region (120º-135º E, 20º-35º N) and El Niño-Southern Oscillation (ENSO) exhibit four asymmetric ENSO-TC relationships. The major relationship types are El Niño-enhanced and La Niña-suppressed, while the minor relationship types are El Niño-suppressed and La Niña-enhanced. The major modulatory processes for the El Niño-enhanced type feature an elongated anomalous cyclone extending from the tropical western NP (WNP) northwestward toward the northwestern NP. This feature intensifies TC formation in the tropical WNP and guides them northward/northwestward increasing TC frequency in the northwestern NP. The El Niño-suppressed type has its anomalous cyclone displacing eastward in the tropical WNP with an accompanying anomalous anticyclone across the northwestern NP. TC formation reduces in the tropical WNP and TC movement is blocked toward the northwestern NP, resulting in decreased TC frequency. The La Niña-suppressed type features a dominant elongated anomalous anticyclone in the WNP to suppress TC formation and movement toward the northwestern NP, yielding reduced TC frequency. The La Niña-enhanced type contains an anomalous anticyclone south of 20º N in the tropical WNP in company with an anomalous cyclone over the northwestern NP. Under this anomalous cyclone, enhanced TC formation and movement in the northwestern NP result in increased TC frequency.

For all relationship types, 30-60-day intraseasonal oscillation (ISO) anomalies feature a dominant anomalous cyclone over the WNP providing favorable conditions that guide TC movement toward its central region over the northwestern NP. Both ENSO and ISO make positive contributions that increase TC frequency in the northwestern NP for the El Niño-enhanced and La Niña-enhanced types. ENSO is the major factor reducing TC frequency in the El Niño-suppressed and La Niña-suppressed types. .

Key word: Tropical cyclone, ENSO, ISO

1. Introduction

Tropical cyclone (TC) formation over the WNP can be modulated by background variability in sea surface temperature (SST), vorticity, humidity, vertical wind shear, and spatial patterns of the monsoon trough (MT) and the western ridge of the Pacific subtropical high (PSH) (Huang et al., 2011; Li and Zhou 2013). In the WNP, TC genesis locations displace northward during summer and shift southward during fall following the meridional migration of the MT and PSH (Chen et al. 2006; Chen et al. 2017). In the South China Sea (SCS), TC genesis mostly occurs in the northern basin during the southwest monsoon season (May-September) facilitated by strongly favorable thermal and dynamic conditions, but moves to the southern basin during the northeast monsoon season (October-December) (Wang et al. 2007). Strong vorticity provided by the MT is key to TC formation (Frank 1987; Lighthill et al., 1994; Ko and Hsu 2006).

TC tracks are mainly influenced by the locations of TC genesis and large-scale steering flows (Wu and Wang, 2004). Chen et al. (2017) demonstrated that the WNP TCs moving westward into the SCS tend to form more westward than TCs with a northward-recurving track. A WNP TC has a better chance to move into the SCS in October-November than August-September. TC activity can be significantly affected by climate variability on interannual and intraseasonal time scales described by El Niño-Southern Oscillation (ENSO) and intraseasonal oscillation (ISO) (Chan, 2000; Wang and Chan, 2002; Wu and Wang, 2004; Chen and Chen, 2011, Zhan et al., 2016; Zhan et al., 2017a; Zhan et al., 2017b; Chen et al., 2018b). Chen et al. (2018a) showed that a high TC genesis rate in the WNP tends to extend eastward during El Niño years, but is constrained more westward during La Niña years. The dominant 30-60-day anomalies steering TC movement from the WNP toward the SCS vary seasonally. TCs are in the southern periphery of an anomalous anticyclone during July and August, between a southern anomalous cyclone and a northern anomalous anticyclone during September, and in the northern periphery of an anomalous cyclone during October and November (Chen et al., 2019). For TCs during fall, Tan et al. (2018) demonstrated that ISO and ENSO jointly impact enhancement or suppression of TC movement entering the SCS during La Niña years, while ISO (ENSO) plays a dominant role in facilitating (hindering) TC entrance into the SCS during El Niño years. TC movement from the WNP into the SCS can either increase or decrease during different ENSO phases, showing an asymmetric ENSO-TC relationship.

Chen et al. (2019) showed that ISO exerts different modulating effects on the westward and northward tracks of the WNP TCs. So far, there is generally a lack of research interpreting large-scale processes affecting northward/northwestward TC movement during summer. The relative influences of ENSO and ISO on TCs tracking northward/northwestward toward the northwestern NP need to be specifically examined. Therefore, this study investigates interannual variability of TC activity over the northwestern NP during summer (June-August), focusing on the relative influences and large-scale modulating processes of ENSO and ISO

2. Data

The examinations of large-scale modulating processes on TC activity in the northwestern NP employ four data sets. Features of TC activity are analyzed from the Joint Typhoon Warning Center (JTWC) best track data. This data set provides six-hourly information on TC position and maximum sustained wind speed near the TC center. The large-scale climate variability affecting TC activity is analyzed from daily data of the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis data (Kalnay et al., 1996). To depict the air-sea interactions caused by various ENSO phases, sea surface temperature (SST) patterns are investigated from monthly variables of extended reconstruction SST (ERSST) version 5 data (Huang et al., 2017). To define various ENSO phases, the Oceanic Niño Index (ONI) compiled by the National Oceanic and Atmospheric Administration (NOAA) is employed. This index is represented by a SST anomaly averaged from the Niño 3.4 domain (120 ^{o}-170oW, 5 ^{o}S-5 ^{o}N). The study analyzes the period 1961-2016.

3. Interannual relationships between TCs in the northwestern NP and ENSO

To demonstrate major TC movement in the WNP, the climatological (1961-2016) mean of summer passage frequency is computed from the 6-hourly JTWC best track data (Figure 1). The passage frequency is represented by counts of TC appearance in every 5o x 5o box accumulated throughout summer. When the WNP TCs track westward, they mainly enter the SCS. On the other hand, if they follow northward/northwestward tracks, they largely recurve toward the northwestern NP. In this study, summer TCs appearing in the northwestern NP over the maximum region of 120^{o}-135 ^{o} E, 20 ^{o} -35 ^{o}N in Figure 1 are selected for analysis. This northwestern NP region is referred to as the analysis domain and indicated by a square box in Figure 1.

The 1961-2016 time series of summer TC numbers appearing in this analysis domain are shown in Fig
ure 2. The time series exhibit evident interannual variability with a long-term mean of 5.1. TC activity in the WNP exhibits interdecadal changes around the 1990s. The 11-year-running means of the 1961-2016 time series of TC numbers are computed and superimposed on Figure 2. Their interdecadal features are consistent with previous works showing increased TC activity in the late 1990s and early 2000s. However, the standard deviation of the interdecadal time series is much smaller than that of the interannual time series, 0.3 vs. 1.58. TC activity in the northwestern NP is apparently dominated by interannual variability. Tan et al. (2018) demonstrated that westward-moving TCs during fall exhibit an asymmetric relationship with ENSO: cold or warm ENSO phases can have either enhanced or suppressed TC activity. Does an asymmetric relationship also occur for summer TCs in the northwestern NP? To investigate this question, the ONI index is used to categorize ENSO phases. A year with a warm (cold) ENSO phase during summer defined by the June-August ONI index greater than 0.5oC (smaller than -0.5 ^{o} C) is categorized as an El Niño (a La Niña) year. An El Niño (a La Niña) year is indicated with a solid (an open) circle in Figure 2.

The relationships between ENSO and summer TC activity in the analysis domain are shown in Table 1. The average TC number for El Niño years is 5.8 and 4.4 for La Niña years, reflecting more summer TCs appearing in the northwestern NP during El Niño years. We thus define years with a TC number higher (lower) than both the ENSO-type and long-term means as the enhanced (suppressed) TC activity type. With this definition, an El Niño year with a TC number greater/smaller than both 5.1 and 5.8 is defined as the El Niño-enhanced (EN-enhanced)/ El Niño-suppressed (EN-suppressed) type. A La Niña year with a TC number larger (smaller) than both 5.1 and 4.4 is sorted as the La Niña-enhanced (LN-enhanced)/La Niña-suppressed (LN-suppressed) type.

4. Concluding Remark

This study examined interannual variability of summer (June-August) TC activity in the northwestern NP during the period 1961-2016.The modulations of ENSO and ISO on TC variability are also investigated. Analyses demonstrate that the number of TCs appearing in the analysis domain (120 ^{o}E-135 ^{o}E, 20 ^{o}N-30 ^{o}N) over the northwestern NP can increase or decrease in warm or cold ENSO phases, revealing the existence of four asymmetric ENSO-TC relationships. The major relationship types are El Niño-enhanced (EN-enhanced) and La Niña-suppressed (LN-suppressed), while the minor relationship types are El Niño-suppressed

(EN-suppressed) and La Niña-enhanced (LN-enhanced). The average number of summer TCs appearing in the analysis domain is larger in El Niño years (5.8) than La Niña years (4.4), with a long-term mean of 5.2.

For the EN-enhanced type, El Niño conditions feature warm SST anomalies and an overlying anomalous convergent X850 center in the tropical eastern Pacific that are accompanied by cold SST anomalies and a divergent X850 center in the tropical western Pacific and Maritime Continent. S850 anomalies respond with a cyclonic anomaly elongating across the tropical WNP and the northwestern NP. TC formation is enhanced in the tropical WNP and these TCs are steered toward an anomalous cyclonic region over the northwestern NP, leading to increased TC frequency. During the EN-suppressed type, a large-scale anomalous cyclone has its western boundary at 135 ^{o}E, which is accompanied by an anomalous anticyclone to the west extending from the analysis domain northeastward toward the northern NP north of the anomalous cyclone. Under these circumstances, TC formation is suppressed in the tropical WNP west of 145 ^{o}E and enhanced to the east in association with an eastward-shifting anomalous cyclone. TCs in the tropical WNP are less formed and the formed TCs are hindered by the anomalous anticyclone to move toward the analysis domain. TC frequency thus reduces over the northwestern NP.

The large-scale processes of the LN-suppressed type are more or less opposite to those of the EN-enhanced type. An elongated anomalous anticyclone crosses the WNP with its center over the Philippine Sea. TC formation is generally suppressed in the tropical WNP. Reduced tropical TCs are further blocked by anomalous northwesterly flows from moving toward the analysis domain. TC frequency in the northwestern NP thus decreases. For the LN-enhanced type, the center of the anomalous anticyclone over the tropical WNP displaces farther eastward than in the LN-suppressed type. A weakened anomalous anticyclone over the Philippine Sea is accompanied by an anomalous cyclone on its northern side across the analysis domain and its eastern surrounds. TC formation is enhanced underneath this anomalous cyclone with increased TC movement inside or toward the anomalous cyclonic center overlying the analysis domain, leading to increased TC frequency in the northwestern NP.

ISO anomalies act to facilitate TC movement toward the northwestern NP in all four ENSO-TC relationship types. The EN-enhanced and EN-suppressed types feature a meridional circulation pair. This is dominated by an anomalous cyclone across the WNP over the 100 ^{o}-160 ^{o}E region. TCs mainly form in the regions to the east and southeast of the anomalous cyclonic center and later move toward the central region over the northwestern NP. The 30-60-day anomaly pair propagates northwestward slowly. For the LN-suppressed and LN-enhanced types, the dominant anomalous cyclone retreats westward to the west of 140 ^{o}E. An anomalous anticyclone appears on its eastern side to form a zonal circulation pair that propagates northward. TC formation mainly takes place in the regions to the east and southeast of the anomalous cyclonic center. As guided by the ISO anomaly, the formed TCs move toward the northwestern NP where the anomalous cyclonic center exists.

ENSO and ISO exert different impacts in the modulatory processes of four ENSO-TC relationship types. Their relative effects are summarized in Table 2. Interannual processes associated with ENSO are effective in determining TC frequency via modulation of TC formation and movement. They make positive contributions increasing TC frequency over the northwestern NP in the EN-enhanced and LN-enhanced types, but negative contributions to suppress TC activity in the EN-suppressed and LN-suppressed types. ISO anomalies provide positive contributions in facilitating TC movement toward the northwestern NP in all four ENSO-TC relationship types. Overall, enhanced TC activity over the northwestern NP in the EN-enhanced and LN-enhanced types are jointly assisted by both ENSO and ISO, while ENSO plays a more important role than ISO in suppressing TC activity in the EN-suppressed and LN-suppressed types. ISO Intensity is not effective to modulate summer TC numbers in the northwestern NP. The key factor modulating TC numbers appears as the interannual circulation anomaly over the WNP. Increased TCs are affected by the circulation pattern of the cyclonic anomaly during El Niño years and the weakening of the anticyclonic anomaly during La Nina years.

SST anomalies in the eastern Pacific exhibit two components: tropical SST anomalies connected with ENSO and subtropical SST anomalies associated with the Pacific meridional mode (PMM; Chiang and Vimont, 2004; Zhang et al. 2016). Hong et al. (2018) found that the ENSO-type SST anomalies act to cause a north-south displacement of mean TC genesis location in the WNP, while the PMM-type SST anomalies act to induce an east-west displacement. Composite SST anomalies of the EN-suppressed type exhibit strong positive anomalies in the tropical eastern Pacific and the northwestern NP to the east of Japan and weak positive anomalies between them. These well-organized meridional patterns reveal the signature of the PMM. The corresponding TC genesis anomalies increase in the eastern WNP and decrease in the western WNP, showing an eastward shift. In 2015 (one of the EN-suppressed years), the eastward shift of TC genesis was found to be influenced by the subtropical SST anomalies associated with the PMM (Murakami et al., 2017). The eastward-displaced TCs tend to move northward toward the northern NP, leading to suppressed TC activity in the northwestern NP. For the EN-enhanced type, strong positive SST anomalies dominate in the tropical eastern Pacific, while subtropical SST anomalies are weak and not well-organized. The corresponding TC genesis anomalies feature a northern decrease-southern increase pattern, reflecting the dominating effects from the ENSO-type SST anomalies. The formed TCs later move northwestward to enhance TC activity in the northwestern NP. Overall, subtropical SST anomalies appear to exert certain effects on the WNP TC activity in the EN-suppressed type, while tropical SST anomalies play the dominant role in modulating TC activity in the EN-enhanced type. The specific effects of the PMM-related subtropical SST anomalies on TC activity in the WNP need to be comprehensively investigated in the future studies.

This study demonstrates the existence of asymmetric ENSO-summer TC relationships in the northwestern NP. Most of these TCs form in the tropical WNP and move northward or northwestward toward the northwestern NP, showing a recurving track. On the other hand, Tan et al. (2018) illustrated the existence of asymmetric ENSO-TC relationships for the WNP TCs moving westward toward the SCS during fall. These results indicate that certain differences in the responses of large-scale circulation anomalies in the WNP to ENSO result in different modulatory effects on TC activity. Such asymmetric relationships are evident for major TC tracks in different seasons; that is, recurving northward during summer and progressing straight in a westward direction during fall (Chen et al. 2017). These two studies also demonstrate that ENSO's impact on TC activity in the WNP is not simply described by a one-to-one response.

The two minor variability types (LN-enhanced, EN-suppressed) only have 3 to 4 member cases for analysis. These member numbers are not large enough to represent a gross feature for certain climate variability type. Analyses for the two minor variability types can be considered to illustrate interesting and particular TC-ENSO relationships for the northwestern NP. Our analyses (not shown) also reveal that composite anomalies of these two minor variability types still reasonably capture the major variability features of their member years and are not solely determined by one particular year. The modulating processes associated with the asymmetric ENSO-TC relationships demonstrated in this study should be helpful in improving track predictions for summer TCs in the WNP.

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Table 1: Member years and summer TC numbers appearing in the northwestern NP (120o-135oE, 20o-35oN) in different ENSO-TC relationship types: El Niño-suppressed (EN-suppressed), El Niño-enhanced (EN-enhanced), La Niña-suppressed (LN-suppressed), and La Niña-enhanced (LN-enhanced).

TC number	El Niño year	type	La Niña year	type
2	2009	EN-suppressed	1988	LN-suppressed
3			1973、1998、2010	
4	1972、1991、2015		1970、1975、1999	
5			1971、2011	
6	1965、1987、1997	EN-enhanced	2000	LN-enhanced
7	1963、1982		1964、1974	
9	2002、2004			

Table 2: The effects of ENSO and ISO on interannual variability of summer TCs in the northwestern NP for the four ENSO-TC relationship types. The modulating factors in each type are listed.

Type	ENSO	ISO	Modulatory factors
EN-enhanced	favorable	favorable	ENSO, ISO
EN-suppressed	unfavorable	favorable	ENSO
LN-enhanced	favorable	favorable	ENSO, ISO
LN-suppressed	unfavorable	favorable	ENSO

Figure 1. The climatological (1961-2016) mean of passage frequency during summer. The square box indicates the analysis domain (120oE-135oE, 20oN-35oN) used to analyze summer TC activity in the northwestern North Pacific in this study.

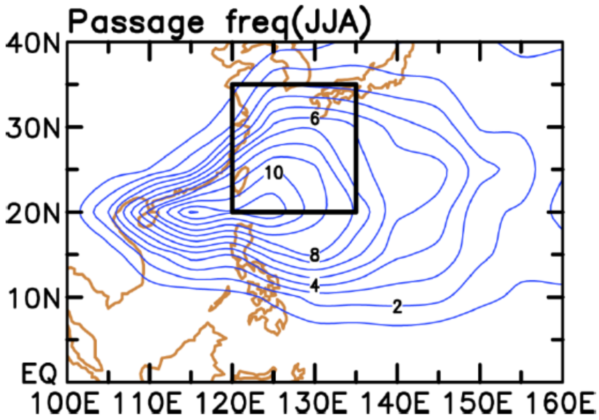

Figure 2. The 1961-2016 time series of summer TC numbers appearing in the northwestern North Pacific domain shown in Figure 1. The horizontal line marks the long-term mean (5.1), while a solid (an open) circle indicates an El Niño (a La Niña) year. Their interdecadal variations are illustrated by the superimposed 11-year-running-mean time series.