Interdecadal variability of tropical cyclone genesis frequency in western North Pacific and South Pacific ocean basins

Kaiyue Shan and Xiping Yu
State Key Laboratory of Hydroscience and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing, People’s Republic of China
E-mail: yuxiping@tsinghua.edu.cn

Keywords: tropical cyclone genesis frequency, interdecadal variability, regional and seasonal variations, environmental factors, intense typhoon

Abstract
Variability of tropical cyclone (TC) genesis frequency in the western North Pacific and South Pacific ocean basins in the interdecadal scale is studied. It is demonstrated that the TC genesis frequency in these ocean basins experienced an abrupt decrease near the end of the 20th century. The decreased occurrence of TC genesis in the two recent decades is mainly located in the low-latitude regions at the eastern side of the two ocean basins. It is also shown that a significant part of the decreased TC genesis occurred during October to December, i.e. the post-peak season in the western North Pacific ocean basin and the pre-peak season in the South Pacific ocean basin. The interdecadal trend of variation in the TC genesis frequency in these adjacent two ocean basins seems to be mainly due to a common mechanism, i.e. the variation in the atmospheric vorticity. In contrast to the decrease in the total TC genesis, the intense typhoon occurrence frequency experienced an interdecadal increase during the same period. This trend for intense typhoons is particularly clear in the western North Pacific ocean basin. The zonal distribution of the increased number in the intense typhoon occurrence shows a similar pattern to the increased value of the sea surface temperature. It is then suggested that the variation in the intense typhoon occurrence frequency in the western North Pacific ocean basin is related to a change in the La Niña-like sea surface warming pattern.

1. Introduction
It has been a major concern of the scientific community as to whether the annual number of tropical cyclone (TC) genesis events, globally or in a particular ocean basin, is affected by the climate change. Globally, no evident trend has been identified over the past decades (Knutson et al 2010, Walsh et al 2016), although global warming has been shown to be an indisputable fact (IPCC 2014, Medhaug et al 2017). However, this does not mean that we can draw the same conclusion with confidence in a particular ocean basin. For example, an increasing trend in the North Atlantic (NA) ocean basin in recent decades (Mann and Emanuel 2006, Bruyère et al 2012) and an abrupt decrease in the western North Pacific (WNP) ocean basin near the end of the 20th century (Liu and Chan 2013, 2019, He et al 2015, Hu et al 2018, Zhao et al 2018b) have been reported. Why does the TC genesis frequency have a particular trend in these ocean basins? Is there a similar or a complementary variation in the TC genesis frequency in the adjacent ocean basins? Are they governed by the same mechanism?

To answer these questions with confidence, a statistical study of the climatological relation between TC genesis frequency and the relevant environmental factors in the ocean basins of interest may be necessary. In fact, quite a number of such studies have been carried out previously (Palmén 1948, Riehl 1954, 1955, Gray 1967, 1979). The most important parameters to represent the environmental effects have been found to be (i) the sea surface temperature (SST), (ii) the relative humidity in the middle-troposphere, i.e. at 700 hPa (denoted by RH_{700}), (iii) the cyclonic vorticity in the lower-troposphere, i.e. at 850 hPa (denoted by \(\xi_{850}\)), and (iv) the vertical wind shear (denoted by \(\Delta V\)), which is measured by the difference in wind speed at 200 hPa and at 850 hPa (Emanuel and Nolan 2004, Chand and Walsh 2009, Bruyère et al 2012). It
Table 1. The total number of TC genesis in the WNP and the SP ocean basins during the whole period of study.

|       | 1979–2018 | 1979–1998 | 1999–2018 |
|-------|-----------|-----------|-----------|
| WNP   |           |           |           |
| TC (\(V_{\text{max}} \geq 35 \text{ kt}\)) | 1008      | 522       | 486       |
| ITY (\(V_{\text{max}} \geq 96 \text{ kt}\)) | 354       | 168       | 186       |
| WTY (\(V_{\text{max}} = 64–95 \text{ kt}\)) | 286       | 169       | 117       |
| SP    |           |           |           |
| TC (\(V_{\text{max}} \geq 35 \text{ kt}\)) | 393       | 212       | 181       |
| ITY (\(V_{\text{max}} \geq 96 \text{ kt}\)) | 101       | 49        | 52        |
| WTY (\(V_{\text{max}} = 64–95 \text{ kt}\)) | 114       | 73        | 41        |

is also clarified that the relative importance of these factors can be very different in different ocean basins, or even in different regions of the same ocean basin (Bruyère et al 2012, Zhao et al 2018b). The difference in dominant factors may explain the significant variation in TC genesis frequency and its trend of change in different ocean basins.

Quite a number of previous studies focused on the interdecadal changes in the TC genesis frequency based on the number of TCs observed in a prescribed peak season (He et al 2015, Hu et al 2018, Zhao et al 2018b). However, in some ocean basins, if not in all, the concentration on a horizontal resolution TC number in a prescribed peak season varies significantly from year to year. In fact, apparent anomalies during September through November have been found in an investigation into the interannual variation in the TC number related to El Niño-Southern Oscillation (ENSO) over the WNP ocean basin, i.e. the TC number is above the normal, especially during these months in the eastern part of the WNP ocean basin in an El Niño year, and below the normal in a La Niña year (Chan 2000). In the South Pacific (SP) ocean basin, the interannual correlation between the TC genesis potential index, which is a combination of the environmental factors related to TC genesis, and the TC number is strong during November through January but not during the usually prescribed peak season (Camargo et al 2007). It is then of interest to find out whether and how the seasonal variability contributed to the interdecadal variation in TC genesis frequency.

Despite the decreasing trend of the genesis frequency of TCs in total, a significant increase in the intense TCs (\(V_{\text{max}} \geq 96 \text{ kt}\), \(V_{\text{max}}\) is the maximum sustained wind velocity throughout the lifespan of a TC) has been observed over the WNP ocean basin since the 1970s (Webster et al 2005, Elsner et al 2008). Klotzbach and Landsea (2015) found a flattening out of the increasing trend for the very intense TCs (\(V_{\text{max}} \geq 113 \text{ kt}\)) reported by Webster et al (2005), after extending the dataset of Webster et al (2005) by ten years, but the increasing tendency for both intense and very intense TCs is still unchanged. In a recent study by Liu and Chan (2019), the frequencies of TC genesis and of very intense TC occurrence were certainly shown to be not necessarily correlated.

In this study, interdecadal variability of TC genesis frequency in the WNP and the SP ocean basins and its relation with environmental factors are investigated based on the observed TC genesis data and the reanalysis data of the environmental parameters during the period from 1979 to 2018. The impacts of seasonal variation and regional difference are emphasized. Special attention is paid to the intense TC occurrence.

2. Data and methods

The datasets used in this study include: (i) TC genesis locations taken from the International Best Track Archive for Climate Stewardship (IBTrACS), version 4 (Knapp et al 2010), which merged the historical best track data from multiple sources (available at https://www.ncdc.noaa.gov/ibtracs/index.php?name=ib-v4-access); (ii) monthly mean data of SST with a horizontal resolution of \(2^\circ \times 2^\circ\) from the Extended Reconstructed Sea Surface Temperature (ERSST), version 5 (Huang et al 2017) (available at http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.v5.html); (iii) monthly mean reanalysis data of RH\(_{700}\), \(\xi_{850}\), and \(\Delta V\) with a horizontal resolution of \(2.5^\circ \times 2.5^\circ\) from the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP-NCAR) (Kalnay et al 1996) (available at https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.pressure.html). All these datasets cover the whole period of the present study from 1979 to 2018. The TC genesis data after 1979 are often considered to be reliable because satellites have been available for TC observations since then.

We study only TCs with \(V_{\text{max}} \geq 35 \text{ kt}\) over the WNP ocean basin, i.e. the ocean basin bounded by \(0^\circ-30^\circ N\), \(100^\circ E-180^\circ\), and the SP ocean basin, i.e. the ocean basin bounded by \(0^\circ-30^\circ S\), \(135^\circ E-130^\circ W\). Tropical depressions are thus excluded. The TCs are classified into different groups in this study, essentially based on the Saffir–Simpson scale that adopts \(V_{\text{max}}\) to represent TC intensity. In particular, TC without a special mention means a TC with \(V_{\text{max}} \geq 35 \text{ kt}\) while a typhoon (TY) refers to a TC with \(V_{\text{max}} \geq 64 \text{ kt}\). A weak typhoon (W TY) (categories 1 and 2 in the Saffir–Simpson scale) is a TY with \(V_{\text{max}} = 64–95 \text{ kt}\), while an intense typhoon (ITY) (categories 3, 4 and 5 in the Saffir–Simpson scale) is a TY with \(V_{\text{max}} \geq 96 \text{ kt}\). It is worthwhile mentioning that there are various suggestions to describe the
Interdecadal variability of TC genesis frequency is our interest in this study. The moving t-test is employed to detect if the TC genesis frequency undergoes an abrupt change in the decadal scale (Affifi and Azen 1972). If the difference in the mean values over a decade is significant with a certain confidence level, an abrupt change is then identified. Note that the t-test has been quite successfully used to find abrupt changes in the annual numbers of TC events (Liu and Chan 2013, Park et al 2014, He et al 2015, Zhao et al 2018b), even its requirement for the annual numbers of TC events to satisfy the Gaussian distribution is not adequately met. The t-value is defined by

$$t = \frac{X_1 - X_2}{\sqrt{(n_1-1)S_1^2 + (n_2-1)S_2^2} \left( \frac{1}{n_1} + \frac{1}{n_2} \right)}$$

where the subscripts 1 and 2 represent the subseries of a prescribed size before and after the cutoff year; $X$, $S$ and $n$ denote the mean, the standard deviation and the size of the relevant series, respectively. A positive t-value then indicates a decrease in the mean value. We take $n_1 = n_2 = 10$ yr in this study. Given the significance level, a threshold value for $t$ can then be obtained from the t-distribution to judge if the variation is an abrupt one. In this study, the difference between the mean values of the subseries before and after the cutoff year is an abrupt change at a significance level of 90% if $|t| \geq 1.81$.

The Bayesian change-point analysis (Chu and Zhao 2004, 2011, Tu et al 2009, Zhao and Chu 2010) may also be used to further confirm possible existence of an abrupt change in a time series of the TC genesis frequency. With this method, annual TC numbers are treated as a discrete Poisson process. The Bayes factor, which is defined as the ratio of the probability for having one change point to that for having no change point, is utilized to judge whether an abrupt change in the time series occurs based on Raftery’s scale (Raftery 1996). Once an abrupt change likely exists, the posterior probability mass function (PMF) may then be evaluated to determine the cutoff year. Details of the method may be referred to in Chu and Zhao (2004) and Chu and Zhao (2011).

3. Variability of TC genesis frequency

3.1. Evidence

Variations in the annual TC number in the WNP and the SP ocean basins during 1979–2018 are plotted in figure 1. The moving t-values of these time series are presented in figure 2. It is then clear that the TC genesis frequency in both the WNP and the SP ocean basins experienced an abrupt decrease near the end of the 20th century. In addition, a sharp increase in the t-values is observed before the change point, which further ensures the largest difference in the mean values of TC number to occur at this change point.
Paying some attention to the great differences in the ocean basins of the northern and southern hemispheres (Maue, 2011), it is reasonable to consider that the abrupt changes for the WNP and SP ocean basins occur simultaneously. In fact, the rapid decrease in the annual TC genesis in the WNP ocean basin has been reported in a number of previous studies (He et al 2015, Hu et al 2018, Zhao et al 2018b), but a focus on the simultaneous decrease in the TC genesis frequency in the WNP and SP ocean basins so as to identify their common reasons does not seem to have been given.

When applying the Bayesian method (Chu and Zhao 2004, 2011), the prior parameters can be estimated using the annual TC numbers during the two periods 1984–1993 and 2004–2013. It is then found that the Raftery’s scale for the variations of the annual TC number is 4.7 (at the positive level) in the WNP and 6.6 (at the strong level) in the SP ocean basins, respectively. Existence of abrupt change points in both the WNP and SP ocean basins is thus certain. Plotted in figures 3 (a) and (b) are variations of the posterior PMF with an assumed cutoff year. It is clearly shown that the probability for occurrence of a cutoff point in the WNP ocean basin is particularly high during the period from 1996–1998, while the most possible cutoff point in the SP ocean basins occur in 1998. The result is in good agreement with that from the t-test. Note that the abrupt change in TC genesis frequency in the WNP ocean basin is very likely to be a multi-annual process. A strict definition of the cutoff year should thus be open to discussions. In this study, the cutoff point is assumed to take place in 1998, based on a balanced consideration of the results for the two adjacent ocean basins and the results from different methods.

To further confirm that the abrupt change in the TC genesis frequency near the end of the 20th century is an interdecadal event, the difference in the mean TC number between the first period (20 years, from 1979 to 1998) and the second period (20 years, from 1999 to 2018) within the whole period of our study is also examined. Quantitatively, the mean TC number decreases from 26 to 24 per year in the WNP ocean basin from the first period to the second period, while the mean TC number decreases from 11 to 9 per year in the SP ocean basin.

3.2. The sensitive region
The spatial distribution of TC genesis density and the difference in TC genesis density between the first period (1979–1998) and the second period (1999–2018) within the whole period of this study are presented in figure 4. The main development regions of TCs (i.e. the region where TC genesis density is greater than 0.01 h⁻² km⁻² yr⁻¹) at the two periods are also compared. It is seen that in the WNP, there is a significant shrinkage of the main development region from the first to the second period, and its eastern boundary shifts from a position at 180° to a position at 165°E. In the SP, the main development regions at the two periods are both within a narrow belt, but the equatorward boundary of the belt shifts poleward obviously from the first to the second period, i.e. from about 7.5°S to 10°S, due to the decrease in TC genesis in the low-latitude regions. It is thus quite clear that the decreased occurrence of TC genesis during the second period mainly falls in the low-latitude regions, with a longitude coverage of 20–30° west of 180°. In addition, an increase in TC genesis frequency during the second period is found over a region in the WNP at the eastern side of the Philippine Islands (10°–20°N, 120°E–150°E).

For the convenience of statistical study, we define the sensitive regions of 0°–12.5°N, 150°E–180° in the WNP ocean basin and of 0°–12.5°S, 160°E–180° in the SP ocean basin. Note that the sensitive regions are delimited by rounded latitude and longitude simply for the convenience of discussions. They are extended to the equator even though TCs do not occur near the equator. Referring to these definitions, it is found that, in the sensitive region of the WNP, the mean TC number decreases from 8.85 to 3.2 per year, while in the sensitive region of the SP, the mean TC number decreases from 2.6 to 1.15 per year from the first to the second period during the whole period of our study. It is also found that, in the WNP ocean basin, the decreased number of TC events from the first to the second period is 36 in total, in contrast to 113 in the sensitive region; while in the SP ocean basin, it is 31 in total, in contrast to 29 in the sensitive region. Evidently, the significant decrease in TC genesis frequency in the sensitive regions dominates the interdecadal decrease in the total TC genesis frequency in the WNP and the SP ocean basins. Note that the decreased number of TC events in the entire WNP ocean basin is smaller than that in the sensitive region owing to a significant increase in the TC
It may be necessary to point out that the spatial distribution of TC genesis frequency differences in our study appears to be different to some previous results (He et al 2015, Zhao et al 2018b). The inconsistency of the results is mainly due to the fact that the interdecadal variation in TC genesis density is based on annual TC genesis events in the present study, but it was based on the number of TC events in the prescribed peak season in the previous studies. In fact, it is hard to achieve a comprehensive understanding of the interdecadal variability of TC genesis based only on the number of TC events occurring in the peak season, since the seasonal variation in TC genesis has an important contribution to the interdecadal variability of TC genesis, as discussed in the following subsection.

3.3. The sensitive season

Figure 5 shows the comparison of monthly variations in TC genesis and TC genesis differences between the first period (1979–1998) and the second period (1999–2018) within the whole period of this study. It is noted that about 55% of the TC events occur during the peak season (July–September) in the WNP ocean basin, in contrast to 36% of the decreased number; about 70% of TC events occur during the peak season (January–March) in the SP ocean basin, in contrast to 52% of the decrease. In particular, there is only a very slight decrease during July in the WNP ocean basin and January in the SP ocean basin. This implies that a large portion of the decreased TC genesis does not occur in the peak season of TC genesis.

Figure 5 also indicates that a significant part of the decreased TC genesis in the two recent decades occurred in the post-peak season (October–December) in the WNP ocean basin, with the largest decrease in October; and in the pre-peak season (also October–December) in the SP ocean basin, with the largest decrease in December. When applying the moving t-test and the Bayesian change-point analysis to the time series of the number of TCs observed during October–December in the WNP and the SP ocean basins, abrupt decreases in 1998 can also be detected, similar to those of the annual TC number in figures 2 and 3.

The fact that a rapid decrease in TC genesis exists in the post-peak season in the WNP ocean basin has also been reported by Hsu et al (2014) who focused on the post-peak season typhoon activity in the WNP ocean basin. That the largest decrease in TC genesis in the WNP ocean basin occurred in October is supported by the study of Zhao et al (2018b) who were interested in the TC events during the active season defined by themselves (June–October). In previous studies, however, very little attention has been paid to how such a decrease is related to the variability of TC genesis in the SP.

Figure 6 gives the monthly variations in TC genesis and TC genesis differences between the two periods within the whole period of the present study in the sensitive regions. Compared to the monthly variations over the entire WNP ocean basin in figure 5(a), it is obvious that more TCs favor occurrence in the post-peak season, with a peak in October in the sensitive region of the WNP ocean basin. And compared to the monthly variations over the entire SP ocean basin in figure 5(b), more TCs favor occurrence in the pre-peak season with a peak in December in the sensitive region of the SP ocean basin. The differences in TC genesis frequency between the two periods show a similar monthly distribution in that a significant decrease in TC genesis is observed during the post-peak season in the sensitive region of the WNP ocean basin and during the pre-peak season in the sensitive region of the SP ocean basin.

3.4. Variability of environmental factors

A decrease in TC genesis frequency is often considered as an impact of the decreased SST, the decreased humidity, the decreased low-level cyclonic vorticity or the increased vertical shear over the relevant region in an ocean basin, and vice versa. Figure 7 presents
the spatial distributions of the differences in these environmental factors between the first period (1979–1998) and the second period (1999–2018) within the whole period of this study. The SST difference between the two periods is shown to be characterized by C-shaped warming/cooling belts over the Western Pacific Ocean, geometrically analogous to the interannual anomalies during La Niña years. The difference of RH_{700} has a similar distribution pattern to the SST difference. This is not a surprise because high correlation between the SST and RH_{700} has been demonstrated in the literature (Stephens 1990). The La Niña-like SST difference pattern in figure 7 also leads to an enhanced Walker circulation, which strengthens both the lower-tropospheric easterlies and the upper-tropospheric westerlies, and thus increases the vertical shear over the eastern tropics of the Western Pacific Ocean (Liu and Chan 2013, Lin and Chan 2015, Hu et al 2018). In short, the La Niña-like SST difference pattern leads to a decreased

Figure 4. (a) Distribution of annual TC genesis density, and (b) the difference in TC genesis density between different periods (the second period minus the first period) within the whole period of study.
humidity and enhanced vertical shear in the eastern tropics of the Western Pacific Ocean, which makes this region less favorable for TC genesis. It may also be worthwhile noting that since the variations in the atmospheric factors are not significant, the increased SST causes an increase in TC genesis over a region in the WNP at the eastern side of the Philippine Islands. The increase in TC genesis in this region, however, does not reverse the trend of TC genesis frequency in the entire WNP ocean basin owing to the overwhelming influence of the decrease in TC genesis in the sensitive region.

The most direct reason for the decrease in TC genesis frequency from the first to the second period within the whole period of our interest in the sensitive regions defined in this study may be the decreased vorticity in this region, as shown in figure 7(d). In fact, the correlation between the annual TC number and $\xi_{850}$ in the sensitive regions is fairly strong, as demonstrated in figure 8. The relatively weaker correlation in the SP ocean basin may be due to the fact that the TC genesis number in the sensitive region of the SP ocean basin may be due to the fact that the TC genesis number in the sensitive region of the SP ocean basin may not be enough to ensure a statistically stable result. Applying the moving t-test to the time series of $\xi_{850}$ in the sensitive regions of the WNP and the SP ocean basins, an abrupt decrease in $\xi_{850}$ is evidently detected at the year around 1998, as indicated in figure 9, which coincides with the trend for TC genesis frequency shown in figures 2 and 3. In addition, the abrupt decrease in the time series of $\xi_{850}$ can be detected using the nonparametric rank-based Mann–Kendall test (Mann 1945, Kendall 1975). It is then suggested that the changes in the vorticity in the sensitive regions in the decadal scale are very likely to be the major reason for the interdecadal variations in the annual TC genesis frequency over the two ocean basins.

Note that the decrease in vorticity in the sensitive regions may be a result of the interdecadal variation in the SST since a link between the interdecadal SST variations and the anti-cyclonic anomalies in the southeastern part of the WNP ocean basin has been addressed in previous studies (Wang et al 2013, Hsu et al 2014, Zhan et al 2014, He et al 2015, Zhao et al 2018a). From the first to the second period in this study, the increased zonal SST gradient may cause a low-level anti-cyclonic anomaly over the central North Pacific, acting to suppress the generation of TCs in the sensitive regions.

The monthly variations in the vorticity in the sensitive region of the WNP and the SP ocean basins are shown in figure 10. It is clearly seen that the vorticity takes relatively small values during the peak seasons of TC genesis in both the WNP and the SP ocean basins, and takes relatively large values during
the post-peak season in the WNP ocean basin and during the pre-peak season in the SP ocean basin. This may explain why the post-peak season in the WNP ocean basin and the pre-peak season in the SP ocean basin are the sensitive seasons in terms of the interdecadal variation in TC genesis. In particular, the significant decrease in the vorticity from the first to the second period within the whole period of the present study in the sensitive region during October to December must be a very important factor in reducing the possibility of TC genesis events during the post-peak season in the WNP ocean basin and the pre-peak season in the SP ocean basin.

The important role of the vorticity in TC genesis during October to December has also been reported in previous studies (Camargo et al 2007, Hsu et al 2014). It was found that the low-level cyclonic vorticities tend to shift southward and play the dominant role in TC genesis in the low-latitude region of the WNP ocean basin during this season (Molinari and Vollaro 2013). Weakening of these vorticities due to increased anti-cyclonic anomaly in the sensitive regions during October to December thus leads to a significant decrease in the TC genesis frequency. Meanwhile, it has been suggested that the increased vertical shear is generally responsible for the
decrease in TC genesis in the peak season in the WNP ocean basin (Wang and Chan 2002, Liu and Chan 2013). However, the contribution of the increased vertical shear to the variation in TC genesis frequency during October to December is relatively less important compared to the decreased vorticity.

4. ITY genesis frequency

In contrast to the decrease in the total TC genesis frequency, the ITY genesis frequency experienced an increase from the first (1979–1998) to the second period (1999–2018) during the whole period of our study, as shown in figure 11. Note that the total number of ITY genesis events in the SP ocean basin may not be enough to ensure a statistically reliable result. Therefore, our discussions on ITYs are mainly referred to those observed in the WNP ocean basin. It may be necessary to point out that the increase in ITY genesis frequency in the WNP ocean basin has been reported in a number of previous studies (Webster et al 2005, Elsner et al 2008). Note that the opposite trends for the ITYs and the total TCs implies that more TCs tend to develop into ITYs over the WNP ocean basin in recent decades. It may also be necessary to emphasize that the occurrence of an ITY depends not only on its generation but also on an intensification process. Therefore, genesis of an ITY in this study
actually refers to the initial formation of a TC that undergoes an intensification process afterwards.

The monthly variations in ITY genesis and ITY genesis difference between the two periods within the whole period of our study are shown in figure 12. It is evident that a significant decrease in the ITY genesis occurred in the post-peak season (October–December) of TC genesis in the WNP ocean basin, as a consequence of the total decrease in TC genesis. This is supported by Hsu et al. (2014) who paid attention to the abrupt decrease in TY genesis over the WNP ocean basin during the post-peak season in 1995. It is also obvious that a significant increase in the ITY genesis exists during the peak season (July–September) and the pre-peak season (April–June) of TC genesis. The increased number of ITYS during the peak season and the pre-peak season surpasses the decrease during the post-peak season and results in a net increase in the ITY genesis frequency. This is supported by Tu et al. (2011) who pointed out an increase in the very intense TCs \( V_{\text{max}} \geq 113 \text{ kt} \) over the WNP ocean basin during the pre-peak season.

The spatial distribution of ITY genesis density and the difference in ITY genesis density between the two periods within the whole period of our study is presented in figure 13. A noticeable increase in the region at the eastern side of the Philippine Islands \( (10^\circ–20^\circ N, 120^\circ E–150^\circ E) \) and a decrease in the sensitive region in the WNP then become obvious. It implies that more TCs, which are generated at the western side of the WNP and geographically have less opportunities to be intensified, actually developed into ITYS in recent decades.

In figure 14, the zonal distribution of the difference in ITY genesis and the difference in its proportion to the relevant number of the total TC genesis is compared with the difference in the SST. High similarity among these distributions suggests that the variation in ITY genesis frequency in the WNP ocean basin is mainly caused by a change in the La Niña-like sea surface warming pattern.

It is now reasonable to link the trend of ITY genesis in the two recent decades to the anomaly of the La Niña-like SST pattern over the WNP ocean basin. The increased zonal SST gradient causes a decrease in atmospheric vorticity over the central North Pacific, acting to suppress TC genesis in the eastern part of the WNP ocean basin, which leads to a proportional decrease in the ITY genesis. This is also supported by results from ensemble simulations (Hsu et al. 2014). On the other hand, the increased SST creates a thermodynamic environment at the western part of the WNP that is favorable for not only TC genesis but also the subsequent development into ITYS.
While the SST level has been suggested to be the most important factor controlling the total TC number within a particular ocean basin in a long-term trend in previous studies (Holland and Bruyère 2014, Done et al 2015), our results indicate that the SST change pattern is an important indicator for regional ITY genesis. By the way, ITYs generated over the WNP ocean basin should be paid some special attention because they have a much higher probability to hit East and Southeast Asian countries (Park et al 2014, Zhan et al 2017).

5. Conclusions

This study focused on the interdecadal variability of TC genesis frequency and its relation with the relevant environmental factors in the WNP and SP ocean basins. It is clearly demonstrated that TC genesis in both the WNP and the SP ocean basins experienced a rapid decrease near the end of the 20th century. The decreased occurrence of TC genesis during the recent decades mainly lies in the low-latitude regions, with a longitude range of 20–30° west of 180°, which are defined as the sensitive regions in this study. It is found that, in addition to a significant decrease during the peak season, the decrease during October to December, i.e. the post-peak season in the WNP ocean basin and the pre-peak season in the SP ocean basin, made a very important contribution. It is demonstrated that the interdecadal variations in TC genesis in the WNP and the SP ocean basins are directly related to the variations in the atmospheric vorticity.

In contrast to the decrease in the total TC genesis frequency, the ITY genesis frequency experienced an interdecadal increase from the first period to the second period within the whole period of our study, especially in the WNP ocean basins. It was demonstrated that there is a significant increase in the ITY genesis in the WNP ocean basin during the peak season (July–September) and the pre-peak season (April–June), which surpasses the decrease during the post-peak season. The zonal distribution of the difference in ITY genesis between the two periods within the whole period of the present study is very similar to the difference in SST. It is then suggested that the variation in ITY genesis frequency in the WNP ocean basin is caused by a change in the La Niña-like sea surface warming pattern, which is also supported by results from ensemble simulations in Hsu et al (2014).
Figure 14. Zonal variations in the difference in the ITY proportion (black circles) and in the ITY number (blue dots) between different periods (the second period minus the first period), with zonal variations in the difference in SST (red dots) in the WNP.

It is worthwhile pointing out that the mechanism for the formation of the La Niña-like SST difference pattern does not seem to be clarified yet. There are studies to link it to the phenomena of Pacific Decadal Oscillation (Meehl et al 2013). Takahashi et al (2017) argued that sulfate aerosol forcing is the major contributor to the La Niña-like SST difference pattern, while Kucharski et al (2011) considered that the warming phase of Atlantic SSTs induces a La Niña-like response by rising the sinking motion and easterly surface wind anomalies in the tropical Pacific. To predict the future trend of TC genesis frequency, however, a better understanding of the La Niña-like SST difference process may be essential.

Acknowledgment
This research is supported by the National Natural Science Foundation of China (NSFC) under Grant No. 11732008.

Data availability
The data that support the findings of this study are all openly available on the NOAA websites. In particular, the tropical cyclone genesis data are available at https://www.ncdc.noaa.gov/ibtracs/index.php?name=ib-v4-access; the sea surface temperature data are available at http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.v5.html; and the reanalysis data of RH920, θ⁸⁵₀, and ΔV are available at https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.pressure.html.

ORCID iDs
Kaiyue Shan https://orcid.org/0000-0002-8013-6850
Xiping Yu https://orcid.org/0000-0003-2867-9660

References
Afifi A A and Azen S P 1972 Statistical Analysis: A Computer Oriented Approach (New York: Academic Press, Harcourt Brace Jovananich Publishers)
Bruyère C L, Holland G J and Towler E 2012 Investigating the use of a genesis potential index for tropical cyclones in the North Atlantic basin J. Clim. 25 8611–26
Camargo S J, Emanuel K A and Sobel A H 2007 Use of a genesis potential index to diagnose ENSO effects on tropical cyclone genesis J. Clim. 20 4819–34
Chan J C L 2000 Tropical cyclone activity over the western North Pacific associated with El Niño and La Niña events J. Clim. 13 2960–72
Chand S S and Walsh K J 2009 Tropical cyclone activity in the Fiji region: spatial patterns and relationship to large-scale circulation J. Clim. 22 3877–93
Chu P S and Zhao X 2004 Bayesian change-point analysis of tropical cyclone activity: the central North Pacific case J. Clim. 17 4893–901
Chu P S and Zhao X 2011 Bayesian analysis for extreme climatic events: a review Atmos. Res. 102 243–62
Done J M, Holland G J, Bruyère C L, Leung L R and Suzuki-Parker A 2015 Modeling high-impact weather and climate: lessons from a tropical cyclone perspective Clim. Change 129 381–95
Elsner J B, Kossin J P and Jagger T H 2008 The increasing intensity of the strongest tropical cyclones Nature 455 92–95
Emanuel K and Nolan O S 2004 Tropical cyclone activity and the global climate system Proc. 26th Conf. Hurricanes and Tropical Meteorology (American Meteorological Society) pp 240–1.
Gray W M 1967 Global View of the Origin of Tropical Disturbances and Storms (Colorado State University, Department of Atmospheric Science).
Gray W M 1979 Hurricanes: their formation, structure and likely role in the tropical circulation. Meteorology Over the Tropical Oceans (Berkshire: Royal Meteorological Society)
He H, Yang J, Gong D, Mao R, Wang Y and Gao M 2015 Decadal changes in tropical cyclone activity over the western North Pacific in the late 1990s Clim. Dyn. 45 3317–29
Holland G and Bruyère C L 2014 Recent intense hurricane response to global climate change Clim. Dyn. 42 617–27
Hsu P, Chu P, Murakami H and Zhao X 2014 An abrupt decrease in the late-season typhoon activity over the Western North Pacific J. Clim. 27 4296–312
Hu E, Li T, Liu J, Bi M and Peng M 2018 Decrease of tropical cyclone genesis frequency in the western North Pacific since 1960s Dyn. Atmos. Oceans 81 42–50
Huang B, Thorne P W, Banzon V F, Boyer T, Chepurin G, Lawrimore J H, Menne M J, Smith T M, Vose R S and Zhang
