Comparison of Different Time Scale Contributions to Tropical Cyclone Genesis over the Western North Pacific in 2015 and 2016

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Abstract

The present study compares contributions of different environmental factors to the tropical cyclone (TC) genesis over the western North Pacific (WNP) during 2015 and 2016. A local instantaneous view of conditions for the TC genesis is adopted in the present study, which is distinct from the previous view of large-scale temporal averaged conditions. The present study also distinguishes the contributions of three time scale variations (synoptic, intraseasonal, and interannual) of a number of factors. Common to 2015 and 2016, the positive contribution of lower-level vorticity and upward motion to the TC genesis is mainly from the intraseasonal and synoptic components; the contribution of the barotropic energy conversion to the development of synoptic disturbances is larger from climatological mean winds and intraseasonal wind variations than from interannual wind variations; all three time scale variations of mid-level specific humidity contribute positively to the TC genesis; the barotropic energy conversion from climatological mean winds is due to the terms in relation to the meridional shear and zonal convergence of zonal wind. In comparison, the positive contribution of lower-level vorticity and mid-level specific humidity is larger in 2015 than in 2016 on all the three time scales; the contribution of the barotropic energy conversion in relation to the meridional shear of interannual variations of zonal wind and the zonal convergence of intraseasonal variations of zonal wind are larger in 2015 than in 2016; the vertical wind shear on all the three time scales and the sea surface temperature on the interannual time scale have a larger positive contribution to the TC genesis in 2016 than in 2015.

Keywords different time scales; TC genesis; the western North Pacific; 2015/2016 El Niño
1. Introduction

The tropical cyclone (TC) genesis over the western North Pacific (WNP) displays different time scale variations (Li 2012). On interannual time scales, the El Niño–Southern Oscillation (ENSO) is found to modulate the location of the TC genesis over the WNP (e.g., Chen et al. 1998; Wang and Chan 2002; Camargo et al. 2007; Wu et al. 2012; Cao et al. 2014a, b). Although the correlation between the number of TCs generated over the WNP and the Niño3.4 sea surface temperature (SST) index during the TC seasons is not statistically significant (Wang and Chan 2002; Li 2012), the frequency of the TC genesis is above normal in the southeast quadrant and below normal in the northwest quadrant of the WNP during El Niño summers, and the features are opposite during La Niña summers (Wang and Chan 2002). The eastward extension of the TC genesis location during El Niño summers coincides well with anomalous low-level cyclonic vorticity, enhanced convection, reduced vertical zonal shear, increased mid-level relative humidity and warmer SST in the southeast quadrant of the WNP (Wu et al. 2012). The TC genesis frequency tends to increase during El Niño developing summers and decrease during El Niño decaying summers (Li 2012; Ha and Zhong 2013). This increase and decrease may be attributed to an anomalous cyclone over the WNP associated with warming in the tropical central and eastern Pacific Ocean and an anomalous anticyclone over the WNP associated with cooling in the tropical WNP and warming in the tropical Indian Ocean, respectively (Du et al. 2011; Li 2012; Xie et al. 2016).

On intraseasonal time scales, the Madden–Julian oscillation (MJO; Madden and Julian 1994) modulates largely the TC genesis and development over the WNP (e.g., Liebmann et al. 1994; Maloney and Hartmann 2001; Camargo et al. 2009; Cao et al. 2012; Yoshida et al. 2014; Zhao et al. 2015). The MJO’s modulation is through the change of background dynamic and thermodynamic factors (Maloney and Hartmann 2001; Camargo et al. 2009) and through barotropic energy conversion by which synoptic-scale disturbances obtain energy from the background flows (Hsu et al. 2011).

The observation shows that 2015/2016 is one of the two strongest El Niño events with SST anomalies over 2°C in the equatorial eastern Pacific (another strongest El Niño event is 1997/1998). Thus, 2015 and 2016 are the developing and decaying years of the strong El Niño case, respectively. According to previous statistical analysis, the TC genesis over the WNP should be more during the TC season in 2015 and less in 2016. However, the actual TC genesis frequencies in 2015 and 2016 are opposite to previous results. The TC genesis numbers are 18 and 25 during summer and autumn of 2015 and 2016, respectively. On average, almost 21 TCs form from June to November over the WNP (east of 120°E and west of the dateline). This suggests that the large-scale seasonal circulation response to SST anomalies cannot explain the difference of TC genesis frequency between 2015 and 2016. It is interesting to note that no TC formed from January to June and all TCs occurred after July in 2016.

Previous studies mostly focused on seasonal mean fields when analyzing the year-to-year changes in the TC genesis. Nevertheless, the TC genesis is a local short-time phenomenon. It is possible that local condition at a specific time is satisfied when TC forms, but the temporal averaged background field is unfavorable for TC. Therefore, a more suitable way to understand the TC genesis would be to examine the state at an instant and locality to find out the contributions of different environmental factors to the TC genesis. As the instant value of an environmental factor at a specific location consists of variations on different time scales, it is worthwhile to distinguish the different time scale variations to reveal their relative contributions to the TC genesis.

The analysis in this study is conducted on local and instantaneous conditions of the TC genesis over the WNP on different time scales. The main purpose is to examine the relative contributions of different time scale variations of various environmental factors to the TC genesis between 2015 and 2016. In the remainder of this paper, Section 2 describes the data and methods. Section 3 presents the spatial distribution and contribution of different time scale variations of environmental factors to the TC genesis over the WNP during boreal summer and autumn in 2015 and 2016. Summary of results and discussion are given in Section 4.

2. Data and methods

The time and position of the TC genesis over the WNP in 2015 and 2016 are obtained from the Joint Typhoon Warning Center (JTWC). The TC data include 6-hourly longitude and latitude of the TC center, the maximum sustained wind speed and the minimum sea level pressure. The time when the maximum sustained wind speed of a TC reaches 25 kts (~12.9 m s⁻¹) is defined as the TC genesis time over the WNP. The analysis is focused on the region extending from 120°E to the dateline and from equator to 25°N and
on the time from June to November (JJASON for brevity). There were four TCs forming to north of 25°N in 2016, which are eliminated in the following analysis, because those TC formations are affected by obviously different large-scale circulations as shown in Figs. 3 and 4 below.

The global atmospheric daily grid fields are obtained from the National Centers for Environmental Prediction–Department of Energy (NCEP–DOE) Atmospheric Model Intercomparison Project II (AMIP-II) reanalysis data starting from 1979 with a horizontal resolution of 2.5° (Kanamitsu et al. 2002). The daily mean SST with a 0.25° horizontal resolution is from the National Oceanic and Atmospheric Administration Optimum Interpolation (NOAA-OI) data starting from November 1981 (Reynolds et al. 2007). The original SST data are converted to 1° horizontal resolution. The climatological daily means are calculated by averaging the values at the same day during the period 1987–2016. The daily anomalies are obtained by removing the corresponding climatological daily means.

Previous studies have shown distinct peaks of spectrum in atmospheric and oceanic variables on intraseasonal and synoptic bands (Hsu et al. 2011). Thus, we separate the original daily anomalies into interannual (> 90 days), intraseasonal (10–90-day), and synoptic (3–8-day) components in 2015 and 2016. Following Cao et al. (2017), the interannual variation (> 90 days) is obtained using a 91-day running mean. In like manner, the 10–90-day variation is obtained using a 9-day running mean minus a 91-day running mean, and the 3–8-day variation is obtained using a 2-day running mean minus a 9-day running mean.

Previous studies have shown that the dynamic effect of circulations associated with intraseasonal and interannual variations on the TC genesis is through barotropic energy conversion (Maloney and Hartmann 2001; Wu et al. 2012; Feng et al. 2014). The equation of the barotropic energy conversion is given by

$$ \frac{\partial K_{\text{baro}}}{\partial t} = -u'v' \frac{\partial \bar{u}}{\partial y} - u'v' \frac{\partial \bar{v}}{\partial x} - u'' \frac{\partial \bar{u}}{\partial x} - v'' \frac{\partial \bar{v}}{\partial y}, $$

where $\frac{\partial K_{\text{baro}}}{\partial t}$ is the rate of change of the eddy kinetic energy through the barotropic energy conversion, $(\bar{u}, \bar{v})$ are the basic flows, and $(u', v')$ are the eddy winds on 3–8-day time scales. The four terms in the right-hand-side of the equation indicate the barotropic energy conversion associated with the meridional shear of zonal wind, the zonal convergence of meridional flow, the zonal convergence of zonal wind, and the meridional shear of meridional flow, respectively.

To investigate the contribution of different time scale variations of the basic flows, $(\bar{u}, \bar{v})$ are separated into long-term daily mean (climatological) winds, interannual (> 90 days) and intraseasonal (10–90-day) wind anomalies. Correspondingly, each of the four terms in the right-hand-side of the above equation includes three parts that are associated with climatological mean winds, interannual and intraseasonal wind variations, respectively.

3. Contribution of different time scale variations to TC genesis

In this section, we compare the contributions of different time scale variations of environmental factors to the TC genesis over the WNP in 2015 and 2016. The comparison is based on a composite of anomalies centered on the location of TC genesis separately in the two years. Before that, we present the seasonal mean fields that correspond to the interannual variations to provide the large-scale background for the TC genesis. After that, we analyze in detail the contributions of different terms to the barotropic energy conversion for the development of synoptic disturbances.

a. Seasonal mean anomalies

Gray (1968) identified some basic large-scale factors for TC genesis. Those factors include SST, conditional instability, relative humidity in the middle level, cyclonic absolute vorticity in the low level, anticyclonic relative vorticity in the high level, and vertical wind shear between high and low levels. To provide background information of TC genesis, we show in Figs. 1a, b and 2a, b, respectively, total anomalies of 850-hPa wind and SST during JJA and SON in 2015 and 2016 from climatological mean during 1987–2016. The climatological mean 850-hPa wind and SST during JJA and SON are shown in Figs. 1c and 2c, respectively.

In 2015, large warm SST anomalies were present in the equatorial central and eastern Pacific during both JJA and SON (Figs. 1a, 2a). Remarkable lower-level westerly wind anomalies were observed over the equatorial western and central Pacific and cyclonic wind anomalies dominated the WNP during both JJA and SON (Figs. 1a, 2a), featuring a Matsuno–Gill type response to the equatorial central–eastern Pacific warm SST anomalies (Matsuno 1966; Gill 1980). Compared to climatological mean winds (Figs. 1c, 2c), these westerly wind anomalies indicate an eastward move of the monsoon trough. The SST anomalies were small in the WNP in 2015. In 2016, moderate cold SST anomalies occupied the equatorial central
Pacific during JJA and SON (Figs. 1b, 2b). Correspondingly, weak and obvious lower-level easterly wind anomalies were observed over the equatorial western Pacific during JJA and SON, respectively (Figs. 1b, 2b). Warm SST anomalies covered the WNP (Figs. 1b, 2b). Over the subtropical WNP, the wind anomalies showed a notable change from westerly in JJA (Fig. 1b) to easterly in SON (Fig. 2b). Nearly all the TC geneses in 2016 occurred in warm SST anomaly region. The location of TC genesis extends eastward in 2015 compared to that in 2016. The averaged longitude of TC geneses is 150.3°E in 2015 and 142.6°E in 2016. The difference in the longitude of the TC genesis location between the two years is significant at the 90 % confidence level based on the Student’s t test. This feature is consistent with the previous studies that identified an obvious eastward shift in the location of TC genesis during the El Niño developing years (Wang and Chan 2002; Camargo et al. 2007; Wu et al. 2012).

For further comparison, we show in Figs. 3 and 4 interannual anomalies of 850-hPa wind, 700-hPa specific humidity, vertical shear of zonal wind between 200 hPa and 850 hPa, and 500-hPa vertical velocity averaged during JJA and SON, respectively, in 2015 and 2016. In 2015, there were positive humidity anomalies over the eastern part of the WNP in association with anomalous cyclonic winds during both JJA

Fig. 1. The 850-hPa wind (vector, m s$^{-1}$) and SST (shading, °C) anomalies in (a) 2015 and (b) 2016 and climatological mean for the period 1987–2016 during JJA. The wind scale is shown at top-right of the respective panel. The blue symbols in (a) and (b) represent the location of TC genesis.

Fig. 2. The same as Fig. 1 except for during SON.
Most of TC genese were associated with positive vorticity and humidity anomalies. In 2016, most TCs formed in the region of weak humidity anomalies except for the three TCs north of 25°N during JJA that were near the subtropical ridge with large positive humidity anomalies (Figs. 3b, 4b). Most TCs formed in the region of westerly wind anomalies during JJA (Fig. 3b) and in the region of easterly wind anomalies during SON (Fig. 4b). Note, however, most of the TC genesis occurred in the region of lower-level cyclonic vorticity and small total vertical shear in both JJA and SON (Figs. 3b, 4b, 3d, 4d). Compared to the climatological monsoon trough location (Figs. 1c, 2c), defined by the zero line of zonal wind (dashed line), the convergence line between westerly and easterly winds in 2015 (solid line) obviously extended eastward, almost close to the dateline near the equator during JJA in 2015 and in 2016. The dashed lines in (a) and (b) denote the location of monsoon trough and subtropical ridge during JJA in 2015 and in 2016.

Fig. 3. (a, b) The anomalies of 850-hPa wind (vector, m s\(^{-1}\), scale at top-right) and 700-hPa specific humidity (shading, g kg\(^{-1}\)), (c, d) total vertical zonal wind shear (contour, m s\(^{-1}\)) and anomalies of vertical zonal wind shear (shading, m s\(^{-1}\)), and (e, f) anomalies of 500-hPa vertical p-velocity (shading, \(10^{-2}\) Pa s\(^{-1}\)). The solid lines in (a) and (b) denote the location of monsoon trough and subtropical ridge during JJA in 2015 and in 2016. The dashed lines in (a) and (b) denote the location of climatological mean monsoon trough and subtropical ridge during JJA for the period 1987–2016.
3b, 4b). In both 2015 and 2016, some TCs formed in regions of large total vertical shear or large shear anomalies during JJA (Figs. 3c, d) and SON (Figs. 4c, d). In particular, the TC north of 25°N in 2016 during SON was under westerly vertical shear of 20 m s$^{-1}$ or more (Fig. 4d). In 2015, almost half of the TCs formed in the region of anomalous descent motion during JJA and SON on interannual time scale variations (Figs. 3e, 4e). In 2016, most of TCs formed in the region of anomalous ascent motion during JJA and SON (Figs. 3f, 4f).

From above analysis, it is clear that not all the environmental factors are favorable for the TC genesis based on seasonal mean or interannual anomalies, such as SST, vertical motion, and vertical shear in 2015 and lower-level wind and mid-level specific humidity in 2016. Thus, the seasonal averaged conditions cannot account for all the TC geneses over the WNP in these two years. This indicates the necessity of examining local instantaneous conditions for the TC genesis.

b. Composite anomalies of different time scale components

To investigate the relative contributions of the environmental factors to the TC genesis, we construct composite anomalies of the six factors. The composite is obtained by averaging the anomalies with the location of the TC genesis as the center within the 2.5° grids. The composite is made for components of dif-

Fig. 4. The same as Fig. 3 except for during SON.
different time scales separately to understand the relative importance of different time scale variations. As noted above, the four TCs north of 25°N in 2016 display features different from other TCs. Thus, they are excluded in the construction of composite anomalies in 2016. The composite is based on 18 TCs in 2015 and 21 TCs in 2016. The composite anomalies are shown in Fig. 5 for 850-hPa wind and relative vorticity, in Fig. 6 for 500-hPa vertical $p$-velocity, in Fig. 7 for vertical shear of zonal wind, in Fig. 8 for 700-hPa specific humidity, in Fig. 9 for SST, and in Fig. 10 for the barotropic energy conversion at 850 hPa. In the following, we compare the composite anomalies on different time scales during JJASON between 2015 and 2016. Note that in the following composite analysis, we do not separate JJA and SON to obtain more TC genesis cases in the composite.

Notable differences are observed in interannual component of 850-hPa wind and relative vorticity anomalies. In 2015, there are obvious westerly wind and positive relative vorticity anomalies southeast of the TC genesis location (Fig. 5a). In contrast, the wind

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**Fig. 5.** The composite anomalies of 850-hPa wind (vector, m s$^{-1}$, scale at top-right) and relative vorticity (shading, $10^{-5}$ s$^{-1}$) centered over the location of TC genesis on (a, b) interannual, (c, d) intraseasonal, and (e, f) synoptic time scales during JJASON in (a, c, e) 2015 and in (b, d, f) 2016. The zero denotes the grid point nearest to the location of TC genesis. The x- and y-axis represent the distance (°) from the location of TC genesis with positive distance to the east and north and negative distance to the west and south of TC location.
and relative vorticity anomalies are very weak in 2016 (Fig. 5b). This difference is attributed to the impacts of SST anomalies in the equatorial central–eastern Pacific (Figs. 1, 2). The weak interannual wind anomalies in 2016 are partly the result of cancellation of opposite wind anomalies during JJA and SON (Figs. 3b, 4b). The intraseasonal wind anomalies display a cyclone with the center located to northwest of the TC genesis location in both 2015 and 2016 (Figs. 5c, d). In comparison, the intraseasonal wind and vorticity anomalies appear weaker in 2016 than in 2015. The synoptic wind anomalies feature alternating cyclone and anticyclone along a northwest–southeast direction with the largest positive vorticity near the TC genesis location in both years (Figs. 5e, f). This indicates that the pre-existing synoptic-scale disturbances provide initial cyclonic vorticity favorable for the TC genesis (Zehr 1992). A difference to note is that the tilt of the cyclonic circulation is larger in 2016 than in 2015 (Figs. 5e, f). This difference is likely related to the longitudinal location of the monsoon trough. The location of the monsoon trough shifted eastward in 2015 (Figs. 3a, 4a) than in 2016 (Figs. 3b, 4b). Wu et al. (2015) showed that the tropical waves triggering the TC formation develop a tilted structure when they move westward. The tropical waves such as easterly waves or tropical depression-type waves would need to travel a longer distance to reach the monsoon trough to develop into TCs in 2016 compared to that in 2015.

![Fig. 6. The same as Fig 5 except for vertical p-velocity at 500 hPa (shading, 10^{-2} \text{ Pa s}^{-1}).]
The vertical velocity anomalies have no obvious discrepancy around the TC genesis location on the three time scales between 2015 and 2016 (Fig. 6). Anomalous upward motion is observed on interannual, intraseasonal, and synoptic time scales in both 2015 and 2016. This indicates a positive contribution to TC genesis of the ascending motion on all the three time scales. In comparison, the largest vertical velocity anomalies are related to the synoptic variation (Figs. 6e, f). This indicates that the synoptic-scale upward motion has the largest positive contribution to the initial ascending motion of the TC genesis.

In general, TCs mostly occur in a weak vertical wind shear condition because strong vertical wind shear disrupts the development of organized deep convection and the building up of an upper-level warm core (Gray 1979; DeMaria 1996; Cheung 2004). In both 2015 and 2016, the TC genesis location is near the zero line of total vertical shear (Fig. 7). Therefore, total vertical wind shear is weak over the TC genesis location, particularly in 2016. The vertical wind shear anomalies, however, display notable differences between 2015 and 2016. In 2015, the composite vertical wind shear anomalies are negative near the TC genesis location on all the three time scales with the magnitude of easterly shear anomalies exceeding...
2 m s$^{-1}$ (Figs. 7a, c, e). In 2016, the composite vertical wind shear anomalies are small, between −1 m s$^{-1}$ and 1 m s$^{-1}$, on the three time scales (Figs. 7b, d, f). The large negative shear anomalies on the interannual time scale in 2015 may be due to the wind response over the WNP (Fig. 5a) to positive SST anomalies in the equatorial central–eastern Pacific (Figs. 1a, 2a).

A high value of humidity in the middle level is favorable for TC genesis (Emanuel 1993). If the middle level is too dry, the cooling induced by evaporation enhances downdrafts, thus inhibiting sustainable convective development. A dry middle level also inhibits the development of convection due to entrainment of dry air by ascending parcels (Cheung 2004). In 2015, positive humidity anomalies on the interannual time scale extend from southeast to TC genesis location (Fig. 8a). In 2016, the interannual positive humidity anomalies are located to southwest of the TC genesis location (Fig. 8b), which appears to be contributed largely by the TCs that formed over the western WNP (Figs. 3b, 4b). Note that there are negative humidity anomalies in the southeast quadrant in 2016, which may be associated with TC genesis during SON. During SON, most TCs formed in the western part of the WNP. In the region to southeast of TC genesis, anomalous easterly winds along the equator lead to negative humidity anomalies (Fig. 4b). On intraseasonal and synoptic time scales, positive humidity anomalies are located around the TC genesis location in both years with some differences in the magnitude.
(Figs. 8c–f). Thus, the humidity anomalies on three time scales have a positive contribution to the TC genesis in both 2015 and 2016. In comparison, the magnitudes of specific humidity anomalies are larger on intraseasonal and synoptic time scales than on interannual time scale.

A warm enough ocean surface provides the necessary energy for convection development (Gray 1968). A pronounced feature is that a robust contribution of SST to the TC genesis is observed in association with its interannual variation (Figs. 9a, b). The magnitude of interannual SST anomalies is much larger in 2016 than in 2015 (Figs. 9a, b). This is consistent with Figs. 1, 2 that almost all the TC geneses in 2016 occurred in anomalous warm SST region. However, the SST variations on intraseasonal and synoptic time scales have a weak and negative contribution to the TC genesis in both 2015 and 2016 (Figs. 9c–f).

Barotropic energy conversion is an important pathway through which large-scale circulations on intraseasonal and interannual time scales have a significant effect on the TC genesis (Maloney and Hartmann 2001; Wu et al. 2012). Large barotropic energy conversion anomalies appear to the southeast of the TC genesis location from interannual, intraseasonal, and climatological mean circulation fields except for the interannual component in 2016 (Fig. 10). As shown in Wu et al. (2015), the positive barotropic energy conversion anomalies occur at the northwest and southeast quadrants of the disturbance due to the hori-
Horizontal structure of disturbance. The barotropic energy conversion results in the northeast–southwest tilt of synoptic-scale disturbances, which further favors the extraction of barotropic energy from the background flows. Such positive feedback tends to enhance the potential for the development of small-scale disturbances. According to Fig. 10, the synoptic-scale disturbances mainly obtain the energy from climatological mean flow and intraseasonal variation of circulation, whereas the interannual variation of circulation has a smaller effect on the development of synoptic-scale disturbances.

c. Discussion of contributions of three time scale variations

To compare quantitatively the difference of contributions of the three time scale variations to the TC genesis between 2015 and 2016, we calculated the anomalies of these quantities averaged in a 2.5° × 2.5° box encompassing the TC genesis location except for vertical wind shear for which the average is based on a 7.5° × 7.5° box and barotropic energy conversion.
The average is based on a 15° × 15° box. The use of different box sizes in the average is based on the distribution of composite anomalies discussed above. The results are shown in Fig. 11 including the averaged value, maximum, upper quartile, median, lower quartile, and minimum of anomalies.

In general, the averaged anomalies of relative vorticity and specific humidity are larger in 2015 than in 2016 on all the three time scales (Figs. 11a, e). For barotropic energy conversion, the averaged anomalies of interannual and intraseasonal variations are larger in 2015 than in 2016 (Fig. 11d). Those results indicate that relative vorticity, specific humidity, and barotropic energy conversion have a larger contribution to the TC genesis in 2015 than in 2016. This is associated with the direct effect of ENSO on the interannual component of anomalies. Previous studies have shown that warm SST anomalies in the equatorial central-eastern Pacific induce anomalous cyclonic vorticity, lower-level convergence, and upper-level divergence, and lead to an increase in the lower- and mid-level moisture over the WNP (Wang and Chan 2002; Wu et al. 2012). Meantime, the ENSO-dependent background fields may modulate the intensity of intraseasonal oscillations (ISOs), with stronger ISOs during the El Niño developing years and weaker ISOs during the El Niño decaying years over the WNP (Lin and Li 2008; Wu and Cao 2017; Wu and Song 2018). This leads to a larger contribution of intraseasonal anomalies of relative vorticity and specific humidity and barotropic energy conversion related to intraseasonal wind variations to the TC genesis in 2015 than in 2016 (Figs. 11a, e, d). Therefore, both the direct and indirect effects of ENSO cause the enhancement of contribu-
tions of the above large-scale factors to the TC genesis on interannual and intraseasonal time scales in 2015 compared to 2016. The averaged absolute values of vertical wind shear are much smaller in 2016 than in 2015 (Fig. 11c). This indicates that the vertical wind shear is more favorable for TC genesis in 2016 than in 2015. Meantime, the interannual SST anomalies are positive in both years, but much larger in 2016 than in 2015 (Fig. 11f). This is because warm SST anomalies tend to develop in the WNP during the El Niño decaying years (e.g., Wu et al. 2014). The intraseasonal and synoptic SST anomalies are small in both years. There are no obvious differences in vertical p-velocity anomalies between these two years (Fig. 11b). The above comparisons indicate that vertical wind shear and SST have a larger contribution to the TC genesis in 2016 than in 2015.

In addition to the difference between 2015 and 2016, there are several differences to note for contributions of some factors to the TC genesis among the three time scale variations. The contribution of synoptic variations of relative vorticity and vertical velocity is the largest and that of interannual variations is the smallest in both years (Figs. 11a, b). The barotropic energy conversion is larger from the intraseasonal component and climatological mean than from the interannual component of winds in 2015 and it is the largest from the climatological mean with secondary contribution from intraseasonal variation (Fig. 11d). The contributions of vertical wind shear and specific humidity are comparable among the three time scale variations (Figs. 11c, e). A robust contribution of SST anomalies to the TC genesis is observed in relation to its interannual variation in both 2015 and 2016 (Fig. 11f). The synoptic and intraseasonal variations of the SST have small, even negative contributions (Fig. 11f). We note that there are large spreads among individual TCs in anomalies of the environmental variables with respect to the averaged mean, in particular, for synoptic and intraseasonal time scales (Fig. 11). Thus, the conclusions based on the composite mean may not apply to all the TC genuses.

In conclusion, our analysis shows that the contributions of vertical wind shear on all the three time scales and the underlying SST on the interannual time scale are more favorable for the TC genesis in 2016 than in 2015. The humidity and vorticity anomalies, however, are larger in 2015 than in 2016 on all the three time scales. Thus, it appears that different factors have inconsistent effects in the difference of TC genesis between the two years.

d. Contributions of different terms to the barotropic energy conversion

While the large-scale circulations provide favorable environmental conditions for TC genesis, the synoptic-scale disturbances are local forcing for TC genesis through inducing lower-level convergence and positive relative vorticity (Shapiro 1977; Zehr 1992; Li 2012), such as the Rossby wave energy dispersion of a preexisting mature TC, mixed Rossby-gravity (MRG) waves, and tropical depression (TD) disturbances over the WNP (Holland 1995; Dickinson and Molinari 2002; Frank and Roundy 2006). The intensity of the synoptic-scale disturbances can be defined by the eddy kinetic energy. Previous studies have suggested that barotropic dynamics for eddy kinetic energy growth is found to be an important mechanism by which the synoptic-scale disturbances develop and eventually evolve into TCs (e.g., Norquist et al. 1977; Maloney and Hartmann 2001; Cao et al. 2012).

As noted above, the monsoon trough displaces an eastward move in 2015, which induces large seasonal mean wind anomaly over the WNP (Figs. 3a, 4a). The associated eastward shift in the location of TC genesis modifies the climatological mean flow around the TC genesis. The modulated mean field in turn affects the intraseasonal flow (Figs. 5c, d). All these may affect the barotropic energy conversion for the synoptic disturbances. To understand the contributions of the different components of background flows to the development of synoptic-scale disturbances, we compare the two terms in the barotropic energy conversion associated with the meridional variation of zonal wind and the zonal variation of zonal wind in 2015 and 2016. Figures 12 and 13 show the two terms of the barotropic energy conversion in 2015 and 2016 in relation to the interannual and intraseasonal wind variations and climatological mean flows, respectively. We note that the two terms of the barotropic energy conversion associated with the meridional wind variations are small in both 2015 and 2016 and thus we do not show the spatial distribution of these two terms.

The term associated with the meridional variation of zonal wind has a larger positive contribution to the barotropic energy conversion in relation to interannual and intraseasonal wind anomalies in 2015 than in 2016 (Figs. 12a–d). The terms associated with interannual wind anomalies are related to the response of lower-level winds over the WNP to ENSO-related SST anomalies. During JJASON of 2015, warm SST anomalies in the equatorial central–eastern Pacific induce an anomalous lower-level cyclone over the WNP as a Rossby wave type response with anomalous
westerly winds located at lower latitudes (Figs. 3a, 4a) (Wang et al. 2003; Wu et al. 2003). The terms in relation to intraseasonal wind anomalies are consistent with large intraseasonal cyclonic wind anomalies centered to west of the TC genesis location (Fig. 5c). In relation to climatological mean winds, the term associated with the meridional variation of zonal wind has a comparable contribution to the barotropic energy conversion in 2015 and 2016 (Figs. 12e, f). This reflects the effect of the monsoon trough east of which most of TCs formed (Figs. 3a, b, 4a, b). The easterly trade winds weaken northward when approaching the subtropical ridge, leading to large meridional shear.

The term associated with the zonal variation of zonal wind is small in relation to interannual wind anomalies in both 2015 and 2016 (Figs. 13a, b). With regard to intraseasonal wind anomalies and climatological mean winds, the term associated with the zonal convergence of zonal wind has a larger positive contribution to the barotropic energy conversion in

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**Fig. 12.** The composite barotropic energy conversion \(10^{-5} \text{ m}^2 \text{ s}^{-3}\) term associated with the meridional variation of zonal wind centered over the location of TC genesis in relation to (a, b) interannual, (c, d) intraseasonal, and (e, f) climatological winds in 2015 and 2016. The zero denotes the grid point nearest to the location of TC genesis. The x- and y-axis represent the distance (°) from the location of TC genesis with positive distance to the east and north, and negative distance to the west and south of the location.
2015 than in 2016 (Figs. 13c–f).

To compare quantitatively the contributions of different terms in the barotropic energy conversion on different time scales, we compute anomalies of four terms in a $15^\circ \times 15^\circ$ box encompassing the TC genesis location in 2015 and 2016. The results are shown in Fig. 14 including the averaged value, maximum, upper quartile, median, lower quartile, and minimum of anomalies.

A major feature to note for the barotropic energy conversion in relation to interannual wind anomalies is that the terms due to the meridional variation of zonal wind is obviously larger in 2015 than in 2016 (Fig. 14a). For the barotropic energy conversion in relation to intraseasonal wind anomalies, the term associated with the meridional shear of zonal wind is very large and comparable in 2015 and 2016 (Fig. 14a), whereas the term due to the zonal convergence of zonal wind is large in 2015, but small in 2016 (Fig. 14c). The term associated with the zonal change of meridional wind has a large negative effect (Fig. 14b). For the barotropic energy conversion in relation to climatological mean winds, the two terms due to the meridional shear of zonal wind and the zonal convergence of zonal wind are both important in the two years (Figs. 14a, c). This is consistent with Ritchie and Holland (1999).
who showed that 70% of the TC genesis is associated with the monsoon shear line and in the monsoon confluence region. In comparison, the term associated with the meridional shear of zonal wind is larger in 2016 (Fig. 14a), whereas the term due to the zonal convergence of zonal flow is larger in 2015 (Fig. 14c). These differences may be explained by the location of TC genesis relative to climatological mean monsoon trough and the horizontal structure of synoptic disturbances. In 2015, more TCs formed to east of 150°E, farther away from climatological monsoon trough, while in 2016 more TCs formed to west of 150°E, closer to climatological monsoon trough. As such, the TCs tend to form in a larger zonal wind shear region in 2016 compared to those in 2015. This leads to a larger effect of the meridional shear of zonal wind in 2016 than in 2015 (Fig. 14a). The synoptic cyclonic winds display a smaller tilt in 2015 than in 2016 (Figs. 10e, f). As such, the synoptic zonal wind component around the TC genesis location tends to be larger in 2015 than in 2016. This leads to a large contribution of the term associated with the zonal convergence of zonal wind in 2015 (Fig. 14c), which is related to the square of synoptic zonal wind anomalies (Wu et al. 2015).

Figure 14 also shows that there exist large spreads in anomalies of four terms with respect to the averaged value on intraseasonal time scale. The anomalies of the two terms in relation to the meridional shear of zonal wind and the zonal convergence of zonal wind of climatological mean display notable spreads as well. This is mainly associated with the location of TC genesis with respect to the background winds.

4. Summary and discussion

Previous studies on the TC genesis have focused on large-scale spatial patterns over a relatively long period. Distinct from previous studies, this study fo-
focuses on local and instantaneous conditions of the TC genesis. The present study examines the contributions of six environmental factors (lower-level relative vorticity, vertical wind shear, middle-level moisture, vertical p-velocity, SST, and barotropic energy conversion) to the TC genesis over the WNP and compares the relative contributions of interannual, intraseasonal, and synoptic variations of these environmental factors between 2015 and 2016.

The results indicate that the contributions of lower-level vorticity, mid-level specific humidity, and barotropic energy conversion to the TC genesis over the WNP are larger in 2015 than in 2016, while the contributions of vertical wind shear and SST are larger in 2016 than in 2015. The barotropic energy conversion in relation to interannual wind variation is obviously enhanced in 2015. Those differences are associated with the direct effect of ENSO on the interannual component of large-scale factors and the indirect effect of ENSO on the intraseasonal component.

The synoptic variation of relative vorticity has a larger contribution than the intraseasonal variation to the TC genesis, while the synoptic variation of vertical velocity has a contribution comparable to the intraseasonal variation. The interannual variations of relative vorticity and vertical velocity have a small contribution to the TC genesis. The interannual SST anomalies have a dominant positive contribution, particularly in 2016. The synoptic-scale disturbances mainly obtain energy from the intraseasonal variation of winds and climatological mean flows. Those results indicate that although large-scale environmental conditions are favorable on interannual time scale, the main contribution to the TC genesis may be from other time scale variations. Thus, the statistical analysis of local and instantaneous conditions of the TC genesis is more appropriate to investigate the contribution of various factors to the TC genesis than the previous analysis of a large spatial scale pattern averaged in a certain period.

Comparison of contributions of different terms to barotropic energy conversion shows that the barotropic energy conversion in relation to interannual wind variations is due to the meridional variation of zonal wind in 2015, while it is negligible in 2016. The barotropic energy conversion in relation to intraseasonal wind variations is mainly contributed by the terms associated with the meridional shear and the zonal convergence of zonal winds in 2015, while the term associated with the meridional shear of zonal wind plays a dominant role in 2016. The barotropic energy conversion in relation to climatological mean winds is due to the terms associated with the meridional shear and the zonal convergence of zonal winds in both 2015 and 2016. The magnitude of the former is larger in 2016, while that of the latter is larger in 2015. The difference is related to shift in the TC genesis location, which leads to a change in the distance relative to climatological monsoon trough and in the structure of synoptic disturbances.

The composite results show that vertical wind shear and the underlying SST have a larger positive contribution to the TC genesis in 2016 than in 2015. However, the lower-level vorticity and mid-level humidity have an opposite contribution in these two years. As such, the large-scale seasonal mean states cannot fully explain the difference of TC genesis frequency between 2015 and 2016. On the other hand, the short-time scale variations (intraseasonal and synoptic time scales) appear to have a larger magnitude in 2015 than in 2016 for lower-level vorticity and mid-level humidity. This suggests that the short-time scale processes the difference of the TC genesis between 2015 and 2016. It is possible that the difference in the TC genesis number between 2015 and 2016 is due to a combination of effects of different factors on the three time scale variations. Further analysis is needed to understand why the TC genesis is more in 2016 than in 2015.

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