Differences in the destructiveness of tropical cyclones over the western North Pacific between slow- and rapid-transforming El Niño years

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Abstract
The relationship between the destructive potential of tropical cyclones (TCs) over the western North Pacific (WNP) (as quantified by the Power Dissipation Index) and El Niño events is investigated in this work. Results show that the destructive potential of TCs is significantly affected by how rapidly El Niño decays from a positive phase to a negative phase. For TCs occurring during ‘slow-transforming’ El Niño, more of them initiate over the southeastern part (0°–15°N, 150°E–180°) of the WNP and the destructive potential of TCs is usually strong. In contrast, weaker destructiveness is indicated during ‘rapid-transforming’ periods, with fewer TC formations in the southeastern area. This weaker destructiveness during rapid-transforming El Niño years is mainly caused by anomalously cooler upper-ocean conditions in the central Pacific, negative relative vorticity anomalies, and increased vertical wind shear in the WNP. These findings may have important implications for the seasonal prediction of TC changes in the WNP.

1. Introduction

Tropical cyclones (TCs) are one of the most destructive natural disasters on Earth, adversely affecting communities, infrastructure, economies and ecosystems, the environment, and even people’s lives and property (Lonfat et al. 2004, Chan 2005, Jiang and Zipser 2010, Mendelsohn et al. 2012, Lin et al. 2015). The western North Pacific (WNP) has the largest TC count on Earth, with nearly one-third of all TCs forming and developing there every year. This undoubtedly has very serious impacts on surrounding areas and countries (Chen et al. 1998, Mei and Xie 2016).

Previous studies have revealed that modes of variability like the quasi-biennial oscillation, Madden–Julian Oscillation, and Pacific Decadal Oscillation have important effects on TC activities (Chan 1995, Sobel and Maloney 2000, Wang and Liu 2016). However, as the strongest large-scale climate mode in the Pacific Ocean, El Niño–Southern Oscillation (ENSO) has a particularly significant impact on TC activities in the WNP region (Camargo et al. 2007, Kim et al. 2011). Several research findings (e.g. Wang and Chan 2002, Camargo and Sobel 2005) indicate that ENSO events usually affect TC activities mainly through direct interaction with the atmospheric and oceanic conditions, and then these conditions can affect the TC activities in the WNP (Emanuel 2000, Webster et al. 2005). Atmospheric vertical wind shear and low-level relative vorticity are the two most obvious dynamic factors impacting upon TC activities (Chen et al. 2006, Ge et al. 2007). During a La Niña year, TC formation and development are suppressed by negative relative vorticity anomalies and large vertical wind shear over the WNP, and thus there is weaker destructive potential in this area (Camargo and Sobel 2005, Tu et al. 2018). The opposite is the case during El Niño events.

Meanwhile, some studies (e.g. Lorenzo et al. 2010, Yeh et al. 2014) have found that there are obvious
differences in the locations of where El Niño events form (eastern or central Pacific: EP or CP). Yang et al (2015) studied the difference in TC activity in the WNP when EP and CP El Niño occur. They pointed out that, during EP El Niño periods, the frequency of TCs landing in the Philippines increases, whereas during CP El Niño, there is an increase in the frequency of TCs entering the South China Seas and making landfall on the South China coast. Xu and Huang (2015) found that, during EP El Niño years, the Pacific Ocean is more likely to generate stronger TCs from July to August, and then the TC maximum activity anomaly center shifts eastwards from September to October; however, when CP El Niño occurs, there is almost no significant change in Pacific TC activity during July–October.

The evolutionary characteristics of the El Niño events are also an issue worthy of study. In previous studies, the phase in which the sea surface temperature anomalies (SSTA) gradually weakens after the maturity of El Niño is usually defined as the decaying phase of the El Niño event (Lin and Li 2008, Jiang et al 2017, Huangfu et al 2018). Different rates at which El Niño events decay modulate the atmospheric circulation and oceanic environment differently in the surrounding areas (Pillai and Chowdary 2016). Based on the length of decaying phase of the El Niño event, Chen et al (2016) divided the El Niño events into short decaying and long decaying type: the first type is defined as the El Niño that terminates in the following summer after the mature phase, and the second type is defined as these El Niño events that persist until the subsequent winter. Then, the responses of the western North Pacific anticyclone anomaly to the short and long decaying El Niño events are analyzed in their work. The El Niño decaying pace impacts the summer climate in East Asian by controlling the changes of Northwestern Pacific Anticyclonic Anomalies (Jiang et al 2019). However, few studies have explored the possible effects of how rapidly El Niño decays from its peak on TC activities over the WNP.

In order to investigate the characteristics of TC destructive potential over the WNP in the decaying year of El Niño events, the different features of how rapidly El Niño decays from a positive phase to a negative phase are roughly divided into two event types: ‘rapid-transforming’ (RT) and ‘slow-transforming’ (ST) events. Based on this categorization, we explore the change in destructive potential and the differences in TC destructive potential over the WNP during the typhoon season (July–November) for ST and RT El Niño events; plus, we attempt to uncover the main reasons behind the differences found.

Following this introduction, section 2 of the paper introduces the data and methods employed in our work; section 3 documents the different influences of ST and RT El Niño events on the destructive potential of TCs over the WNP; section 4 explores the possible mechanism of impact; section 5 sets out our conclusions and discussion.

2. Data and methods

Based on a previous study (Huang et al 2017), we use the monthly Niño3.4 index (Niño3.4 region: 5°S–5°N, 170°–120°W) obtained from the globally complete sea-ice and sea surface temperature (SST) data (i.e. HadISST, Rayner et al 2003) from the Hadley Center to investigate the temporal characteristics of El Niño. According to statistics of all El Niño events since 1950, we find that the average state of El Niño was terminated in April of the decaying year. As the typhoon season of WNP begins in July, there has three months interval of April and July. Therefore, in this work, RT El Niño is characterized by a rapid transformation that from an El Niño to a La Niña over no more than three months. Compared with previous studies (Chen et al 2016, Jiang et al 2019), this definition of RT El Niño is more beneficial for the seasonal prediction of TCs over the WNP region.

Further, we counted all of the La Niña events and found that the La Niña events rarely develops after October. Here, we define these El Niño events with no reduction from +0.5 °C to −0.5 °C within six months (April–October) as ST El Niño. This kind of events enter a neutral year or build again to become the next El Niño event during the decaying phase.

Following the above definition, there are five RT El Niño events (1972/73, 1982/83, 1987/88, 1997/98, 2009/10), and nine ST events (1951/52, 1957/58, 1965/66, 1977/78, 1991/92, 1994/95, 2002/03, 2004/05, 2006/07) since 1950. The temporal evolutions of these El Niño events are shown in figures 1(a) and (b), respectively, and their spatial evolution features are presented in figure 6. Here, most of the RT El Niño events are strong, while the ST El Niño events are generally weak. Therefore, El Niño intensity has some influences on our classification method, but RT and ST are not consistent with strong and weak El Niño completely.

The best-track TC data for the WNP used in this work are from the IBTrACS-JTWC dataset (IBTrACS: International Best Track Archive for Climate Stewardship; JTWC: Joint Typhoon Warning Center) version 03r10 (Knapp et al 2010), which include the maximum sustained surface wind speed, minimum air pressure, and positions near the TC center every six hours. All of the TCs, including tropical depressions, tropical storms and category 1–5, are considered in this work.

To estimate the TC destructive potential, we use the Power Dissipation Index (PDI) proposed by Emanuel (2005), which integrates the contributions of TC number, intensity (the maximum sustained surface wind speed every six hours), and duration (the time between TC formation and disappearance). For each typhoon season (here, July–November), the total
PDI is calculated as:

\[ \text{PDI} = \sum_{i=1}^{N} \int_{0}^{\tau_i} V_{\text{max}}^3 \, dt, \]

where \( V_{\text{max}} \) is the maximum sustained surface wind speed every six hours, \( \tau_i \) is the lifetime of each TC, and \( N \) is the count of TCs in each typhoon season. The PDI during the typhoon season of ST and RT El Niño events and in the climatology (average during 1981–2010) accounts for 79.1%, 93.3% and 81.6% of the total yearly PDI, respectively.

Similarly, to investigate the regional PDI difference during the two periods, we also calculate the regional PDI on a \( 2^\circ \times 2^\circ \) grid over the WNP, during the typhoon season of ST and RT El Niño events. The regional PDI is defined in a similar way as the above formula, but for the TC recordings (in the IBTrACS-JTWC dataset) entering into an individual \( 2^\circ \times 2^\circ \) grid. However, unlike the total PDI defined above, the regional PDI defined here is mainly contributed by the regional intensity and track density of TCs. In order to better display the spatial distribution of the regional PDI, we utilize a spatial nine-point filter, which is defined as:

\[ \chi_{ij} = \frac{1}{9} \sum_{m,n=-1}^{m,n=1} x_{i+m,j+n}. \]

The results are shown in figure 2. Based on this approach, we also investigate the track density and the regional intensity differences of TC change between RT and ST El Niño events (figure 3).

To investigate the differences in TC destructive potential in the WNP during the decaying phase of ST and RT El Niño events and their possible mechanisms, we use monthly National Centers for Environmental Prediction data (Kalnay 1996) from National Oceanic and Atmospheric Administration (NOAA), with a \( 2.5^\circ \times 2.5^\circ \) horizontal resolution. Specifically, we use the data to explore the differences in relative vorticity (at 850 hPa), vertical wind shear (200 hPa minus 850 hPa), and 500 hPa geopotential height between ST and RT El Niño years.

In addition to the above atmospheric factors, the thermal conditions of the upper ocean also have an important influence on TC change over the WNP. Thus, we also examine if there is a significant difference in the contribution of the SST and upper-ocean thermal conditions to TC destructive potential in the WNP between RT and ST El Niño years. To do so, the
HadISST data (Rayner et al. 2003) and an *in situ* ocean temperature and salinity profile and objective analysis dataset (i.e. EN4, Good et al. 2013), on a $1^\circ \times 1^\circ$ grid from the Hadley Center, are used, respectively.

The TC heat potential (TCHP) represents the heat contained in the upper layer of the 26°C isotherm of the ocean. Based on previous studies (Leipper 1964, Guo and Tan 2018), it is defined as:

$$\text{TCHP} = c_p \rho \int_{D_{26}}^0 [T(z) - 26] dz,$$

where $c_p$ is the constant pressure specific heat capacity, which is usually taken as 4178 J kg$^{-1}$ °C$^{-1}$; $\rho$ is the density of sea water, taken as 1026 kg m$^{-3}$ in the upper ocean; $D_{26}$ is the depth of the 26°C isotherm; and $T(z)$ is the *in situ* temperature from EN4.

### 3. Influences of St and RT El Niño on TC destructiveness

The ENSO cycle is closely related to TC activities in the WNP (Wang and Chan 2002, Camargo and Sobel 2005, Tu et al. 2018). As shown in figure 1, different ratios of decay for El Niño events will also have various impacts on TC activities—even the monthly distribution of TC count and destructive potential (figures 1(c), (d)). At the time of onset for ST El Niño events, except in November and December, the frequency of TC genesis is more than for RT El Niño in each individual month, while there is no TC genesis in February. TCs have the greatest destructive potential in the October of ST and RT El Niño events, and the total PDI in the typhoon season of RT El Niño is less than for ST El Niño in each individual month.

Figures 1(e) and (f) show the TC best-track data over the WNP during the typhoon season for ST and RT events. What we find is that TC genesis is low over the southeastern part of the WNP (red frame in figure 1(f)); 0$^\circ$–15 $^\circ$N, 150 $^\circ$E–180$^\circ$; just two TC formations) when RT El Niño occurs, and vice versa during ST El Niño (33 TCs; figure 1(e)). To quantitatively evaluate the impact of ST and RT El Niño on TC destructive potential, the composite total PDI and other TC parameters of the typhoon season are calculated (table 1). For ST El Niño, the average total PDI of the typhoon season in the WNP is 67.78 $\pm$ 1.15 $\times$ 10$^{10}$ m$^3$ s$^{-2}$; whereas, it is only 41.90 $\pm$ 8.43 $\times$ 10$^{10}$ m$^3$ s$^{-2}$ for RT El Niño, indicating a reduction of approximately 38.2% ($P = 0.01$) compared with ST events. Meanwhile, we find that TC destructive potential during RT El Niño events also has a ratio one-third ($P = 0.04$) less than the 1981–2010 climatological result. This indicates that TC destructive potential is significantly weakened in the decaying year of RT El Niño events.

To examine the variations in count, intensity, and duration of TCs during ST and RT events, we calculate the average values (table 1). The TC count in the typhoon season of RT El Niño is 22.67 $\pm$ 2.49, which represents a rate of 10.9% ($P = 0.23$), compared with ST El Niño. According to this result, we find that changes in TC destructive potential over the WNP are not only contributed by the reduction in TC frequency, but are also influenced by other factors like intensity and duration. The composite values of TC maximum intensity, climatologically and for the El Niño events classified by how quickly they decay, show that the average maximum intensity of TCs (41.16 $\pm$ 2.68 m s$^{-1}$) generated in the typhoon season of ST El Niño is greater than the climatological average (39.52 $\pm$ 1.47 m s$^{-1}$) and for RT El Niño (37.26 $\pm$ 3.63 m s$^{-1}$; $P = 0.10$, albeit failing to reach the 95% confidence level). The average lifetime of TCs is also quite different; during the typhoon season of ST El Niño events, it is about 7.43 $\pm$ 0.46 d, which is 6.3% less than the climatological situation ($P < 0.01$). Meanwhile, the average lifetime of TCs for RT El Niño is the shortest, at only 6.56 $\pm$ 0.60 d, compared with the climatology (7.95 $\pm$ 0.29 d) and ST events, representing a reduction by 17.3% ($P < 0.01$) and 11.7% ($P = 0.03$), respectively.

Meanwhile, the position of TC formation also shows large variation (table 1). The average formation position of TCs in the typhoon season of ST El Niño events is 141.53 $\pm$ 2.24 $^\circ$E, whereas for RT El Niño it is further west, being mainly concentrated around 133.83 $\pm$ 3.02 $^\circ$E. This represents a westward shift of about 7.70$^\circ$ ($P < 0.01$) compared with ST El Niño. The average genesis position of TCs shows a northward tendency during RT periods. Such a westward
and northward shift in TC genesis location during the typhoon season of RT El Niño is an important aspect that leads to the decrease in average TC intensity and duration. Furthermore, it is mainly caused by the reduced TC formation over the southeastern part of the WNP (0°–15° N, 150° E–180°). This reduction provides a spatial possibility for the weakening of TC destructive potential over the WNP during RT El Niño years.

In addition to the differences in the above TC properties, our results also show that the spatial distribution characteristics of regional PDI are also quite different in the typhoon season of these two events (see figure 2). The PDI is mainly concentrated in the...
northeastern part of the Philippines (15°–25°N, 125°–135°E), with a $0.8 \times 10^{10}$ m$^2$ s$^{-2}$ peak value, during ST El Niño events. However, for RT El Niño, the PDI is mainly concentrated in the eastern area of the Philippines (13°–17°N, 125°–130°E), demonstrating a notable southwestward migration compared with ST years. Figure 2(c) shows the difference in the regional PDI patterns between RT and ST El Niño years (RT minus ST). The majority of the WNP basin shows a decrease in regional PDI values. There is a clear northeastern–southwestern PDI pattern, with stronger potential destructive of TCs in the vicinity of the Philippines, and weaker potential destructive over Taiwan, the southeastern part of China, and south part of Japan. This means that, compared to ST El Niño years, the potential destructive of TC activities in the surrounding areas and countries of the WNP is significantly reduced, increasing only in the vicinity of the Philippines.

Regional PDI is mainly affected by the distribution of TC track density and regional intensity. We calculate the differences in the spatial distribution of track density and average regional intensity of TCs over the WNP region between RT and ST El Niño years (shown in figure 3). In RT El Niño years, except for the increase in the South China Sea (not significant), the track density in most areas of the WNP is significantly smaller than in ST El Niño years, and the number of TCs landing in Eastern Japan and Southeastern China is lower. As shown in figure 3(b), we find that the average intensity of TCs near the vicinity of the Philippines and the southern part of Indochina Peninsula is enhanced during RT El Niño. The average regional intensity of TCs, however, is weaker than that of ST El Niño years, especially in the coastal areas of the Southeastern China, Taiwan, and Eastern Japan. Regional PDI changes in nearshore and terrestrial areas are mainly affected by changes in the average intensity of TCs.

4. Mechanistic analysis

From the above analysis, it is apparent that a northwestern average TC formation position may lead to weaker intensity and shorter duration, subsequently contributing to the change in destructive potential.
during the typhoon season of RT El Niño events. But how does RT El Niño affect the destructive potential of TC activity over the WNP region?

Accordingly, we estimate the differences in the upper-ocean thermal conditions between the typhoon seasons of RT and ST El Niño events. As shown in Figure 4(a), there are negative TCHP differences over the central Pacific region, and positive TCHP differences over the western Pacific. Several studies (e.g. Elsner et al 2006, Jin et al 2014, Mei et al 2015, Guo and Tan 2018) have pointed out that the activities of TCs bear a significant relationship with the thermal conditions of the upper ocean; and if a larger upper-ocean heat content is associated with more intense TC activities, and, when the TCHP is small, this will not be conducive to the formation and development of TCs. However, previous results (e.g. Tu et al 2018) indicate that TC destructive potential is inversely related to the change in upper-ocean thermal conditions over the main development region (5°–30°N, 122°E–180°) of the WNP. This means that a large TCHP reserve tends to correspond to a weaker TC destructive potential in this region, which is mainly determined by the different heat transport from the tropical Pacific. As a result, more energy is stored in the WNP, and the energy supplied to TC activities is significantly reduced. Therefore, the PDI is weaker in the typhoon season of RT El Niño events. Meanwhile, the TCHP conditions over the main development region in the typhoon season of ST El Niño events are not the same. As such, stronger and more suitable thermodynamic conditions can be provided for the TC destructive potential of the WNP than in ST years. Similar characteristics can be seen in the SST differences (figure 4(b)). The RT minus ST El Niño differences in SST over the CP during the typhoon season are also not conducive to an active lower atmosphere, which leads to the lower PDI in this period. This is also why it is hard for TCs to form in this area (figure 1(f)).

Aside from the influences of oceanic thermal conditions, atmospheric dynamic conditions are also an important influence on TC activities. For example, the relative vorticity of the lower atmosphere and vertical wind shear are the two main dynamic conditions affecting TC activities. Figure 5(a) shows the RT minus ST El Niño differences in the composite lower-atmosphere relative vorticity over the WNP area during the

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**Figure 4.** Differences (RT minus ST) in upper-ocean thermal conditions during the typhoon season of St and RT El Niño: (a) TCHP differences (units: J m⁻²), (b) SST differences (units: °C). Dots mark areas statistically significant at the 95% confidence level.
Typhoon season. Compared with when ST El Niño events occur, the TC main development region and the South China Sea feature significantly negative relative vorticity differences during the typhoon season in RT El Niño years, and can thus cause TCs with weaker intensity. Moreover, the vertical wind shear is also different between the two periods (figure 5(b)). The vertical wind shear of the main TC active area in the WNP increases significantly during RT El Niño years. This also represents a significant role in the weakening of TC destructiveness, especially in the southeast part of the WNP (red frame in figure 1(f)).

Figure 5. Differences (RT minus ST) in the (a) relative vorticity at 850 hPa (units: $10^{-5} \text{s}^{-1}$), and (b) vertical wind shear (850 hPa minus 200 hPa, units: m s$^{-1}$), dots mark areas that are statistically significant at the 95% confidence level (c) shows the subtropical high at 500 hPa (units: gpm) over the WNP basin during the typhoon season in ST and RT El Niño years.
In addition, changes in the subtropical high over the WNP also affect the destructive potential of TCs, with it being difficult for TCs to form and develop under a strong subtropical high. Figure 5(c) shows the distribution of the subtropical high in the WNP during the ST and RT El Niño years. What we find is that, in the typhoon season of RT El Niño events, an enhanced WNP subtropical high might be highly unfavorable for the activities of TCs in this region, making it a contributor to the weakening of TC destructive potential.

In general, the cooling oceanic thermal structure in the CP lead to a weakening of regional atmospheric convective activity, which is not conducive to the formation of tropical disturbances, and thus there is less TC activity in this area. Meanwhile, in the process of TC genesis migrating northwest, the destructive potential of TCs in the WNP during RT El Niño periods weakens, combined with relatively unfavorable atmospheric environmental conditions (negative relative vorticity differences, positive vertical wind shear differences, and an enhanced subtropical high).

5. Conclusions and discussion

Two types of El Niño events using different rates of transition are defined in this study, allowing us to identify five RT El Niño events and nine ST El Niño events since 1950. We then focus on the differences in TC destructive potential over the WNP in the typhoon season between ST and RT events. The results show that the TC destructive potential during the typhoon season of RT El Niño years has a 38.2% rate of decline compared with ST El Niño. Also, the average TC frequency, peak intensity, and lifetime are less than in ST El Niño years. Meanwhile, we find that few TCs form over the southeastern part of the WNP. Furthermore, the regional PDI of RT El Niño is mainly concentrated in the eastern part of the Philippines, which represents a significant southwestward migration compared to ST years. Plus, the average position of TC genesis is relatively more northwest, but the zonal distribution of the regional PDI in RT El Niño years shows a striking southward trend because of the strengthened subtropical high.

Compared to ST El Niño years, the regional PDI shows a clear northeastern–southwestern pattern in RT El Niño years; the destructive potential of TC activities over Taiwan, the southeastern part of China, and the south part of Japan of the WNP is significantly reduced, with an increase seen only in the vicinity of the Philippines. Also, there are fewer landfalling TCs in the Eastern Japan and the Southeastern China in RT El Niño events compared with ST events, and it can be found that the regional intensity of TCs decreased in those areas and increased in the Philippines and the southern part of Indochina Peninsula region.

A significant strengthening of the subtropical high together with enhanced vertical shear and weaker relative vorticity over the WNP area causes the weakening of TC destructive potential during RT events. Meanwhile, conducive upper-oceanic thermal conditions remain, leading to few TC formations over the southeastern part of the WNP in RT El Niño years.

However, based on the analysis presented above, can we predict this situation in advance? Figure 6 shows the spatial evolution of ST and RT El Niño. We can see that ST El Niño events are usually weaker than RT El Niño events, and the onset time of El Niño is later than in RT El Niño events. Meanwhile, the termination of the El Niño period is basically the same for both types of events, synchronously turning to a neutral state from March to April of year(+1). During the typhoon season of the year(+1), ST El Niño changes slowly, and the negative SSTA appears in the eastern equatorial Pacific until August, but with almost no
negative SSTA in the Niño3.4 area. In RT El Niño years, meanwhile, El Niño begins to decay over the central and western regions of the equatorial Pacific, and the warmer SSTA remains in the eastern equatorial Pacific until the formation of La Niña in the central equatorial Pacific in June. According to our research, the active season of TCs in the WNP is mainly from July to November. Here, we can predict the TC changes over the WNP in the upcoming typhoon season by the SSTA changes in the equatorial Pacific before the active season of TCs.

For example, if an El Niño event in the equatorial Pacific (Niño3.4 region) disappears in April and a negative SSTA appears in the region in June, it means that an RT El Niño event is likely occurring, and thus TC activities affecting the Philippines will increase. This will allow relevant organizations in the region to take measures towards disaster prevention and mitigation. On the contrary, if the positive SST in the equatorial Pacific is observed to be weak, but the change is slow, and it has not become a La Niña event in June or even July, then this will mean that an ST El Niño event is likely forming, and the influence of TCs in the Philippines region might be reduced. However, TCs landing in the Eastern Japan and the southeastern China might be more prevalent, and the intensity of TC activities in southeast China and Taiwan increased significantly, so again the relevant departments can take measures in advance to alleviate economic losses and casualties caused by TC activities.

As shown in table 1, the average TC genesis position shifts obviously northwards when RT El Niño events develop, but there is a significant southward shift in PDI zonal distributions compared with ST El Niño. This phenomenon indicates that TC activities during RT El Niño are more westward and less northward in location than during ST El Niño, and the destructive potential of TCs is mainly concentrated in the low-latitude region. Thus, the destructiveness of TCs at the subtropical region is obviously small during RT years, and the westward movement of TCs after their generation is mainly due to the enhanced subtropical high.

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Data availability
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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