



## RESEARCH LETTER

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## Key Points:

- The latitude where a storm reaches peak intensity is separated into two linear parts to investigate their different contributions
- Interdecadal fluctuation of annual average tropical cyclone genesis latitude is linked to the Interdecadal Pacific Oscillation
- Long-term increase of the annual mean distance from genesis to peak intensity is likely due to increasing sea surface temperatures

## Supporting Information:

- Supporting Information S1

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## What Has Controlled the Poleward Migration of Annual Averaged Location of Tropical Cyclone Lifetime Maximum Intensity Over the Western North Pacific Since 1961?

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**Abstract** The long-term tendency of the average latitude at which tropical cyclones (TCs) reach their lifetime maximum intensity (LMI) over the western North Pacific (WNP) is investigated in this study. Despite the post-1961 significant poleward shift in the annual mean LMI latitude, the migration rate is nonuniform on decadal timescales, having an insignificant trend and a significant increasing trend before and after 1980, respectively. Interdecadal fluctuations of TC genesis latitude ( $\varphi_G$ ) as well as increases in latitudinal distance between genesis position and LMI location ( $\Delta\varphi$ ) are both responsible for the observed LMI latitude trends. The former is linked to the Interdecadal Pacific Oscillation (IPO), which favors TCs forming in the northwestern (southeastern) quadrant of the WNP in negative (positive) IPO phases. The latter primarily results from the continuous warming of WNP sea surface temperature, which further increases the maximum potential intensity and extends the region favorable for TC development to higher latitudes.

### 1. Introduction

Increasing attention has been paid to long-term trends in tropical cyclone (TC) activity over the global oceans during the past few decades (Knutson et al., 2010; Walsh et al., 2016). Kossin et al. (2014) has recently proposed a new climatological TC activity indicator by computing the annual averaged latitudinal location where TCs reached their lifetime maximum intensity (LMI). They found that this metric has more consistency and less uncertainty in various storm data sources than other metrics. They also reported a global poleward migration of TC LMI latitude ( $\varphi_{LMI}$ ) between 1982 and 2009, which was further linked to notable changes in the large-scale environment of TCs associated with tropical expansion (Kossin et al., 2014). Kossin et al. (2014) argued that the poleward shift of global TC  $\varphi_{LMI}$  could be regulated by both intrabasin and interbasin changes in TC activity. After quantifying different contributions, Kossin et al. (2014) further indicated that the global TC  $\varphi_{LMI}$  trend was dominated by the intrabasin poleward migration of LMI. However, Moon et al. (2015) found that for the Northern Hemisphere, the vast majority (92%) of the increasing  $\varphi_{LMI}$  tendency resulted from basin-to-basin TC frequency changes.

Despite controversy on the drivers of the global TC  $\varphi_{LMI}$  trend, both studies found that there was a significant poleward tendency of  $\varphi_{LMI}$  over the western North Pacific (WNP). This poleward migration rate of  $\varphi_{LMI}$  in the WNP was much larger than those found in other basins (Kossin et al., 2014; Moon et al., 2015) and was consistent with the northward shift of storm surge over the WNP after the 1980s (Oey & Chou, 2016). The northward  $\varphi_{LMI}$  tendency over the past several decades was reproduced by using an ensemble of numerical Coupled Model Intercomparison Project Phase 5 (CMIP5) models (Kossin et al., 2016), which also indicated a continuing poleward migration into the future following the emission projections of the representative concentration pathway 8.5 (RCP8.5).

Several papers have investigated the potential contributors to the poleward shift of WNP TC  $\varphi_{LMI}$ . Daloz and Camargo (2017) showed that due to a northward migration of favorable environmental conditions, TC genesis moved toward higher latitudes from 1980 to 2013, which further resulted in the northward shift of  $\varphi_{LMI}$ . In addition, Zhan and Wang (2017) demonstrated that the  $\varphi_{LMI}$  variation of weak TCs (with LMI lower than  $33 \text{ m s}^{-1}$ ) was the dominant factor contributing to the poleward  $\varphi_{LMI}$  shift of WNP TCs since 1980.

Most  $\varphi_{\text{LMI}}$ -related publications have focused on the period since the early 1980s. This time span, which is only around 30 years in length, may be too short to distinguish long-term trends from interdecadal variations (Chan, 2006). Decadal oscillations, e.g., the Interdecadal Pacific Oscillation (IPO) or the Pacific Decadal Oscillation (PDO), which exert significant influence on the interdecadal variability of WNP TC activity (e.g., Lee et al., 2012; Liu & Chan, 2008; Matsuura et al., 2003; Maue, 2011; Yumoto & Matsuura, 2001), possibly modulate the fluctuation of TC  $\varphi_{\text{LMI}}$  over the WNP. Kossin et al. (2016) investigated  $\varphi_{\text{LMI}}$  variations in different best track data sets since as early as 1945 and noted that the long-term trend of  $\varphi_{\text{LMI}}$  was somewhat reduced when the analyzed period was extended back to the middle of the last century. This varying trend in the poleward migration rate of  $\varphi_{\text{LMI}}$  can be attributed to interdecadal variability of the large-scale environments influencing storm activity. For instance, Kossin et al. (2016) indicated that the warm and cool PDO phases were related to the southward and northward shifts of  $\varphi_{\text{LMI}}$ , respectively. However, how the PDO controls the meridional displacement of  $\varphi_{\text{LMI}}$  needs further investigation. In response to these questions, this study investigates changes of WNP TC  $\varphi_{\text{LMI}}$  as well as its contributors from 1961 to 2016. Year 1961 was chosen as the starting year for three reasons. The first is that the Television Infrared Observation Satellite began monitoring in 1960, and consequently, since that time, TCs have been continuously observed (Lee et al., 2012; Liu & Chan, 2013). The second is that reconnaissance aircrafts were frequently used to detect TC formations since 1960 (Joint Typhoon Warning Center (JTWC), 1960). The third is that four agencies, including the Joint Typhoon Warning Center (JTWC), Japan Meteorological Agency (JMA), China Meteorological Administration (CMA), and Hong Kong Observatory (HKO), provide continuous TC best track data from 1961 to present. The rest of the paper is organized as follows. Section 2 describes the data and methodology used. The decadal variation of WNP TC  $\varphi_{\text{LMI}}$  and its contributors are examined in section 3. The paper concludes with a summary and discussion in section 4.

## 2. Data and Methodology

The JTWC best track data of WNP TCs between 1961 and 2016 used in this study are from the International Best Track Archive for Climate Stewardship project (v03r10; Knapp et al., 2010), including 6-hourly storm positions and intensities. In order to reduce the uncertainty among data sources and enhance the robustness of the results, only TCs simultaneously recorded in the JTWC, JMA, CMA, and HKO data sets are considered here. The  $\varphi_{\text{LMI}}$  is defined as the latitude where LMI is first reached (Kossin et al., 2014, 2016). The  $\varphi_{\text{LMI}}$  is insensitive to the temporally evolving techniques utilized to estimate the storm absolute intensity, and it was found to be of reasonable quality when the period is extended back to the presatellite era (Kossin et al., 2016).

In this study,  $\varphi_{\text{LMI}}$  can be decomposed into

$$\varphi_{\text{LMI}} = \varphi_{\text{G}} + \Delta\varphi = \varphi_{\text{G}} + V_{\varphi} \times \Delta t. \quad (1)$$

Here  $\varphi_{\text{G}}$  is the latitude of the genesis location, while  $\Delta\varphi$  and  $\Delta t$  are the latitudinal distance and the duration between storm formation and LMI, respectively.  $V_{\varphi}$  equals the proportion of  $\Delta\varphi$  to  $\Delta t$ , which indicates the mean latitudinal translational speed when the storm is undergoing intensification.

There are two primary methods that have been used in the past to define TC formation. One approach considers the initial position in the best track file as the storm genesis point (e.g., Lee et al., 2008; Ritchie & Holland, 1999). Due to the discrepancy in the length of the TC track from different best track data sets (Kruk et al., 2010), the reliability of  $\varphi_{\text{G}}$  is reduced by interagency heterogeneity in the first recorded TC location. The other method defines storm genesis when the TC maximum sustained wind first exceeds a threshold, such as  $17 \text{ m s}^{-1}$  (e.g., Yokoi et al., 2013) or  $20 \text{ m s}^{-1}$  (e.g., Daloz & Camargo, 2017). The reliability of  $\varphi_{\text{G}}$  relies on the quality of the estimated storm absolute intensity. There exists significant uncertainty in  $\varphi_{\text{G}}$  in the presatellite era because of problematic intensity estimating techniques.

To overcome the aforementioned shortcomings of both techniques, TC formation in this study refers to the first record that is simultaneously listed by all four agencies. Two reasons are given here to illustrate the reliability of this definition. First, prior to 1987, WNP TCs were routinely monitored by aircraft reconnaissance (Martin & Gray, 1993). Unlike the vast majority of TC intensity estimates, which were done indirectly, the central positions of storms were directly observed by aircraft radar (JTWC, 1962), which markedly improved the quality of  $\varphi_{\text{G}}$  from the presatellite best track data. Second, it is of great value to compare TC tracks from

various agencies before analysis (Chu et al., 2002). The consistency in multiple best track data sets can promote the robustness and reliability of  $\varphi_G$ . Kossin et al. (2016) made similar arguments for  $\varphi_{LMI}$ . In addition, although the operational observations of WNP TCs in the presatellite era were less frequent during the night than the day, there does not exist significant difference between daytime and nighttime  $\varphi_G$  or  $\varphi_{LMI}$  (Figure S1 in the supporting information). This means that the results in our study are not significantly influenced by the issue of detection frequency.

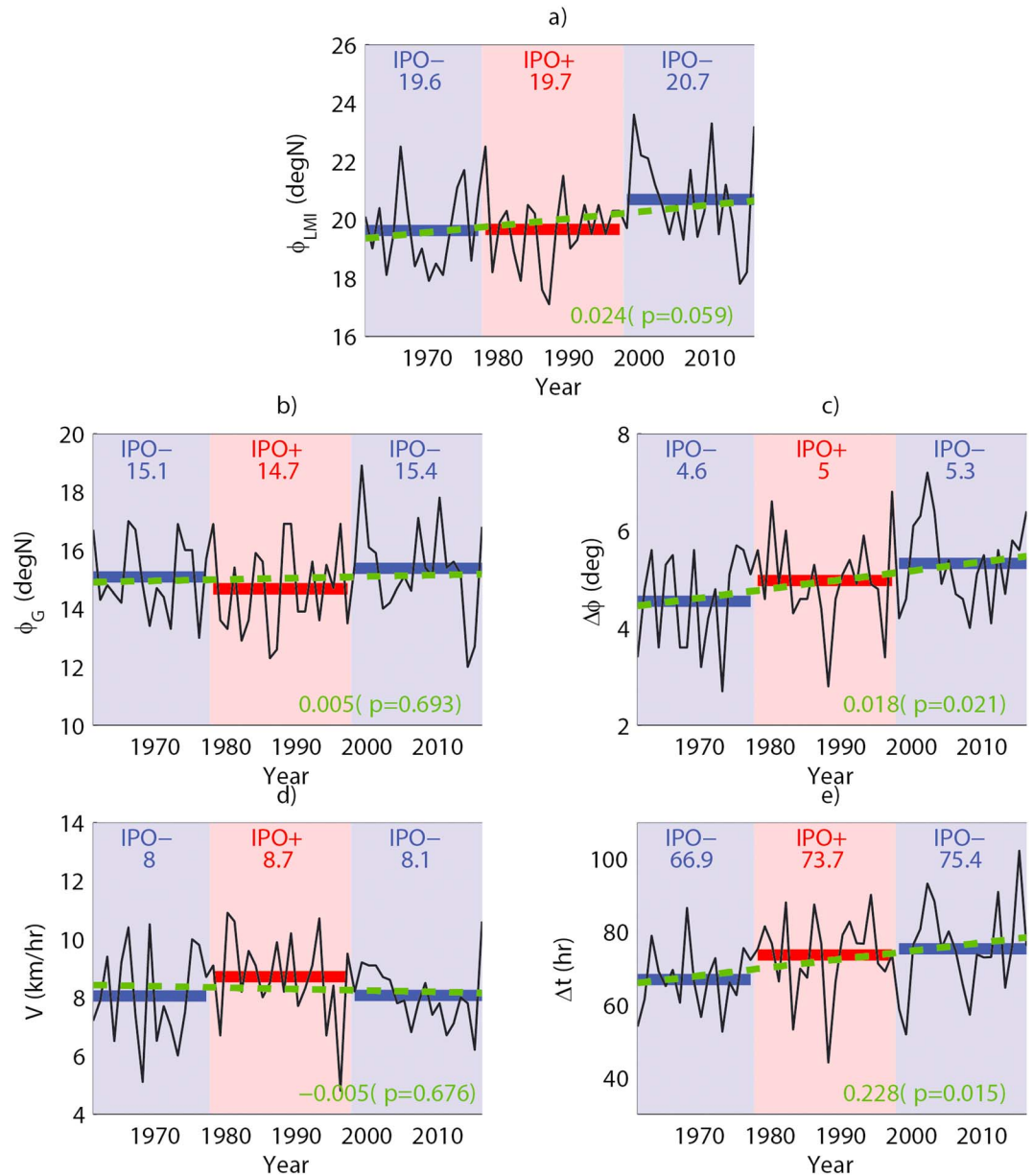
Monthly mean sea surface temperature (SST) data are obtained from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST V4 (Huang et al., 2014), with a horizontal resolution of  $2^\circ \times 2^\circ$ . Monthly mean atmospheric data are provided by the National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis over a  $2.5^\circ \times 2.5^\circ$  grid (Kalnay et al., 1996), which are interpolated to a  $2^\circ \times 2^\circ$  resolution for computing the maximum potential intensity (MPI) of TCs (Emanuel, 1988). Unlike Kossin et al. (2016) and Zhan and Wang (2017), oceanic and atmospheric fields are calculated as annual averages in this study. Annual averages of several monthly indices are also applied to discuss the relationship between  $\varphi_{LMI}$  and climate modes, including the Niño-3.4 SST and the PDO index provided by the NOAA's Earth System Research Laboratory Physical Sciences Division (Mantua et al., 1997; Rayner et al., 2003) and the Tripole Index for the IPO (TPI) (Henley et al., 2015).

### 3. Results

#### 3.1. Nonuniform Increase of $\varphi_{LMI}$ From 1961 to 2016

Figure 1a displays the annual variation of WNP TC  $\varphi_{LMI}$  over the period from 1961 to 2016. There exists a poleward  $\varphi_{LMI}$  trend of  $0.24^\circ$  latitude decade<sup>-1</sup> (statistically significant at the 0.05 level based on an *F* test), indicating a notable northward shift of TC LMI location since 1961. Note that this rate is much smaller than that documented in previous publications (Daloz & Camargo, 2017; Kossin et al., 2014; Moon et al., 2015; Zhan & Wang, 2017), which only analyzed  $\varphi_{LMI}$  trends since the early 1980s. This raw trend is comparable to the 1945–2013  $\varphi_{LMI}$  tendency of  $0.21^\circ$  latitude decade<sup>-1</sup> after removing the influences of El Niño–Southern Oscillation (ENSO) and PDO found by Kossin et al. (2016). Consistent with Kossin et al. (2016), the poleward migration rate of  $\varphi_{LMI}$  is not uniform over the past 56 years. No significant trend in  $\varphi_{LMI}$  is found before 1980, with a linear trend of only  $0.03^\circ$  latitude decade<sup>-1</sup> between 1961 and 1979. The poleward migration rate of  $\varphi_{LMI}$  increases markedly to  $0.51^\circ$  latitude decade<sup>-1</sup> from 1980 to 2016, which is significant at the 0.01 level based on an *F* test. This rate is similar to what was found in Zhan and Wang (2017).

To investigate the interdecadal behavior of  $\varphi_{LMI}$  in detail, the full study period is divided into three subperiods (1961–1977, 1978–1997, and 1998–2016) based on the filtered TPI, which identifies different IPO phases (Figure 1a). In the first two subperiods (1961–1997), the average  $\varphi_{LMI}$  are similar ( $19.6^\circ\text{N}$  and  $19.7^\circ\text{N}$  for 1961–1977 and 1978–1997, respectively) despite being in opposite IPO phases, which further leads to an insignificant  $\varphi_{LMI}$  tendency during these 37 years ( $0.06^\circ$  latitude decade<sup>-1</sup>). In contrast, the mean  $\varphi_{LMI}$  increases to  $20.7^\circ\text{N}$  during the last subperiod (1998–2016), which represents a marked difference from the averaged  $\varphi_{LMI}$  in the previous negative IPO phase (1961–1977). Note that our result is different from Kossin et al. (2016), which linked the decadal behavior of  $\varphi_{LMI}$  to the PDO (IPO). Kossin et al. (2016) indicated that the cool (warm) PDO phase was related to northward (southward)  $\varphi_{LMI}$  migration. However, the correlation between the filtered TPI and  $\varphi_{LMI}$  is  $-0.09$ , which is not significant at the 0.05 level based on a Student's *t* test. To explain this difference, the relationship between  $\varphi_{LMI}$  and several indices are discussed below in detail. During the period from 1961 to 2016, significant correlations are found between  $\varphi_{LMI}$  and the Niño-3.4 SST ( $-0.35$ ), the PDO index ( $-0.20$ ), and the unfiltered TPI ( $-0.35$ ), which indicates that the  $\varphi_{LMI}$  change is notably influenced by ENSO and PDO (IPO) variability on interannual timescales. Nonetheless, the insignificant relationship between  $\varphi_{LMI}$  and the filtered TPI means that there is not a strong relationship between  $\varphi_{LMI}$  and PDO (IPO) on decadal timescales. This is further confirmed by the results of the cross-spectrum analysis (Figure S2), which estimates significant correlations between  $\varphi_{LMI}$  and the Niño-3.4 SST, the PDO index, and the unfiltered TPI only at periods of around 5 years. Besides obtaining differing relationships based on different timescales investigated, another reason for differences in results between Kossin et al. (2016) and our study may be due to different data sources used and time periods investigated. The  $\varphi_{LMI}$  from TCs simultaneously recorded by all four agencies is considered here, which is slightly different from all the TCs analyzed in Kossin et al. (2016). In addition, the annual averaged TPI is applied to describe the PDO (IPO) phenomenon,

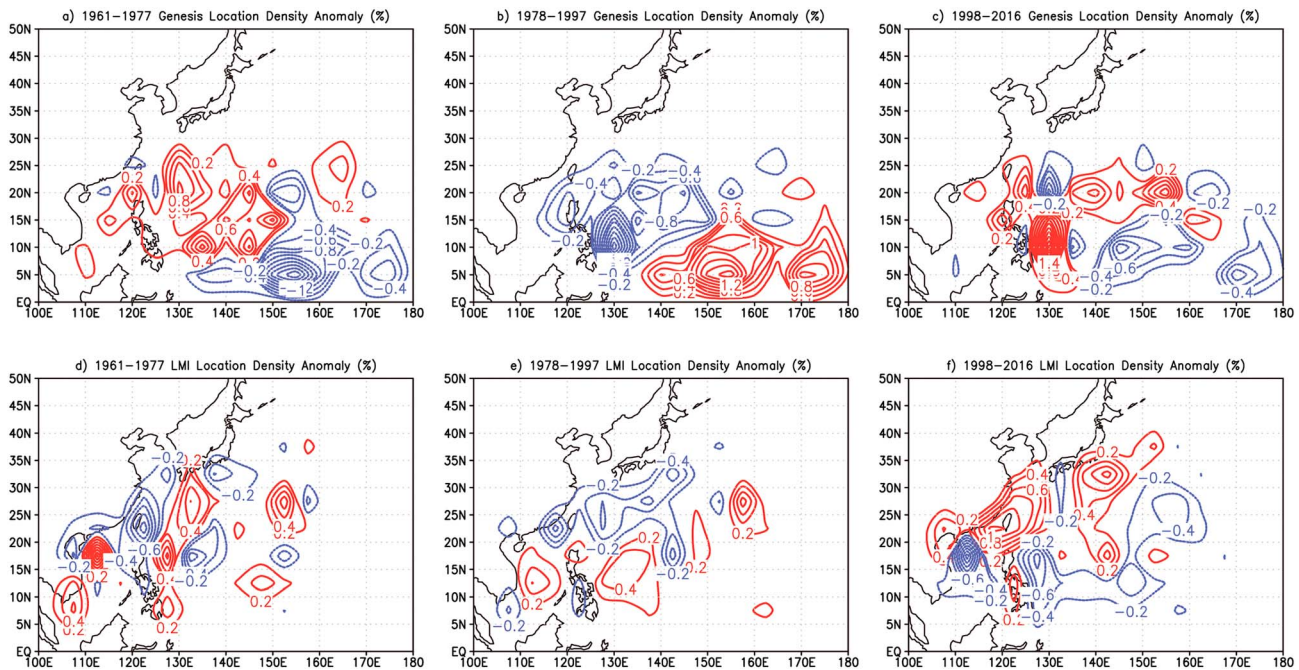


**Figure 1.** Time series (black solid lines) of annual mean (a)  $\phi_{LMI}$ , (b)  $\phi_G$ , (c)  $\Delta\phi$ , (d)  $V_\varphi$ , and (e)  $\Delta t$  of TCs over the WNP from 1961 to 2016. The horizontal red and blue solid lines refer to the averages in positive and negative IPO phases, respectively. Linear trends are displayed with green dashed lines. The rate of the linear trend and confidence level are displayed in the bottom right of each panel.

compared with the seasonal (July–November) averaged PDO index from NOAA’s Earth System Research Laboratory Physical Sciences Division (Mantua et al., 1997) used by Kossin et al. (2016). In the following sections, we examine interdecadal variations of  $\phi_G$  and  $\Delta\phi$ , since the  $\phi_{LMI}$  is simply the linear combination of these two quantities.

**3.2. Interdecadal Fluctuation of  $\phi_G$**

Figure 1b represents the annual variation of WNP TC  $\phi_G$  from 1961 to 2016. We find that the  $\phi_G$  tends to be at lower latitudes in a positive IPO phase than in a negative IPO phase. The  $\phi_G$  averaged 14.7°N from 1978 to 1997, which is 0.4° and 0.7° lower than the  $\phi_G$  averaged from 1961 to 1977 and 1998 to 2016, respectively. The anomalies of TC genesis frequency density in different IPO phases are further illustrated in Figures 2a–2c.



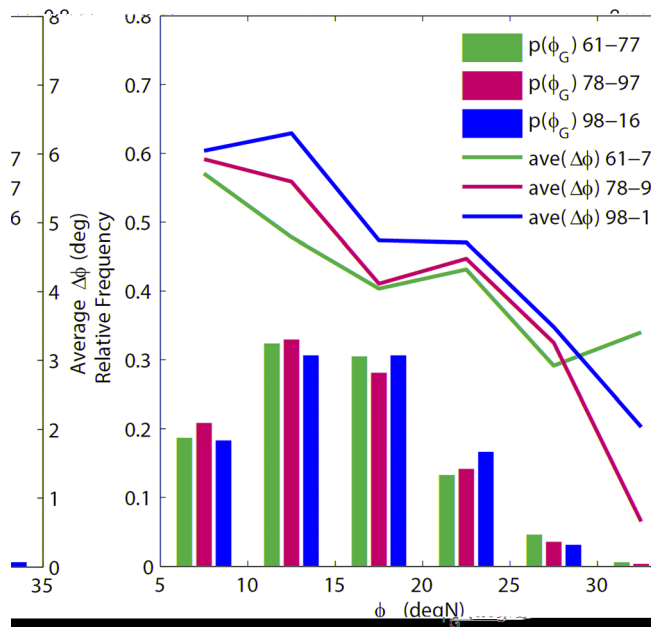
**Figure 2.** Density anomalies (unit: %) of (a–c) TC genesis location and (d–f) TC LMI position over a  $5^\circ \times 5^\circ$  grid in different IPO phases, including 1961–1977 (Figures 2a and 2d), 1978–1997 (Figures 2b and 2e), and 1998–2016 (Figures 2c and 2f). The red and blue contours represent positive and negative anomalies, respectively.

In general, TCs form more northwest (southeast) in the negative (positive) IPO phase. The primary reason is related to the interaction between the IPO and the El Niño–Southern Oscillation (ENSO). More La Niña (El Niño) events occur in the negative (positive) IPO phase (Newman et al., 2016), which tends to induce more TC occurrences in the northwestern (southeastern) quadrant of the WNP (Camargo et al., 2007; Chan, 2000).

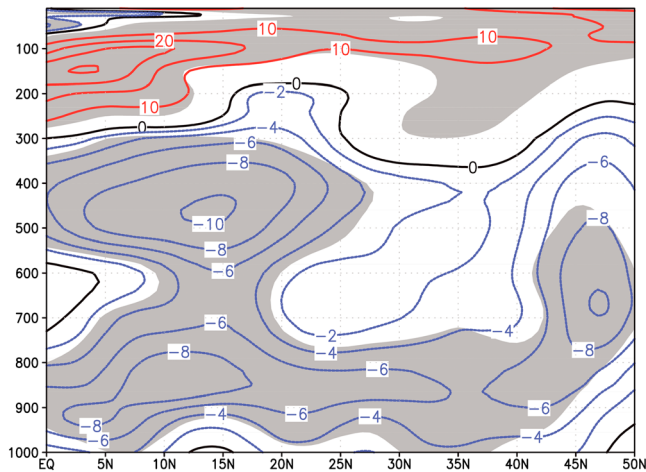
In addition, after removing the influence of ENSO, there are ENSO-like spatial signatures between different IPO phases not only in the SST field (Zhang et al., 1997) but also in the atmospheric circulation (Aiyyer & Thorncroft, 2011), which further support the observed northwest-southeast shift of TC formation (Liu & Chan, 2013).

Due to the shift of TC genesis location in different IPO phases, the linear trend in  $\phi_G$  from 1961 to 2016 is insignificant, with a rate of  $0.05^\circ$  latitude decade<sup>-1</sup> (Figure 1b). This rate is much less than the rate of  $\phi_G$  indicated by Daloz and Camargo (2017), who considered the shorter period of 1980–2013. We find that an interdecadal oscillation fits the  $\phi_G$  variation better than a linear trend does. There was a general decrease in  $\phi_G$  from the 1960s to the 1980s and a general increase since that time.

The inconsistency between features of  $\phi_{LMI}$  and  $\phi_G$  is represented in both the temporal variation (Figures 1a and 1b) as well as in the spatial distribution (Figure 2). The migration of LMI location should be greatly influenced by the shift of genesis position, with the premise being that a storm forming further north reaches its LMI at a higher latitude (Daloz & Camargo, 2017). With the shift of genesis position, the LMI location should on average migrate to the northwest (southeast) in the negative (positive) IPO phases, which can be confirmed in the last two IPO phases (1978–2016; Figures 2e and 2f). This statement does not hold true during 1961–1977, however, as there is no clear latitudinal separation between positive and negative LMI location density anomalies (Figure 2d). This implies that the movement of LMI location is not solely determined by the change in genesis position.



**Figure 3.** Relative frequencies (bars) and averages of  $\Delta\phi$  (lines) for storms forming in each  $5^\circ$  latitudinal band during different IPO phases. The blue, green, and red indicate the periods of 1961–1977, 1978–1997, and 1998–2016, respectively.



**Figure 4.** Linear trend ( $\times 10^{-2} \text{ m s}^{-1} \text{ decade}^{-1}$ ) of the meridional wind averaged between  $100^\circ\text{E}$  and  $180^\circ$  for 1961–2016. Positive and negative tendencies are represented by red and blue lines, respectively. Trends significant at the 0.05 level based on the  $F$  test are shaded.

### 3.3. Long-Term Uniform Increase of $\Delta\phi$

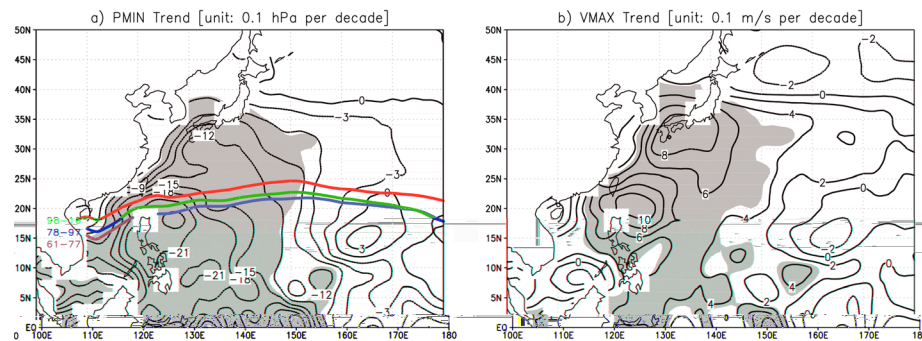
Unlike the interdecadal fluctuation of  $\phi_G$ , there is a long-term increasing trend of  $\Delta\phi$  of  $0.18^\circ \text{ latitude decade}^{-1}$  between 1961 and 2016, which is significant at the 0.05 level based on an  $F$  test (Figure 1c). The averages of  $\Delta\phi$  are  $4.6^\circ$ ,  $5.0^\circ$ , and  $5.3^\circ$  in 1961–1977, 1977–1997, and 1998–2016, respectively. Figure 3 further shows the differences of mean  $\Delta\phi$  categorized by the  $\phi_G$  into each  $5^\circ$  latitudinal band during the three subperiods, in order to remove the influence of the genesis frequency difference. In general,  $\Delta\phi$  tends to decrease with increasing  $\phi_G$ . The observed  $\Delta\phi$  increase occurs in almost all latitudinal bands from the first subperiod to the last one, except in the  $30^\circ\text{N}$ – $35^\circ\text{N}$  belt, which has a relatively small number of observed TC formations (Figure 3). This means that the increase of  $\Delta\phi$  occurs for TCs forming in various latitudinal bins in the WNP.

The  $\Delta\phi$  increase impacts  $\phi_{\text{LMI}}$  variations in several different ways. First, the fact that the  $\phi_{\text{LMI}}$  in the latter negative IPO phase (1998–2016) is much larger than that in the former negative IPO phase (1961–1977) is predominately a result of the upward trend in  $\Delta\phi$ . Second, the increasing tendency of  $\Delta\phi$  is balanced by the decreasing trend of  $\phi_G$  before

1980, which results in an insignificant trend in  $\phi_{\text{LMI}}$ . By contrast, the significant poleward shift of  $\phi_{\text{LMI}}$  since the early 1980s is attributed to upward trends in both  $\phi_G$  and  $\Delta\phi$ . Furthermore, the long-term variation of  $\Delta\phi$  dominates that of  $\phi_{\text{LMI}}$  over the period of 1961–2016, explaining 75% ( $0.18^\circ \text{ latitude decade}^{-1} / 0.24^\circ \text{ latitude decade}^{-1}$ ) of the  $\phi_{\text{LMI}}$  linear trend.

To evaluate what caused the change of  $\Delta\phi$ , the variations of  $V_\phi$  and  $\Delta t$  from 1961 to 2016 are presented in Figures 1d and 1e. There is a slight decreasing trend of  $V_\phi$  during 1961–2016, with a rate of  $-0.05 \text{ km h}^{-1} \text{ decade}^{-1}$  (Figure 1d). Note that the tendency of  $\Delta\phi$  is opposite to that of  $V_\phi$ , which means that the former is not positively correlated with the latter. Figure 4 displays the linear trend of annual mean meridional winds averaged between  $100^\circ\text{E}$  and  $180^\circ$  from 1961 to 2016. The weakened northerlies and southerlies are separated at around 300 hPa, respectively. There is a significant downward tendency of southerlies from the surface to 300 hPa in the tropical WNP ( $0$ – $30^\circ\text{N}$ ), with two maxima at around 450 hPa and 850 hPa (Figure 4). Over the subtropical WNP ( $30^\circ\text{N}$ – $45^\circ\text{N}$ ), decreasing southerlies are found at lower levels (Figure 4). Through averaging meridional winds from 925 hPa to 300 hPa (Wu et al., 2003; Yang et al., 2008), the northward steering flow of WNP TCs decreases at a rate of  $-0.15 \text{ km h}^{-1} \text{ decade}^{-1}$ , which is larger than the downward trend of  $V_\phi$  but has the same sign. Since the motion of a TC is primarily determined by its surrounding environmental flow (Holland, 1983; Roy & Kovordanyi, 2012), the decrease of  $\Delta\phi$  is largely modulated by the decelerating northward steering current over the WNP. Moreover, the decreasing environmental flow can be linked to the intensification of the Northern Hemisphere Hadley cell (Liu et al., 2012; Mitas & Clement, 2005; Nguyen et al., 2013) and the attenuation of the East Asian summer monsoon (Tanaka et al., 2004; Yu et al., 2004; Zhou et al., 2009), which can lead to both northerly (southerly) wind anomalies at lower (upper) levels.

The means of  $\Delta t$  are 66.9 h, 73.7 h, and 75.4 h in 1961–1977, 1977–1997, and 1998–2016, respectively (Figure 1f). This indicates an increasing trend of  $\Delta t$  between 1961 and 2016, with a value of  $2.3 \text{ h decade}^{-1}$  (statistically significant at the 0.05 level based on  $F$  test). This trend is consistent with the increasing lifetime of WNP TCs in recent decades (Emanuel, 2007; Webster et al., 2005; Wu et al., 2008). Because the  $\Delta t$  refers to the time span between genesis and LMI, this represents the duration of TC intensification. Figure 5 shows the 1961–2016 trend of the TC maximum potential intensity (MPI) (Bister & Emanuel, 1998; Emanuel, 1988) over the WNP. In the western region of the WNP (west of  $150^\circ\text{E}$ ), there are significant increasing trends in MPI ranging from  $-1.1 \text{ hPa decade}^{-1}$  to  $-2.4 \text{ hPa decade}^{-1}$  (Figure 5a) and  $0.6 \text{ m/s decade}^{-1}$  to  $1.0 \text{ m/s decade}^{-1}$  (Figure 5b), which is consistent with the continuous warming of the tropical WNP SST during the last century (Cravatte et al., 2009; Deser et al., 2010). The region favorable for TC development and intensification has therefore been enlarged from 1961 to 2016, which means that storms can undergo intensification over a longer time period. Hart and Evans (2001) applied the 960 hPa MPI contour as the northern boundary at which purely tropical development is no longer possible. From 1961–1977 to 1998–2016, the 960 hPa MPI



**Figure 5.** Linear trends for annual averages of the monthly MPI calculated from oceanic and atmospheric fields between 1961 and 2016. (a and b) The MPI trends in terms of minimum sea level pressure and maximum sustained wind, respectively. Areas with tendencies significant at the 0.05 level based on the  $F$  test are shaded. In Figure 5a, the blue, green, and red lines denote the 960 hPa MPI contours in 1961–1977, 1978–1997, and 1998–2016, respectively.

contour shifted approximately  $3^\circ$  northward (Figure 5a). This poleward migration of the 960 hPa MPI contour confirms the extended area for TC intensification. The extended region for TC intensification that is induced by the WNP SST warming first allows more time for the TC to reach its LMI, then causes the increasing latitudinal distance between the TC genesis position and LMI location, and finally contributes to the poleward shift of  $\phi_{LMI}$ .

#### 4. Summary and Discussion

In this study, long-term tendencies of WNP TC  $\phi_{LMI}$  and its components ( $\phi_G$ ,  $\Delta\phi$ ,  $V_{\phi}$ , and  $\Delta t$ ) are examined from 1961 to 2016. Although there is a notable poleward shift of annual mean  $\phi_{LMI}$  since 1961, the poleward migration rate is much smaller than those studies examining trends since  $\sim 1980$  (Daloz & Camargo, 2017; Kossin et al., 2014; Moon et al., 2015; Zhan & Wang, 2017). These differences in results occur due to there being little trend in  $\phi_{LMI}$  prior to 1980. The nonuniform increase of  $\phi_{LMI}$  is jointly influenced by interdecadal fluctuation of  $\phi_G$  and a persistent increase of  $\Delta\phi$  during 1961–2016. The effect of the upward  $\Delta\phi$  on the  $\phi_{LMI}$  change before 1980 is counteracted by the decreasing  $\phi_G$  due to the IPO phase shifting from negative to positive. In contrast, the poleward migration rate of  $\phi_{LMI}$  is amplified over the most recent three decades when the IPO phase changes from positive to negative, due to the increasing trends in both  $\phi_G$  and  $\Delta\phi$ . Moreover, the increasing  $\Delta\phi$  between 1961 and 2016 is caused by a continuous increase of  $\Delta t$ , which measures the duration of storm intensification. Because of the steady warming of WNP SST during the past few decades, the region favorable for TC development has been enlarged, and its northern boundary is shifting poleward. Consequently, WNP TCs are more likely to begin weakening at higher latitudes, which further leads to their LMI location shifting poleward.

Kossin et al. (2016) documented a predicted continued poleward migration of WNP TC  $\phi_{LMI}$  due to continued anthropogenic forcing throughout the 21st century. Given the contribution of  $\Delta\phi$  to  $\phi_{LMI}$  identified in this study, one possible primary reason is the continued extension of the distance between storm genesis point and LMI position over the next several decades, which is primarily linked to SST warming and the increase of MPI over the WNP predicted by both phase 3 of the Coupled Model Intercomparison Project (CMIP3) as well as CMIP5 (Camargo, 2013; Emanuel, 2013; Wu et al., 2014). In addition, Kossin et al. (2016) represented a reduced poleward migration of  $\phi_{LMI}$  in the 21th-century RCP8.5 projection, for WNP TCs both explicitly generated within the CMIP5 models and downscaled from CMIP5 model output. We further argue that this slowdown in the poleward migration rate of  $\phi_{LMI}$  may result from a projected transition to a positive IPO phase in the immediate future (Meehl et al., 2016; Thoma et al., 2015).

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