Enhanced understanding of poleward migration of tropical cyclone genesis

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Abstract

The known trends of poleward migration for the tropical cyclone (TC) genesis in both hemispheres are discussed from different perspectives. It is shown that the poleward migration rate of the annually averaged latitude of TC genesis in the Northern Hemisphere is significantly affected by the regional variations of TC number in recent decades, especially an increase in the North Atlantic Ocean and a decrease in the western North Pacific Ocean. The poleward migration rates of TC genesis in the two hemispheres get closer when the effect of the regional TC number variation is excluded. The poleward migration of TC genesis without the effect of regional TC number variation is found to have a good correlation with the poleward shift of the edges of the tropics in both hemispheres. A decreasing trend of the cyclonic vorticity in the lower-troposphere over the tropical ocean regions is also identified in both hemispheres, which leads to a poleward shift of the equatorward boundary for TC genesis. The poleward migration of TC genesis after the effect of regional TC number variation is excluded and can thus be considered as a result of the tropical expansion. It is shown that the genesis of TCs with a different intensity has a different migration rate. When excluding the effect of the regional TC number variation, the poleward migration of TCs with a different intensity has a similar trend in both hemispheres. The tropical storms and intense typhoons have significant poleward migration trends, while the weak typhoons behave differently.

1. Introduction

In recent years, scientists have noticed a globally statistical trend of poleward migration for tropical cyclone (TC) activities in recent decades (Kossin et al 2014, Daloz and Camargo 2018). It was demonstrated that the geographical locations at which TCs experience their lifetime-maximum intensities (LMIs) have a clear tendency to shift towards the poles in both hemispheres (Kossin et al 2014). The trend identified may have a direct impact on the high-latitude coastal regions considering an increased level of risk of being subjected to TC disasters (Kossin et al 2016). A major concern of the policy makers in these regions is hence how far such a migration trend would go. For a satisfactory answer, it is then important to understand the physics underlying the trend.

Intuitively, the statistical trend of poleward shift for TC LMIs can be the result of a relevant shift of the TC genesis or a spatial variation of the intensification factors, or both combined. In fact, a poleward migration trend of the TC genesis has already been discussed (Daloz and Camargo 2018, Sharmila and Walsh 2018). Although the migration rate of TC genesis was shown to be somewhat faster than that of the TC LMI in the Northern Hemisphere (NH) (Studholme and Gulev 2018), we are almost sure that the poleward shift of the TC LMI is essentially contributed by the migration of TC genesis. This contribution is further ensured if we pay attention to the fact that the annually averaged latitudinal difference between the LMI and the genesis locations of TCs does not have a long-term trend of change.

Only limited studies on the physical mechanism that drives the poleward migration of TC activities have been conducted. According to Sharmila and Walsh (2018), the poleward migration of TC genesis may be related to a particular variation of the Hadley
circulation. It was found that the anomalous weakening of the rising branch of the Hadley circulation at the upper level probably suppressed TC genesis in the low latitudes, but caused a poleward displacement of the favorable climate conditions for TC genesis.

Previous studies showed that TCs with different intensities may have a very different contribution to the statistical results of the poleward shift of TC activities. In the western North Pacific (WNP) Ocean basin, the tropical storms (TCs with relatively low intensities) are found to be very influential in determining the entire poleward migration rate of TC LMI compared to a much less significant role of the typhoons (TCs with relatively high intensities) (Zhan and Wang 2017). It is also known that intense-typhoon genesis tended to appear at tropical latitudes south of 20°N in both the North Atlantic (NA) and WNP Ocean basins (Kossin et al 2010, Zhao et al 2014), while weaker TCs have a tendency to form further north and west.

It may be a reasonable assumption that part of the poleward migration of TC activities is contributed by a long-term temporal evolution of the climate system, while the other part is a cumulated effect of the spatial variation of the environmental factors that affect TC genesis. The former part may be a direct impact of such phenomena as global warming and is likely to be irreversible in a geological time scale. The latter part may be more possibly an indirect result of the climate change and is essentially of a decadal or multi-decadal time scale. Since reliable data for global TC events have been available only in recent decades (Knapp and Kruk 2009), it is still difficult to distinguish multi-decadal or even decadal variations from the long-term variation straightforwardly based on a statistical analysis.

In the present study, the trends of poleward migration for the global TC genesis in both hemispheres are discussed from different perspectives. The effect of the TC number variations in different ocean basins, which are considered as decadal phenomena, is investigated in detail. The remaining part of the poleward migration of TC genesis is more likely to be a direct impact of global warming. Note that there really are reports on the important role of the regional TC number variation in the poleward migration of TC LMI (Moon et al 2015, Wang et al 2016). Contributions to the poleward migration by TCs with a different intensity are also discussed in this study.

2. Data and methods

TC genesis data used in this study are derived from the International Best Track Archive for Climate Stewardship (IBTrACS) v04 (Knapp et al 2010). IBTrACS is a data set that integrates best track data from professional meteorological institutions and TC warning centers around the world. Due to the questionable quality of data in the pre-satellite era, this study only uses records during the period 1979–2018. TC genesis is simply defined as the first occurrence of an event. We focus mainly on TCs with their lifetime maximum sustained wind speed equal to or greater than 55 kt. Based on the Saffir–Simpson scale, TCs are classified into tropical storms (35 kt ≤ V_m ≤ 63 kt), weak typhoons (64 kt ≤ V_m ≤ 95 kt) and intense typhoons (V_m ≥ 96 kt), where V_m denotes the lifetime maximum sustained wind speed of a TC. Statistical information on the geneses of TCs with different intensities is summarized in table 1.

Ocean basins where TCs occur include WNP, NA, eastern North Pacific (ENP), North Indian (NI) in the NH, as well as South Pacific (SP), South Indian (SI) and South Atlantic (SA) in the Southern Hemisphere (SH). Statistical information on the TC geneses in each ocean basin is summarized in table 2.

Monthly mean data for the outgoing longwave radiation (OLR) at the top of the atmosphere (F_top) with a horizontal resolution of 0.25°×0.25° during 1979–2018 are available from the fifth generation of ECMWF atmospheric reanalyses of the global climate (ERA 5 Reanalysis) (Malarde et al 2015). Note that the latitude with a prescribed high value of F_top may be used to determine the edge of tropics (Hu and Fu 2007). Monthly mean reanalysis data for the cyclonic vorticity at 850 hPa (ζ_850) with a horizontal resolution of 2.5°×2.5° during 1979–2018 are available from National Centers for Environmental Prediction and National Center for Atmospheric Research (NECP-NCAR) (Kalnay et al 1996). ζ_850 represents a combined effect of the Coriolis parameter and the relative vorticity in the lower troposphere, which is often used to interpret the long-term variation of TC genesis (Gray 1998). The Nino-3.4 index, which is defined as the monthly averaged sea surface temperature (SST) anomaly in the region bounded by 5°N–5°S and 170°W–120°W (Bamston et al 1997), is adopted as an indicator of El Niño/Southern Oscillation (ENSO).

The contribution of regional TC number variations to the poleward migration of TC genesis can be estimated following the method of Moon et al (2015). Therefore, we decompose the latitude of any TC genesis (Gray 2010) into three components:

\[ \psi = \bar{\psi} + \psi' + \psi'' \]  

where \( \bar{\psi} \) is the averaged latitude of all TC genuses that occurred in a hemisphere during the period from 1979–2018; \( \psi' \) is the deviation from \( \bar{\psi} \) of the averaged latitude of all TC genuses in the ocean basin concerned, also during the period from 1979–2018; \( \psi'' \) is the deviated latitude of an individual TC genesis from \( \bar{\psi} + \psi' \). If the annual numbers of TC genuses in a particular ocean basin and in the entire hemisphere are denoted by \( m \) and \( M \), respectively, the contribution of the regional TC number variation to the annually
Table 1. Statistical information on the TCs with different intensities during the period 1979–2018.

|                | NH            | SH            |
|----------------|---------------|---------------|
|                | Tropical storm| Weak typhoon  | Intense typhoon| Total |
| Number of TC events | 1003          | 636           | 645           | 2284  |
| Range of TC geneses | [1.8°N–46.0°N] | [1.3°N–44.0°N] | [0.1°N–31.8°N] | [0.1°N–46.0°N] |
| Mean position of TC geneses | 15.3°N       | 14.7°N       | 11.7°N       | 14.1°N |
|                | [3°S–33.6°S]  | [2.5°S–34.7°S] | [2.8°S–23.1°S] | [2.5°S–34.7°S] |
|                | 12.5°S        | 12.0°S        | 11.0°S        | 11.9°S  |
Table 2. Statistical information on the TC genese in each ocean basin during the period 1979–2018.

|                | NH          |               |               |               | SH          |               |               |               |
|----------------|-------------|---------------|---------------|---------------|-------------|---------------|---------------|---------------|
|                | WNP         | NA            | ENP           | NI            | Total       | SP            | SI            | SA            |
| Number of TC events | 1008        | 472           | 612           | 192           | 2284        | 393           | 604           | 2             | 999          |
| Range of TC genese | [0.1°N–31.3°N] | [7.2°N–46.0°N] | [1.9°N–29.5°N] | [1.6°N–22.0°N] | [0.1°N–46.0°N] | [3.2°S–27°S] | [2.5°S–34.7°S] | –             | [2.5°S–34.7°S] |
| Mean position of TC genese | 12.5°N | 20.3°N        | 13.0°N        | 11.3°N        | 14.1°N      | 13.0°S        | 11.3°S        | –             | 11.9°S       |
averaged latitude of TC genesis in a hemisphere can then be described by,
\[
\tilde{\psi}_1 = \frac{1}{M} \sum \left( \psi \times m \right),
\]
where the summation is taken over all ocean basins in the relevant hemisphere. Note that \( M = \sum m \). The remaining part of the annual variation of the latitude of TC genesis in the hemisphere is thus,
\[
\tilde{\psi}_2 = \frac{1}{M} \sum \left( \psi'' \times m \right),
\]
where the tilde stands for annual average. Note that the long-term trend of \( \tilde{\psi}_1 + \tilde{\psi}_2 \) yields the poleward migration of TC genesis. The trend of \( \tilde{\psi}_1 \) is the contribution of TC number variation in each ocean basin. Since the TC number variation in each ocean basin is widely recognized as a decadal or multi-decadal phenomenon, the trend of \( \tilde{\psi}_1 \) is likely to be a cumulated effect of the spatial variation of the environmental factors that affect TC genesis and is indirectly related to the global climate change. Because \( \tilde{\psi}_1 \) is separated, the trend of \( \tilde{\psi}_2 \), which is a measure of the poleward migration rate in the hemispherical scale after a dominant part representing decadal and multi-decadal effects is excluded, should thus be more possibly caused by such factors as global warming and is more likely to be irreversible in a geological time scale.

3. Poleward migration of TC genesis due to different mechanisms

Shown in figure 1 are the variations of the annually averaged TC genesis latitude in both hemispheres over the period from 1979–2018. The significant trends of the poleward migration for TC genesis are shown to be indisputable both in the NH and in the SH, with the mean migration rates being 0.63° and 0.32° per decade, respectively, at a significance level of 95%. Similar trends were also reported by Studholme and Gulev (2018), but with a mean migration rate of 0.40° per decade in the NH. It is necessary to point out that the mean migration rate of TC genesis may vary significantly if the period of the data record differs. In fact, the mean migration rate of the LMI in the NH was found to be 0.48° and 0.47° per decade in the studies of Kossin et al (2014) and Moon et al (2015), respectively, who covered the period 1982–2012. However, the same variable takes a value of 0.10° per decade in the study of Studholme and Gulev (2018), who extended the duration to 1981–2016. Such a great variation of the mean migration rate with the period of data record implies that the effect of factors with multiannual to multi-decadal scales should be separated in order to achieve a better understanding of the physics behind the poleward migration of TC genesis.

In figures 2 (a) and (b), the contributions of the regional TC number variation to the poleward migration of TC genesis in both hemispheres are presented. It is shown that the regional TC number variation causes the annually averaged latitude of TC genesis to drift towards the pole at a mean rate of 0.22° per decade in the NH, but its effect is negligibly small in the SH. The remaining part of the poleward migration rate of TC genesis is thus 0.41° per decade in the NH and 0.33° per decade in the SH, both with a significance level of 95%, as shown in figures 2 (c) and (d). Note that the poleward migration rates in the NH and in the SH get closer after the effect of the regional TC number variation is separated, implying that they are more likely to be directly caused by such common factors as global warming.

It is not difficult to understand the notable effect of the regional number variation on the trend of the poleward migration of TC genesis, noting that clear trends of increasing in the NA and decreasing in the WNP of TC events have been confirmed in recent decades (Landsea et al 2010, Maue 2011). Since the mean latitude of TC genesis in the NA is located much more poleward than the mean latitude in the whole NH, as shown in table 2, the increasing trend of TC number in the NA is actually a very important factor responsible for the poleward migration of the averaged TC genesis. The decreasing trend of TC activities in the WNP was first pointed out by Maue (2011). Shan and Yu (2020) further identified that decreasing of TC genesis in the WNP mainly occurs in a sensitive low-latitude region at the eastern side of the ocean basin. This decreasing trend of TC genesis in the tropic region then necessarily contributes to the poleward migration of the mean location. In the SP, Shan and Yu (2020) showed that the main development region of TCs is a narrow-banded belt parallel to the equator. The effect of the regional number variation on the poleward migration of TC genesis is thus small.

Most of the previous studies confirmed that the variation of TC genesis frequency in a particular ocean basin is essentially a phenomenon of inter-decadal scale. It was claimed that the La Niña-like SST pattern in the tropical Pacific, is probably related to the variation of TC frequency in the WNP and the NA (Kucharski et al 2011, Lin and Chan 2015, He et al 2015). The interrelated variation of TC frequency in the WNP and the NA was found to be a direct result of the Pacific Decadal Oscillation (PDO), which is of an interdecadal scale, through modifying atmospheric circulation patterns (Maue 2009, Zhao et al 2018, Johnson et al 2020, Tu et al 2020).

ENSO has been reported to have an effect on the location of TC genesis (Camargo et al 2007). It may thus be necessary to clarify whether ENSO also has an effect on the poleward migration trend of TC genesis. Following the method adopted by previous authors (Kossin et al 2014, Moon et al 2015, Wang and Liu 2016, Houk et al 2020), a regression analysis can be carried out to establish the relationships between the
annually mean latitude of TC genesis and an indicator of ENSO in both the NH and SH. Then, the effect of ENSO on the trend of the poleward migration of TC genesis may be identified following a residual analysis. Note that the indicator of ENSO in this study is defined by averaging the monthly values of the Nino-3.4 index during the active TC season (i.e. July to September in the NH and January to March in the SH). The variations of the annually averaged latitude of TC genesis in the two hemispheres with the effect of ENSO excluded are obtained, as shown in figure 3. It is found that the mean migration rates change only slightly in both hemispheres when the ENSO effect is removed (the migration rate changes from 0.63° to 0.65° per decade in the NH and from 0.32° to 0.27° per decade in the SH). Considering that the statistical result is less accurate in the SH due to a much smaller number of TC genesis, it may be concluded that ENSO plays an insignificant role in the poleward migration trend of TC genesis. This conclusion is also in agreement with the previous result on the poleward migration of TC LMI (Kossin et al 2014, Moon et al 2015).

A similar analysis is also carried out to study the effect of PDO on the poleward migration trend of TC genesis in the NH. Namely, a residual analysis is performed to identify the effect of PDO on the poleward migration trend of TC genesis based on a regression relation between the annually mean latitude of TC genesis and an indicator of PDO. It can be shown that the poleward migration rate of TC genesis in the NH is reduced to 0.40° per decade when excluding the effect of PDO. Not surprisingly, this value coincides with the migration rate of TC genesis after removing the effect of regional TC number variation, which is 0.41° per decade in the NH. It is simply confirmed that the effect of the regional TC number variation is nearly equivalent to the effect of PDO. In fact, the regional TC number variation in the NH is dominated by a significant decrease in WNP and a significant increase in NA, which has been reported to be mainly governed by PDO (Zhao et al 2018, Johnson et al 2020, Tu et al., 2020).

In this study, we believe that the poleward migration of TC genesis without the effect of regional number variation is more directly related to global
warming, since this part of the poleward migration of TC genesis is closely related to the phenomenon of tropical expansion. Following Hu and Fu (2007), we define the edges of the tropics by the tropical boundaries of the high OLR belt regions with $I_{\text{top}} \geq 260 \text{ W m}^{-2}$, where $I_{\text{top}}$ refers to the mean value of OLR at the top of the atmosphere in the month when TC activities are most concentrated. The high OLR belt regions are known to be the result of dryness and lack of clouds in these regions due to subtropical descending motion at the subsidence branch of the Hadley circulation (Staten et al 2018). In figure 4, the averaged latitudes of the edges of tropics in the month when TC activities are most concentrated, i.e. August and February in the NH and SH, respectively, are clearly demonstrated to have a poleward shift trend. More importantly, this trend of poleward shift shows a very good correlation with that for the poleward migration of TC genesis without the effect of regional number variation in the NH and SH. The correlation coefficient is 0.60 and 0.48 in the NH and SH, respectively. This fact provides direct evidence of the probable link between the poleward migration of TC genesis and the tropical expansion in recent decades, which was inferred in the previous studies (Kossin et al 2014, Sharmila and Walsh 2018).

The close correlation between the tropical expansion and poleward migration of TC genesis may also
be identified by observing the poleward shift of the equatorward boundary of TC genesis identified both in the NH and SH (Lucas et al 2014, Staten et al 2018). Since TCs are known to be rarely created in the tropical oceans due to a minimum level of the cyclonic vorticity in the atmospheric flow over there, equatorward boundaries of TC genesis certainly exist in both hemispheres. Figure 5 shows that hardly any TC genesis is observed in the tropical region limited by $\xi_{850} = 2.0 \times 10^{-5} \text{ s}^{-1}$ throughout the month when TC activities are most concentrated, i.e. August and February in the NH and SH, respectively, indicating that equatorward boundaries of TC genesis may be defined by a threshold value of $\xi_{850}$. The annually averaged location of the equatorward boundary of TC genesis in a hemisphere, however, may also be statistically defined by the 0.1 quantiles of the TC genesis latitude observed within the year. In figure 6, annual variations of the statistically defined equatorward boundary of TC genesis are presented. A tendency of poleward shift is evident.

In figure 6, variations of the annually averaged values of the cyclonic vorticity $\xi_{850}$ over the tropical ocean regions in the NH (0–10°N) and SH (0–10°S; west of 160°W) and over the active seasons (i.e. July to September in the NH and January to March in the SH), are also plotted. A decreasing trend of $\xi_{850}$ is observed in both hemispheres. This implies not only a good correlation between the equatorward boundary of TC genesis and the value of $\xi_{850}$ in the tropical ocean regions, but a tropical expansion in recent decades. Note that a smaller decreasing rate of the annually averaged values of $\xi_{850}$ in the tropical regions of the SH is probably related to the relatively mild variation of $\xi_{850}$ in the horizontal direction of the tropical oceans. There are many studies supporting the idea that the decreasing trend of the cyclonic vorticity over the tropical ocean regions is related to the tropical expansion (Lucas et al 2014, Xiang et al 2014, Sharmila and Walsh 2018). This is because an increased atmospheric stability accompanied by the tropical expansion, which is responsible for the decreased cyclonic vorticity at the low-level troposphere, has been observed.

Quite a number of previous studies tried to estimate the rate of tropical expansion in recent decades. Although different values have been reported because of a variety in definition and in source of data (Lucas et al 2014, Staten et al 2018), the rates of the tropical expansion are often believed to lie in the range of 0.3°–0.5° per decade both in the NH and SH (Zhou et al 2011, Allen et al 2012, Lucas et al 2012). This magnitude of expansion rate is actually in fairly good agreement with the mean poleward migration.
rate of TC genesis with the effect of regional number variation excluded. Note that the tropical expansion leads to a significant poleward shift of large-scale atmospheric circulation systems (Seidel et al. 2008, Lucas et al. 2014), which finally causes an overall shift of TC activities in the whole hemisphere. Current theories and modeling results indicate that the global warming associated with anthropogenic greenhouse gas emissions and stratospheric ozone depletion is the most likely cause of the tropical expansion in recent decades (Reichler 2009, Dai 2011, Staten et al. 2018). According to the simulation with global climate models, the tropical expansion would continue as a consequence of anthropogenic climate change in the future (Amaya et al. 2018).

4. Poleward migration for genesis of TCs with different intensities

The genesis locations of all TCs with different intensities, i.e. the genesis locations of the tropical storms, weak typhoons and intense typhoons, during the period from 1979–2018, are plotted in figure 7. It can be seen that, in a general sense, the geneses of intense typhoons are much closer to the equator than the tropical storms and weak typhoons. This trend
Figure 6. Variations of the 0.1 quantiles of the genesis latitude (squares) (a) in the NH, (b) in the SH during 1979–2018 as well as the variations of $\xi_{850}$ (circles) at the low latitudes ($0^\circ - 10^\circ$ N in the NH, $0^\circ - 10^\circ$ S, $0^\circ - 160^\circ$ W in the SH) during the same period. Linear trends are shown (dashed lines).

becomes more significant in the NH, where the mean latitude of genesis for the intense typhoons is $11.7^\circ$ N and those for the tropical storms and weak typhoons are approximately $15.0^\circ$ N, as shown in table 1. In addition, the latitudinal range of the intense typhoon genuses is much narrower. We also investigated the averaged latitude difference between the genesis and LMI locations for TCs of different intensity. It is found that the weak typhoons require almost the same latitudinal span to reach their LMI as the intense typhoons, about $7.5^\circ$ in the NH and $6.1^\circ$ in the SH, respectively.

Figure 8 shows the variations of the annually averaged genesis latitudes of the tropical storms, weak typhoons and intense typhoons in the NH (figures 8(a)–(c)) and SH (figures 8(d)–(f)) during the period 1979–2018. It is demonstrated that the genesis location of the tropical storms has the most significant trend of poleward migration, with mean rates of $0.87^\circ$ and $0.50^\circ$ per decade in the NH and SH, respectively, at the significance level of 95%. It is thus clear that the tropical storms play a major role in the poleward migration of TC genesis in general, which agrees with the results obtained for the mean latitude of LMI (Zhan and Wang 2017). What must be emphasized in this study is that the genesis location of the intense typhoons in the NH also has a very significant poleward migration trend, with a mean rate of $0.67^\circ$ per decade at the significance level of 95%. Since it is the intense typhoons that largely affect the hazard exposure and mortality risk in coastal communities, special attention should be given to the migration trend of the intense typhoons as well as the physics behind the trend.

The contributions of the regional TC number variation to the poleward migration of genesis for TCs with a different intensity during the period 1979–2018 are also examined. It is found that the averaged migration rates for the genesis frequency of TCs with a different intensity will decrease by about $0.1^\circ$ to $0.2^\circ$ per decade in the NH when the effect of the regional TC number variation is excluded. In the SH, however, the results are more scattered, probably because the relevant number of TCs is not large enough to ensure a statistically meaningful estimation. When removing the effect of the regional number variation, the remaining part of the poleward migration rate for TCs with a different intensity is presented in figure 9.

In general, it can be seen that the poleward migration rate decreases against the intensity for relatively weak TCs, while the trend is the opposite for relatively intense TCs both in the NH and SH. It is also indicated that when the effect of regional TC number variation is excluded, the poleward migration of TCs with a different intensity has a much similar trend in the NH and SH, i.e. the tropical storms and intense
Figure 7. Locations of TC genuses with different intensities.
typhoons have significant poleward migration trends while the weak typhoons behave somehow differently. In fact, the poleward migration rates of the tropical storms are $0.68^\circ$ and $0.31^\circ$ per decade in the NH and SH, respectively; while the poleward migration rates of the intense typhoons are $0.56^\circ$ and $0.55^\circ$ per decade in the NH and SH, respectively. All these rates are guaranteed with a significance level of 95%. On the other hand, the weak typhoons only have a very insignificant trend of poleward migration both in the NH and SH.

To further explore the phenomenon of poleward migration trend for TCs with different intensity, latitudinal distributions of the genesis frequencies as well as the mean rates of the annual number variation for the tropical storms, weak typhoons and intense typhoons are plotted in figure 10. It is then found that the distribution patterns of the genesis frequencies for TCs with a different intensity are similar (figures 10(a), (b) and (c)) but the distribution patterns of the mean rates of the annual number variation are rather different between those for the weak typhoons (figure 10(e)) and those for the tropical storms as well as the intense typhoons (figures 10(d) and (f)). The positive mean rates of the annual number variation at high latitude in addition to the negative mean at low latitude for the tropical storms and intense typhoons finally yield the significant poleward trends of their genuses, as shown in figure 9.

5. Conclusion

The poleward migration trends of the annually averaged latitude of global TC genesis in both hemispheres are investigated in this study. In order to achieve a better understanding of the physics behind the phenomena, the contribution of the regional TC number variation to the trends is separated. It is
found that the regional TC number variation does affect the poleward migration rate of TC genesis in the NH. Since the mean latitude of TC genesis in the NA is located much more poleward and the mean latitude of the TC genesis in the sensitive region of the WNP is located rather equatorward, relative to the mean latitude of TC genesis in the whole NH, the increasing trend of TC number in the NA and decreasing trend in the WNP are responsible, to a significant extent, for the poleward migration of the averaged TC genesis in recent decades. By removing the effect of the regional TC number variation, the remaining part of the poleward migration of TC genesis in the NH and SH get closer. The remaining part of the poleward migration of TC genesis is demonstrated to have a good correlation with the poleward shift of the edges of tropics in the NH and SH, with a correlation coefficient of 0.60 and 0.48, respectively. In addition, a decreasing trend of the cyclonic vorticity in the lower-troposphere over the tropical ocean regions is also observed in both hemispheres, which leads to a poleward shift of the equatorward boundary of TC genesis. These facts directly support the link between the tropical expansion and poleward migration of TC genesis without the effect of regional TC number variation in recent decades.

The poleward migration trends for TCs with a different intensity are also studied. The tropical storms are shown to have very significant poleward trends both in the NH and SH. The intense typhoons in the NH are also found to have a significant poleward migration trend. When excluding the effect of the regional TC number variation, the poleward migration of TCs with a different intensity has a much similar trend in the NH and SH. The tropical storms and intense typhoons have significant poleward migration trends while the weak typhoons behave differently. The positive mean rates of the annual number variation at high latitude in addition to the negative mean rates at low latitude for the tropical storms and intense typhoons are closely related to the significant poleward trends of their geneses.

The important contribution of this study is that the poleward migration of TC genesis is systematically shown to include a part which is mainly related to the decadal and multi-decadal phenomena that occurred as a consequence of climate change and a part which is more likely to be a direct consequence of global warming. Relatively strong evidence is provided for the link between the latter part and the tropical expansion. It is also identified that TCs with a different intensity have a different migration rate, i.e. the tropical storms and intense typhoons have significant poleward migration trends while the weak typhoons behave differently.
Figure 10. Latitudinal distributions of genesis frequencies of (a) tropical storm, (b) weak typhoon and (c) intense typhoon and mean rates of annual number variation for (d) tropical storm, (e) weak typhoon and (f) intense typhoon during 1979–2018. Dots represent the migration trend at a significance level of 95% while circles represent the insignificant migration trend.

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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://ncdc.noaa.gov/ibtracs/index.php?name=ibv4-access.

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