Contribution of the intensity of intraseasonal oscillation to the interannual variation of tropical cyclogenesis over the western North Pacific

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Abstract

The present study compares the contributions of seasonal, intraseasonal, and synoptic variations of environmental factors, i.e., mid-level moisture, vertical instability, and lower-level relative vorticity, to the interannual variation of tropical cyclone (TC) genesis over the western North Pacific (WNP) during July–August–September–October (JASO) of 1979–2015. It is found that the TC genesis frequency has a significant positive correlation with the intensity of intraseasonal oscillation, but a weak correlation with the intensity of synoptic variation of environmental factors during JASO in the WNP. In addition, the intraseasonal components of convection and lower-level vorticity at the location of TC genesis have a larger contribution than the interannual and synoptic components to the differences between more and less TC years over the WNP. The present results indicate that the intensity of intraseasonal oscillation of environmental factors has an important effect on the interannual variation of the TC genesis frequency over the WNP. This study enhances our understanding of the impacts of intraseasonal oscillation on the interannual variation of the WNP TC activity and indicates that the intensity of intraseasonal oscillation has the potential to be used in the seasonal prediction of the WNP TC genesis.

1. Introduction

The western North Pacific (WNP) is the most active basin of tropical cyclone (TC) genesis in the globe, with about 30% of TC genesis there. The TCs exert large impacts on economics and social activities. The pioneering work by Gray (1968) identified some basic environmental factors of TC genesis, including conditional instability, mid-level high specific humidity, lower-level cyclonic absolute vorticity, large planetary vorticity, weak vertical wind shear, and high sea surface temperature (SST). The most unique environment for the TC genesis in the WNP is the large deep and warm pool with mean SST above 29 °C and the favorable lower-level winds with a zonal convergence and a meridional shear line (Ritchie and Holland 1999; Li 2012).

The interannual variation of TC genesis over the WNP is subject to large impacts of El Niño–Southern Oscillation (ENSO) (e.g., Wang and Chan 2002, Chia and Ropelewski 2002, Camargo and Sobel 2005, Chen et al 2006, Camargo et al 2007, Cao et al 2020a). Although the correlation between the entire WNP TC genesis number and canonical ENSO is statistically insignificant, the region of the TC genesis over the WNP is to a great extent modulated by the ENSO (Wang and Chan 2002, Li 2012). In addition, previous studies have shown the effects of SST anomalies in different basins on interannual variation of TC genesis over the WNP. These include ENSO Modoki (Chen and Tam 2010, Cao et al 2018, Liu and Chen 2018, Liu et al 2019), the tropical Indian Ocean (Zhan et al 2011, Du et al 2011, Ha et al 2015, Wu et al 2019, 2020), the northern tropical Atlantic
and the Pacific meridional mode (Zhang et al. 2016). For example, Chen and Tam (2010) identified a significant positive correlation between the TC genesis number over the WNP and the ENSO Modoki. Liu and Chen (2018) and Cao et al. (2018) detected an intensified impact of the ENSO Modoki on TC genesis frequency during summer and fall over the WNP since early 1990s. This intensified impact is largely attributed to the expansion of the ENSO Modoki SST anomalies and the joint contribution of SST anomalies in several other regions. The atmospheric circulation response is often considered as a bridge connecting anomalous oceanic forcing to interannual variations in the TC activity over the WNP. The TC genesis, however, is subject to influences of synoptic disturbances, which are related to atmospheric internal processes. Thus, one issue to be addressed in the present study is whether the association of the WNP TC genesis with interannual variations of atmospheric background fields is robust or not.

Previous studies have revealed that TC genesis is characterized by 1–2-week active periods followed by 2–3-week period of resting stage (Gray 1979). The Madden–Julian oscillation (MJO) plays an important role in the TC genesis and development over the WNP (e.g., Liebmann et al. 1994, Madden and Julian 1994, Sobel and Maloney 2000, Maloney and Hartmann 2001, Camargo et al. 2009, Jiang et al. 2012, Zhao et al. 2015a, You et al. 2019, Cao and Wu 2020). MJO may modulate the TC genesis through the modification of atmospheric background fields including lower-level convergence, relative vorticity, vertical wind shear, and mid-level specific humidity (Maloney and Hartmann 2001, Camargo et al. 2009, Zhao et al. 2015a). Those previous studies mainly focused on the relationship between intraseasonal variations of the TC genesis and intraseasonal oscillations over the WNP. A question is whether the intensity of intraseasonal oscillations of environmental factors affects in the interannual variation of TC genesis over the WNP. Thus, another issue to be addressed in the present study is the relationship between the WNP TC genesis and intensity of intraseasonal oscillations.

TC genesis over the WNP is associated with various types of tropical synoptic disturbances. Previous studies revealed that the association of the TC genesis over the WNP with the pre-existing TC energy dispersion, convective equatorial Rossby wave, synoptic wave train, and easterly wave (Holland 1995, Sobel and Maloney 2000, Fu et al. 2007, Schreck et al. 2011, Li 2012, Cao et al. 2013, Chen and Chou 2014). Those equatorial waves provide a common precursor disturbance and increase the background lower-level cyclonic vorticity and convection for the TC genesis (Frank and Roundy 2006, Schreck et al. 2011).

The TC genesis over the WNP is influenced by environmental factors with variations on different time scales (Li 2012). Cao et al. (2018) compared relative contributions of different temporal variations of environmental factors to the TC genesis over the WNP during active TC seasons by adopting a local and instantaneous view of the TC genesis. The composite local and instantaneous conditions of TC genesis show that the contribution of convection, lower-level vorticity and mid-level specific humidity to the TC genesis is mainly due to intraseasonal variation with a secondary role from synoptic variation. Motivated by the issues mentioned above, this present study extends the work of Cao et al. (2018) to investigate which temporal component of environmental factors has the most prominent interannual variation of contributions to the TC genesis over the WNP. The purpose is to better understand the interannual relationship between TC genesis and environmental factors, which may help to improve the seasonal prediction of TC genesis over the WNP.

The remainder of the paper is arranged as follows. Section 2 describes the data and methods. Section 3 examines the interannual relationship between tropical cyclogenesis over the WNP and various large-scale environmental factors on three time scales through regression analysis and composite analysis. Contributions of different time scale variations of large-scale factors to tropical cyclogenesis during more and less TC years are compared in section 4. A summary is provided in section 5 along with a short discussion.

2. Data and methods

The TC genesis data over the WNP are obtained from Joint Typhoon Warning Center (JTWC), which is archived in National Climate Data Center’s (NCDC) International Best Track Archive for Climate Stewardship (IBTrACS) v03r10 (Knapp et al. 2010). This TC data include the time, longitude and latitude of the TC position and intensities measured by the maximum sustained wind speed at each 6-hourly interval. Only TCs with the maximum wind speed exceeding 25 kts are considered. The first time when wind speed reaches greater than 25 kts is defined as the TC genesis time. The present analysis focuses on the region extending from 120°E to the 180° and from 0° to 30°N and the July–August–September–October (JASO) from 1979 to 2015. Then the TC genesis frequency index is defined as the total genesis number of TCs during JASO over the WNP.

The daily mean interpolated satellite Outgoing Long-wave Radiation (OLR) is obtained from the National Oceanic and Atmosphere Administration (NOAA) (Liebmann and Smith 1996), which is regarded as an indicator for deep convection. Atmospheric factors including relative vorticity, pressure vertical velocity and specific humidity are derived from the European Centre for 6-hourly Medium-Range Weather Forecasting.
(ECMWF) ERA-Interim dataset (Dee et al. 2011). The variables are interpolated to grids with a 2.5° horizontal resolution in latitude and longitude. Four environmental factors are considered, including mid-level moisture as measured by 700 hPa specific humidity, vertical instability as measured by OLR and 500 hPa vertical p-velocity, and lower-level relative vorticity at 850 hPa.

Previous studies are mainly focused on effects of total anomalies or individual component of total anomalies on the TC genesis (e.g., Maloney and Hartmann 2001, Wang and Chan 2002, Camargo et al. 2009). The TC develops from an initial disturbance that is composed of components of interannual, intraseasonal and synoptic variations. The effects of the three components are likely related to their magnitudes. The present study decomposes total anomalies into interannual, intraseasonal and synoptic components to investigate the relative contributions of different time scale variations of various environmental factors to the TC genesis. The interannual, intraseasonal, and synoptic components of various environmental factors are derived by using similar method as Cao et al. (2018). For instance, the interannual component with a period more than 90 days is derived by applying a 91-day running mean to the daily anomaly time series. The intraseasonal component with a period of 10–90 days is derived by subtracting a 91-day running mean from a 9-day running mean of the daily anomaly time series. The synoptic component with a period smaller than 8 days is derived by subtracting a 9-day running mean from the daily anomaly time series.

The present study only considers the variation of interannual time scale with periods less than 7 years. All variables are subjected to a Lanczos high filter to extract the interannual time scale component (Duchan 1979). The relationship of TC genesis to the intensity of the three components of variations of environmental factors is examined using correlation, regression and composite analyses in the present analysis. Because variances are not normally distributed, the conventional Student t-test is not applicable to the estimation of the significance level of the statistical relation. A bootstrap resampling technique (Efron 1979) is used in the estimation of statistical significance of correlation and regression coefficients. The large-scale factors are selected randomly with replacement from the sample 1000 times. The regression coefficient with a magnitude that occurs fewer than 5% of the time in the random sample is considered to be statistically significant in the present study. Note that TC frequency number tends to follow the normal distribution. The statistical significance of correlation in relation to the seasonal mean anomalies and composite results is determined using the two-tailed Student t-test.

3. Interannual relationship of tropical cyclogenesis with different time scale components

In this section, we investigate the interannual relationship between tropical cyclogenesis and different temporal components of environmental factors during JASO from 1979 to 2015. The seasonal mean anomalies during JASO stand for the interannual components of large-scale factors. The variances of intraseasonal and synoptic variations of large-scale factors are used to measure the intensity of intraseasonal and synoptic variations of large-scale factors, following Wu and Cao (2017).

Figures 1–3 display anomalies of OLR, relative vorticity at 850 hPa, vertical p-velocity at 500 hPa, and specific humidity at 700 hPa on interannual, intraseasonal and synoptic time scales, respectively, obtained as regression on the normalized JASO TC genesis frequency index over the WNP during 1979–2015. In the interannual time scale, there are obvious seasonal anomalies of OLR and vertical p-velocity in the central part of the WNP (figure 1). Obvious positive anomalies of relative vorticity and specific humidity are located in the northern part of the WNP (figure 1). In the southern part of the WNP, there are negative anomalies of relative vorticity and specific humidity (figure 1). The variances of intraseasonal variation of OLR, relative vorticity at 850 hPa, vertical p-velocity at 500 hPa, and specific humidity at 700 hPa tend to display consistent variation over the whole WNP (figure 2). This means that when the intensity of intraseasonal oscillation is stronger during JASO, there are more TC genesis cases over the WNP. The intensity of synoptic variation of large-scale factors does not show obvious and consistent anomalies over the whole WNP (figure 3). It indicates that TC genesis frequency over the WNP has no significant correlation with the intensity of synoptic variations of the environmental factors. The weak association is confirmed by parallel analyses using NCEP-NCAR and ERA5 reanalysis datasets (figures not shown). Note that previous studies have found that the TC seeds as the variance of 2–8 day bandpass filtered 850-hPa vorticity are a main driver of the TC activity responding to global warming in the models (Li et al. 2010, Vecchi et al. 2019). This discrepancy may be related to the definition of TC genesis index. We calculated the grid-point correlation between the variance of synoptic scale component and the TC genesis frequency index interpolated to a 5° × 5° grid box. A significant positive correlation is detected in the southeastern part of the WNP, while the correlation is weak in other regions. This explains why the relationship is weak between the variance of synoptic scale vorticity and the basin-wide TC genesis frequency for the whole WNP region.
In order to confirm the results of the above regression analysis, we conduct a composite analysis for more and less TC genesis years. The normalized TC genesis index with signals of time periods more than 7 years removed is used to identify more and less TC years based on the criterion that the absolute magnitude of interannual anomaly of the TC genesis frequency is larger than half of one standard deviation (figure not shown).

According to the above method, 9 more TC years are selected as follows: 1984, 1989, 1991, 1994, 1996, 2000, 2004, 2009, and 2013 and 10 less TC years are 1979, 1983, 1986, 1990, 1993, 1997, 2002, 2008, 2010, and 2014. The composite difference of four environmental factors between more and less TC years is almost similar to the regression analysis in interannual, intraseasonal and synoptic time scales (figures not shown).

Table 1 shows the correlation coefficients between TC genesis frequency and the intensity of interannual, intraseasonal and synoptic variations of environmental factors averaged over the whole WNP. The intensities of intraseasonal components of the four factors including relative vorticity, OLR, specific humidity and vertical p-velocity have a significant positive correlation with TC genesis frequency over the WNP. All the four correlation coefficients are significant over the 95% confidence level. The seasonal mean anomalies of relative vorticity and vertical p-velocity have obvious positive and negative correlations with TC genesis frequency over...
the WNP, respectively. For seasonal mean anomalies of specific humidity and OLR, the area-mean correlation is insignificant because their anomalies are opposite in the northern and southern parts of the WNP as shown in figure 1. The last row of table 1 shows that the WNP TC genesis frequency has an insignificant correlation with the intensities of synoptic components of the four factors.

Based on the above analyses, the TC genesis frequency over the whole WNP has a close relation with the intensity of intraseasonal oscillation of four factors during JASO. The stronger the intraseasonal oscillation of environmental factors is, more frequently TC genesis occurs over the whole WNP. Previous studies have shown that TCs tend to occur during the convective phase of the intraseasonal oscillation because the large-scale conditions associated with convective phase create a favorable environment for TC genesis (e.g., Maloney and Hartmann 2001, Camargo et al 2009). The present study shows that the intensity of intraseasonal oscillation of large-scale factors plays an important role in the interannual variation of TC genesis frequency over the WNP. When the intensity of intraseasonal variations of relative vorticity, OLR, vertical motion, and specific humidity is stronger, the tropical disturbances have a greater chance to develop into TC over the WNP. The intensity of intraseasonal oscillation of large-scale factors is a meaningful index to represent the interannual variation of TC genesis over the whole WNP.

4. The comparison between more and less TC years from a local perspective

The above section is mainly concerned with the environmental conditions of the TC genesis over the whole WNP averaged in JASO period. Although TC genesis frequency is tied to the large-scale atmospheric and oceanic conditions, TC is a synoptic–scale weather event that develops in a local region. A combination of various environmental variables on different time scales determines the local background fields for the TC genesis. As
such, the seasonal mean and intraseasonal large-scale conditions over the whole WNP may not reflect the real atmospheric states around the location of TC genesis. Accordingly, it is necessary to examine the contributions of different components of large-scale factors to the TC genesis over the WNP from the perspective of instantaneous state around the location of TC genesis. This local view was recently adopted by Cao et al. (2018, 2019a, 2019b, 2020b) in their analysis of TC genesis and track over the WNP, the northern Atlantic Ocean and South China Sea. Their results indicated that the approach based on local and instantaneous state around the location of TC genesis can better capture the background fields for the TC activity. In this study, we apply the same approach to investigate the interannual change in contributions of different components of environmental factors to TC genesis over the WNP during more and less TC years.

Based on the classification of more and less TC years in section 3, we construct the composite anomalies centered at the location of TC genesis in more and less TC years and their difference. There are 183 and 130 TC genesis cases in the more and less TC years, respectively. Then, the composite anomalies of interannual, intraseasonal, and synoptic components of various factors are calculated in a $7.5\degree \times 7.5\degree$ box encompassing TC genesis location to examine their respective contributions. Note that the composite results for the intraseasonal and synoptic time scales refer to intraseasonal and synoptic components of anomalies, not the intraseasonal and synoptic variances. The composite anomalies in more and less TC years are shown in figure 4 for OLR, in figure 5 for 500 hPa vertical p-velocity, in figure 6 for 850 hPa relative vorticity, and in figure 7 for specific humidity at 700 hPa. Then, we compare the respective contributions from anomalies of interannual, intraseasonal, and synoptic variations of the two factors over the WNP during the more and less TC years in figure 8.

Both OLR and mid-level vertical p-velocity are used as a proxy for deep convection over the WNP. During both more and less TC years, there are large negative anomalies of OLR and vertical p-velocity around TC genesis (figures 4(a) and (e); 5(a) and (e)). During the two types of years, the largest contribution is from the synoptic variation (figures 4(d) and (h); 5(d) and (h)), followed by the intraseasonal variation (figures 4(c) and (g); 5(c) and (g)).
The difference fields of OLR and vertical p-velocity between more and less TC years display positive anomalies around TC genesis (figures 4(i) and 5(i)). This means that the absolute averaged anomalies of OLR and vertical p-velocity around TC genesis during more TC years are smaller than those during less TC years. The synoptic component has the largest negative contribution to the difference fields in OLR and vertical p-velocity (figures 4(l) and 5(l)). However, the intraseasonal and interannual components of OLR and vertical p-velocity have larger positive contribution to TC genesis during more TC years than during less TC years (figures 4(j), (k) and 5(j), (k)).

The relative vorticity and specific humidity anomalies are large and positive around the TC genesis region in both types of years (figures 6(a), (e) and 7(a), (e)). The contribution from the synoptic component is the largest, followed by the intraseasonal component in both types of years (figures 6(c), (d), (g), (h) and 7(c), (d), (g), (h)). The contribution from the interannual component is small (figures 6(b), (f) and 7(b), (f)). The difference fields of relative vorticity show positive values around the location of TC genesis (figure 6(i)). It indicates that the averaged anomalies of relative vorticity around TC genesis during more TC years are larger than those during less TC years. Among the three time scales, the largest positive contribution to the difference of relative vorticity is from the intraseasonal variation (figure 6(k)). For specific humidity, although there are no significant differences between more and less TC years around the location of TC genesis (figure 7(i)), the averaged intraseasonal anomalies of specific humidity around TC genesis are significantly larger during more TC years than during less TC years (figure 7(k)).

The composite results based on the location of TC genesis display that the absolute intraseasonal anomalies of OLR, vertical p-velocity, relative vorticity and specific humidity are larger during more TC years than during less TC years. It indicates that the intraseasonal components of four factors have a larger contribution to TC genesis during more TC years than during less TC years.

The averaged values during more and less TC years reflect the averaged level from all the TC cases. However, the large-scale fields around the location of TC genesis may be opposite and offset each other. Based on the total anomalies around location of the TC genesis, at least 95% of TCs appear when the OLR anomalies are below zero or the lower-level vorticity anomalies are above zero during more and less TC years. However, for the vertical p-velocity and specific humidity, almost 50% of TCs occur when the large-scale conditions are unfavorable. This suggests that the vertical motion and moisture fields are not as critical as the vorticity and OLR fields for the TC generation.
genesis over the WNP. Figure 8 shows the total averaged positive contribution of OLR and relative vorticity during more and less TC years along with their difference on the three time scales. Those averaged positive contributions of two environmental factors to TC genesis in various time scales are calculated by dividing the averaged anomaly on one time scale by the value of the averaged total anomaly when the large-scale conditions are favorable for TC genesis. The percent has been re-scaled by multiplying the ratio of the TC numbers in more and less TC years over the total TC number in all the years.

The largest difference between the two types is in the intraseasonal component (figure 8). This indicates that the intraseasonal component has the largest interannual change, though it is not the component of the greatest contribution to the TC genesis in more or less TC years. From the perspective of TC genesis location, the intraseasonal components of variables have a larger contribution to TC genesis during more TC years than during less TC years. From the perspective of the whole WNP and the TC season, the intensity of intraseasonal oscillation of large-scale factors plays an important role in the interannual variation of TC genesis frequency over the WNP. The results of these two perspectives indicate that when the intensity of intraseasonal oscillation is stronger over the whole WNP, more TCs are generated with a larger contribution from intraseasonal environmental conditions. We note that the differences of synoptic components of OLR and 850-hPa vorticity in figure 8 appear to be inconsistent with those on figures 4 and 6. This discrepancy arises from the re-scaling based on the numbers of TCs in more and less TC years when obtaining the anomalies in figure 8.

5. Summary and discussion

The present study investigated the interannual variation of contributions of three time scales, i.e., seasonal, intraseasonal and synoptic variations of environmental factors, respectively, to the TC genesis frequency over the WNP. The regression and composite analysis shows that the intensity of intraseasonal oscillation of large-scale factors plays the most important role in the interannual variation of TC genesis frequency over the whole WNP compared to the seasonal mean anomalies and intensity of synoptic component.

The present study conducted the composite analysis using two methods. One method is conventional and concerned with the environmental conditions of the TC genesis over the whole WNP averaged in JASO. The
analyses display that the TC genesis frequency over the whole WNP has a significant positive correlation with the intensities of intraseasonal components of environmental factors including relative vorticity, OLR, specific humidity, and vertical p-velocity. Meantime, the TC genesis frequency over the whole WNP have obvious

Figure 7. Same as figure 4, except for specific humidity at 700 hPa (g kg$^{-1}$).

Figure 8. The percent of TC genesis with positive contributions from anomalies of (a) OLR and (b) relative vorticity on interannual (red bar), intraseasonal (green bar), and synoptic (orange bar) time scales over the WNP during more and less TC years and the more minus less TC year difference.
positive and negative correlations with seasonal mean anomalies of relative vorticity and vertical p-velocity, respectively. In comparison, the TC genesis frequency over the whole WNP has a greater correlation with the intensities of intraseasonal components of environmental factors compared with seasonal mean anomalies. The TC genesis frequency over the whole WNP has a weak correlation with the intensities of synoptic components of environmental factors. This method not only includes anomalies at the time and position when there are TC genesees, but also includes anomalies at the time and position when there are not TC genesees.

Further investigation is conducted for the influence of local environmental factors on the TC genesis. The results display that the intraseasonal components of four factors have a larger contribution to TC genesis during more TC years than during less TC years. Meantime, the total averaged positive contribution of OLR and relative vorticity from various time scales shows that the main difference between the more and less TC years is in the intraseasonal component. This indicates that the intraseasonal component has an obvious consistent interannual variation with the TC genesis. The anomalies of environmental factors obtained based on this method better capture the background conditions for TC genesis and their contributions in various time scales.

The composites from the above two methods indicate that when the intensity of intraseasonal variations of relative vorticity, OLR, vertical motion, and specific humidity is stronger (weaker) over the whole WNP, the tropical disturbances have a greater (smaller) probability to develop into TCs over the WNP. Meantime, the averaged anomalies and percent contribution from the intraseasonal components of large-scale factors are enhanced (decreased) around the TC genesis location. As such, the TC activity tends to be more (less) frequent in the years of strong (weak) intraseasonal oscillation. This indicates that intraseasonal oscillation not only affects the intraseasonal variations of TC genesis, but also the interannual variations of TC genesis over the WNP. Thus, understanding the mechanisms of intraseasonal oscillation and its intensity changes has a broad implication for communities.

Previous studies have shown that seasonal anomalies can modulate the intensity of intraseasonal oscillation over the WNP (Wu and Cao 2017, Wu and Song 2018, Wang and Wu 2020). For example, Wu and Cao (2017) showed that the intensity of intraseasonal oscillation over the WNP is strengthened in El Niño developing years. The present study indicates that the intensity of intraseasonal oscillation may contribute to the interannual variation of the TC genesis over the WNP. This suggests that the seasonal mean anomalies have two types of impacts on the TC genesis over the WNP. One is through a direct modulation of the seasonal mean background of the TC genesis. The other is an indirect influence through modulating intensity of the intraseasonal oscillations. In the future, further studies will be conducted on the role of multi-scale interactions in the TC genesis over the WNP.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.1002/qj.828 or https://www.ecmwf.int/en/research/climate-reanalysis/era-interim.

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