Have steering flows in the western North Pacific and the South China Sea changed over the last 50 years?

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[1] Long-term trends in steering flows over the western North Pacific (WNP) and the South China Sea (SCS) are examined during the peak typhoon season. A nonparametric and robust trend detection method is employed. Both the NCEP and ERA reanalysis data sets suggest a statistically significant decreasing trend in steering flows in the subtropical region of the western WNP (between 120°E or near Taiwan and 145°E) and the northern SCS during 1958–2001. Over this period, the decrease in the WNP is quite large with a magnitude of 1.1 m s^{-1} given that the background mean steering flow is only 3.26 m s^{-1}. This decrease corresponds approximately to one third of the mean flow. When the data are extended from 1958 to 2009 the long-term decrease in steering flows in the aforementioned subtropical region are still significant, although more modest at a rate of 0.7 m s^{-1}. Time series of translational speeds averaged over the same subtropical region also exhibit a slow-down of storms' motion over the last 52 years. This is consistent with the weakening of easterly steering flows analyzed from independent data sets. Results of this study imply a longer life span for tropical cyclones and a greater tendency for storms along prevailing typhoon tracks to recurve. **Citation:** Chu, P.-S., J.-H. Kim, and Y. Ruan Chen (2012), Have steering flows in the western North Pacific and the South China Sea changed over the last 50 years?, *Geophys. Res. Lett.*, *39*, L10704, doi:10.1029/2012GL051709.

1. Introduction

[2] It is well known that tropical cyclone (TC) motion is mainly governed by the basic current, or steering flow, and a minor deviation from that steering flow due to the ß-effect [*Holland*, 1983; *Chan*, 2005]. Therefore, the effects of steering flow play a major role in determining TC motion and track. Along with storm intensity, the storm track is a major concern for society. The prevailing typhoon tracks in the western part of the western North Pacific (WNP) have undergone a pronounced shift over the last four decades. The subtropical East Asia has seen more typhoon activity while the South China Sea has experienced decreased storm frequency [*Wu et al.*, 2005]. *Wu et al.* [2005] suggest that changes in steering flow are responsible for this shift. Independently, *Tu et al.* [2009] found an abrupt northward shift of typhoon tracks over the WNP-East Asian (WNPEA) region since 2000. This northward shift of the typhoon track, namely, an increase of typhoon frequency north of 20°N and a decrease south of 20°N, tends to be associated with typhoon-enhancing environmental conditions over the WNPEA. Noticeable among them are the weakening and eastward retreat of the WNP subtropical high, the strengthening of the Asian summer monsoon trough, and enhanced positive vorticity anomalies in the lower troposphere.

[3] Future variations in typhoon tracks due to anthropogenic climate change were studied by *Wu and Wang* [2004]. They used a coarse-resolution coupled general circulation model (GCM) with the Intergovernmental Panel on Climate Change (IPCC) scenario forcing A2 and B2. The large-scale steering flow in the future state (i.e., 2000–2029 and 2030–2059) is calculated from the projected wind fields. Compared to the present-day climate, easterly steering anomalies dominate in the tropics while westerly anomalies prevail in the subtropics and midlatitudes in the future climate. More recently, *Murakami et al.* [2011] conducted a study to investigate future changes (2075–2099) in typhoon activity using a high resolution (20 km) global atmospheric model with A1B emission scenario. One of the major findings is the reduction of the frequency of typhoon occurrence in the future, which is attributable to changes in TC genesis locations and motions. Relative to the present-day (1979–2003), a reduced TC speed and weakened easterly steering flows in the tropics are noted in the future. The latter is different from *Wu and Wang* [2004].

[4] Using the Joint Typhoon Warning Center best-track records, *Chu et al.* [2010a] recently clustered historical TC tracks over the WNP into eight patterns based on a mixture Gaussian model [*Camargo et al.*, 2007]. Subsequently, the TC frequency, intensity, lifespan, and accumulated cyclone energy of each pattern are individually examined for temporal changes over the last 60 years. For storms' lifetime, it is noteworthy that the majority of these eight patterns exhibit an increasing level of storm days. Because large-scale circulation exerts a major influence on the movement of TCs, it is hypothesized that easterly steering flows over the WNP have become weaker, making storms traverse more slowly and thus increasing the lifespan of the storm. In the past, long-term variations between typhoon tracks and large-scale flows were studied [e.g., *Wu et al.*, 2005; *Tu et al.*, 2009]. However, rigorous statistical analysis has not yet been done to determine how steering flows in the WNP have changed. In this study, we use a robust trend detection method to investigate possible changes in steering currents over the WNP from two separate reanalysis data sets. Independently,

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we will also examine concurrent changes in storms' translational speed.

2. Data and Methods

[5] Horizontal winds at standard vertical levels are derived from the NCEP/NCAR [*Kalnay et al.*, 1996] and the ERA40 [*Uppala et al.*, 2005] reanalysis data, with a horizontal resolution of 2.5° latitude × 2.5° longitude. Steering flows are computed as the pressure-weighted tropospheric layer-mean flows from the 850 hPa to 300 hPa and are vertically integrated values. The steering flow of a TC was originally defined as an area-average vertically integrated wind around the storm [*Chan and Gray*, 1982]. To simplify the analysis, we computed the vertically integrated wind at discrete grid points of the reanalysis data, without following the storm. This simplified method is commonly used to represent the mean-state (seasonal or monthly mean) of the large-scale circulation to the overall TC translation, and is called large-scale steering flows [e.g., *Holland*, 1983; *Wu et al.*, 2005]. The total period of record is 1949–2009 for the NCEP/NCAR data set and 1958–2001 for ERA40. Due to the difference in the total period, the common period of 1958–2001 is first used to check the consistency in steering flows between these two data sets. Subsequently, the extended period until 2009 is used to show the steering flow speed and TC translation speed in the NCEP/NCAR reanalysis and TC best-track data sets.

[6] TC best-track data archived by the Regional Specialized Meteorological Center (RSMC) Tokyo-Typhoon Center are used to calculate the translation speed of TCs for all 6-hourly center positions (http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/RSMC_HP.htm). For comparison, TC translation speed from the Joint Typhoon Warning Center (JTWC) are also employed. To obtain a more reliable translation speed for each 6-hourly observed position, the traveling distance is computed using the spherical Law of Cosines, which yields the great circle distance between two points over a sphere. The translation speed values along all TC tracks are then binned into a 2.5° × 2.5 ° grid box each month to produce the monthly TC translation speed data. The derived translation speed data from the RSMC are almost identical if the other sources (e.g., JTWC, Hong Kong Obesrvatory, and Shanghai Typhoon Institute of China Meteorological Administration) are selected, ensuring the robustness of the result.

[7] The trends of the steering flows and translational speeds are estimated by the nonparametric Mann-Kendall test and Sen's method. The former tests whether the trend is increasing or decreasing and estimates the significance of the trend, while the latter quantifies the slope of the trend [e.g., *Chu et al.*, 2010b]. In contrast to the commonly used trend detection method by linear regression [e.g., *Chu and Wang*, 1997], the advantages of the Mann-Kendall and Sen's techniques used in this study are that the underlying data need not conform to any particular probability distribution and missing observations are allowed. Moreover, the Sen's method is robust against outliers and skewed distributions.

3. Results

[8] Before looking into the spatial distribution of the trends in steering flows, it is important to understand the climatological mean monthly flow patterns and the WNP subtropical high during the peak typhoon season, which usually runs from July through September [e.g., *Chia and Ropelewski*, 2002]. The ridge of the Pacific subtropical high is known as the main steering flow that controls the typhoon tracks [*Ho et al.*, 2004; *Wu et al.*, 2005]. To represent the variation of the subtropical high ridge over the WNPEA region at the 500-hPa surface, the 5870-gpm contour is used in this study. Because the strength of the easterly steering flow is related to the horizontal pressure gradient, the 5860-gpm contour is also added to illustrate gradient force near the subtropical high pressure area in Figure 1. Moreover, there is a well-known climate shift that occurred in the late 1970s [e.g., *Trenberth and Hurrell*, 1994]. To determine whether this decadal shift has any impact on the steering flows and displacement of the subtropical high pressure ridge, the data are partitioned into two epochs, the 1958–1979 and 1980–2001 periods. This partition is similar to that of *Ho et al.* [2004].

[9] Figure 1a shows the mean flow pattern and subtropical ridge for the peak season during 1958–1979. Strong easterly steering flows are noted between 5°N–25°N and 125°E–180°. These easterly flows not only gradually reduce in strength as they approach Philippines and Taiwan but also turn with a more southerly direction. Consequently, weak southeasterly currents are evident in the Philippine Sea. Strong southwesterly flows found in the higher latitudes of the East Asia and WNP are forming a gigantic anticyclonic circulation gyre covering the WNPEA. For the 1980–2001 epoch (Figure 1b), the pattern of the steering flows is similar to that for first epoch; however, there is a marked westward extension in the 5870-gpm contour, from its westernmost location near 133°E in the first epoch to 117°E in the second epoch. This represents a 16° (more than 1700 km) westward displacement in the subtropical high pressure. Based on numerical experiments with five atmospheric GCMs, *Zhou et al.* [2009] suggested that the westward extension of the western Pacific subtropical high since the late 1970s is explained by an Indian Ocean-western Pacific warming. Also noticeable in Figure 1b is the southward extension of the subtropical high pressure region, as represented by the 5870-gpm contour, from approximately 23°N during the first epoch to 16°–20°N over most of the WNP during the second epoch. Taken together, the subtropical high in the WNP has undergone a southwestward extension from the first to the second epoch. Relative to the first epoch, the pressure gradient to the south of the subtropical high in the second epoch is weaker (Figure 1b), which is consistent with weaker easterly steering flows in the second epoch. To better see the change in large scale circulation, the difference in steering flows between the two epochs is presented in Figure 1c. Between 20°–30°N (the subtropical belt) and the equator to 10°N (the equatorial belt), westerly anomalies prevail. This is indicative of weaker easterly steering flows during the second epoch. Also note large westerly anomalies between Japan and Taiwan. Strong easterly anomalies dominate at higher latitudes in Figure 1c.

[10] The spatial pattern of the mean frequency of TC occurrence over the last 52 years is shown in Figure 2. The prevailing typhoon tracks are labeled as I and II. It is interesting to note that the prevailing typhoon path I is along or located just slightly equatorward of the aforementioned subtropical belt where westerly anomalies are dominant (Figures 1c and 2). Westerly steering anomalies also dominate along track II. The large westerly anomalies in the

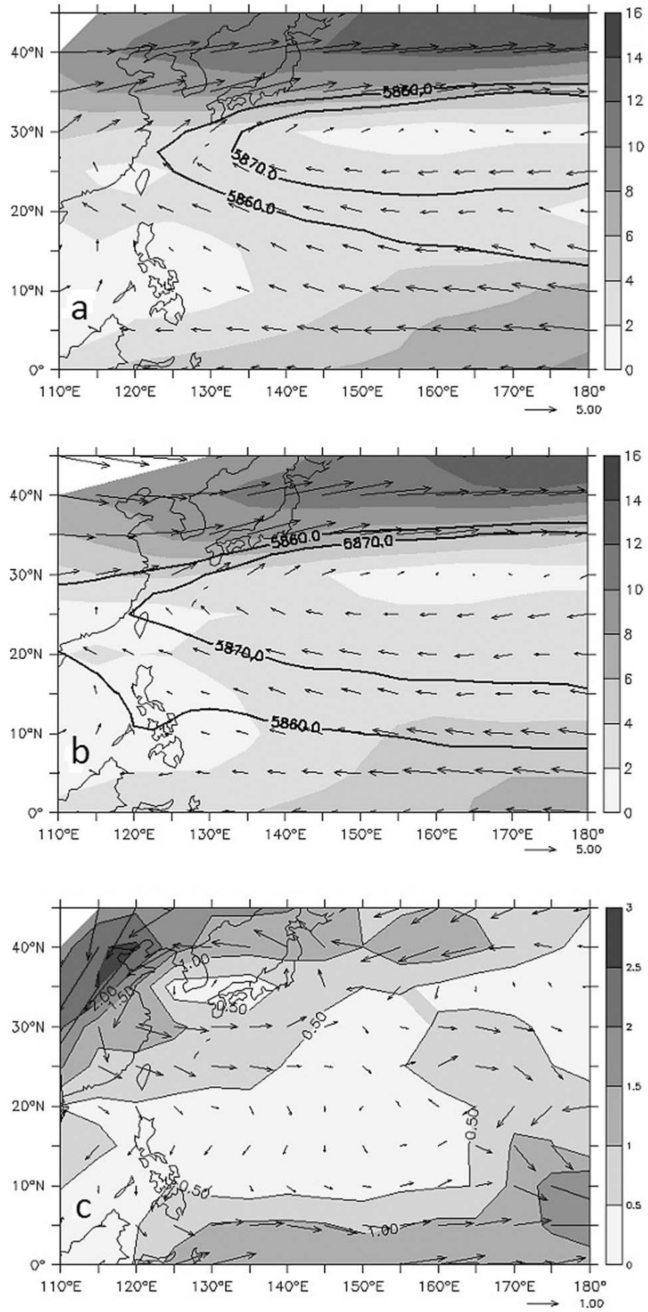

Figure 1. (a) Steering flows for the peak typhoon season (July–September) during 1958–1979 from the NCEP reanalysis. The 5870- and 5860-gpm contours are shown. (b) Same as in Figure 1a except for the 1980–2001. (c) The difference in steering flows between 1980–2001 and 1958–1979. The shading in Figures 1a and 1b is wind speed, and in Figure 1c is the absolute difference in wind speed between the two time periods.

equatorial band (Figure 1c) are not meaningful for steering flows because the location is too far south of the main typhoon tracks (Figure 2).

[11] Figure 3a shows the estimated slope of steering currents in the peak season from 1958 to 2001 based on the NCEP reanalysis data set. The most noteworthy feature is the prevalence of negative and statistically significant slopes in steering flows over the subtropical western portion of the WNP and the northern South China Sea (Figure 3a). Because this subtropical region is located in the preferred TC tracks (Figure 2), the long-term weakening of steering flows would impact TC motions. Another region with statistically significant negative slopes is found at lower latitudes between 150°E and the dateline (Figure 3a). However, very few TCs in the WNP form at such low latitudes and eastern longitudes.

[12] To confirm the results obtained from the NCEP data set, a similar analysis is carried out using the ERA reanalysis data set. The pattern of negative and significant slopes dominates in the western portion of the subtropical WNP (Figure 3b) and this region coincides well with the corresponding downward slopes estimated independently from the NCEP data set (Figure 3a). Therefore, there is a certain degree of confidence that the decreased steering flows in the subtropical WNP to the west of 145°E since 1958 are a valid signal. The region containing the statistically significant negative trend in steering flows also extends westward into the northern South China Sea in Figure 3b. The major difference in the trend of steering currents between these two datasets is the area of negative and significant slopes over the southeast corner of the tropical WNP seen in the NCEP reanalysis mainly disappears in the ERA (Figures 3a and 3b).

[13] To further illustrate the temporal variation of steering currents from 1958 to 2001, Figure 4a displays the time series plot of the area-averaged flows during the peak season from the NCEP reanalysis. The area chosen is taken from Figure 3 (the boxed region). For illustrative purposes, a straight line fitted from a simple regression analysis is shown. A downward trend is clearly evident from this data set. Over the last 44 yr, the decrease in steering currents, as judged from the simple regression analysis, is approximately 1.1 m s^{-1}. This decrease is quite large given the mean value of the steering flow during this period is only 3.26 m s^{-1}. For the ERA reanalysis data (Figure 4b), the long-term decrease in steering flows is again conspicuous and the slope (-0.023) is very close to the corresponding estimate from

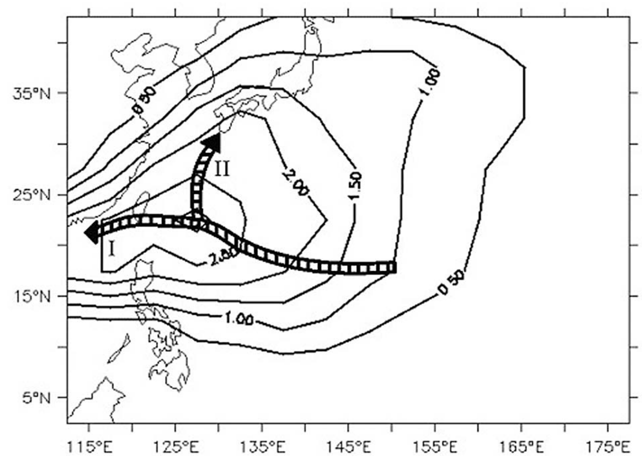

Figure 2. Typhoon frequency climatology during the peak season (July–September) over the period 1958–2009. The contour interval is 0.5 per season. Prevailing typhoon tracks are denoted by labels I and II.

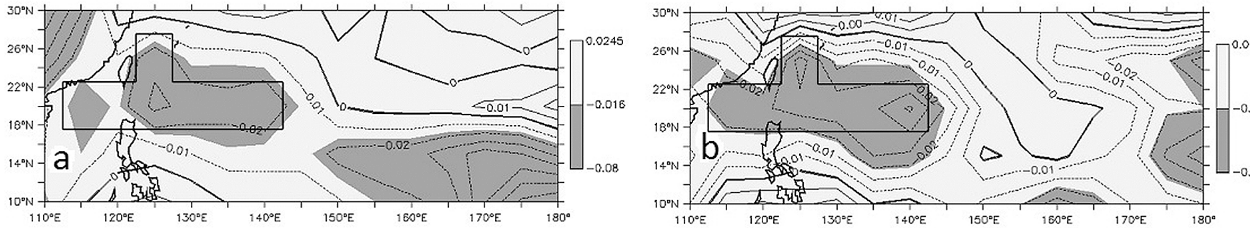

Figure 3. (a) Trends in steering flows for July–September from 1958–2001 detected by a non-parametric Mann-Kendall test and Sen's method based on the NCEP/NCAR reanalysis data. Shading indicates statistical significance at 5% level. The box delineates the region used for further analysis in Figure 4. Broken lines denote negative trend. Unit of trend is m s^{-1} yr^{-1}. (b) Same as Figure 3a but for the ERA reanalysis data.

the NCEP dataset (−0.024). The Pearson correlation between these two data sets in Figures 4a and 4b is 0.93. Because the ERA data set terminates in 2001, it would be of interest to further examine recent variations of the steering flow. For this purpose, we updated the time series plot to 2009 based on the NCEP reanalysis (solid line in Figure 4c). Over the last 52 yrs (1958–2009), there is a decadal variation in steering currents. In terms of the trend, the long-term decrease in steering flow is estimated to be approximately 0.71 m s^{-1}. Thus, steering flows over the western part of the subtropical WNP have experienced a significant decreasing trend. However, the decrease is more moderate when the entire 52 years are considered relative to the 1958–2001 (44 years).

[14] The previous analysis was based entirely on the reanalysis datasets. There was some concern whether these datasets could be biased. Independently, we also calculated the long-term trend based on translation speeds of TCs using the best-track archives from the RSMC. Also shown in Figure 4c is the interannual and decadal variation of storms' translational speed over the last 52 years (broken line). Again, a negative trend with a value of 0.48 m s^{-1} is noted, suggesting storms have moved a bit slower since 1958. A correlation of 0.37 is found between steering flows and translation speed during the last 52 years. Although significant at the 5% level, this correlation is only modest. This could be caused by the method used in the calculation of steering currents as described in the previous section. After removing trends for both series, the correlation between the steering current and translation speed is 0.35, still statistically significant. For comparison, the Pearson correlation between the large-scale steering flows and translation speed derived from the JTWC is only 0.27 (not

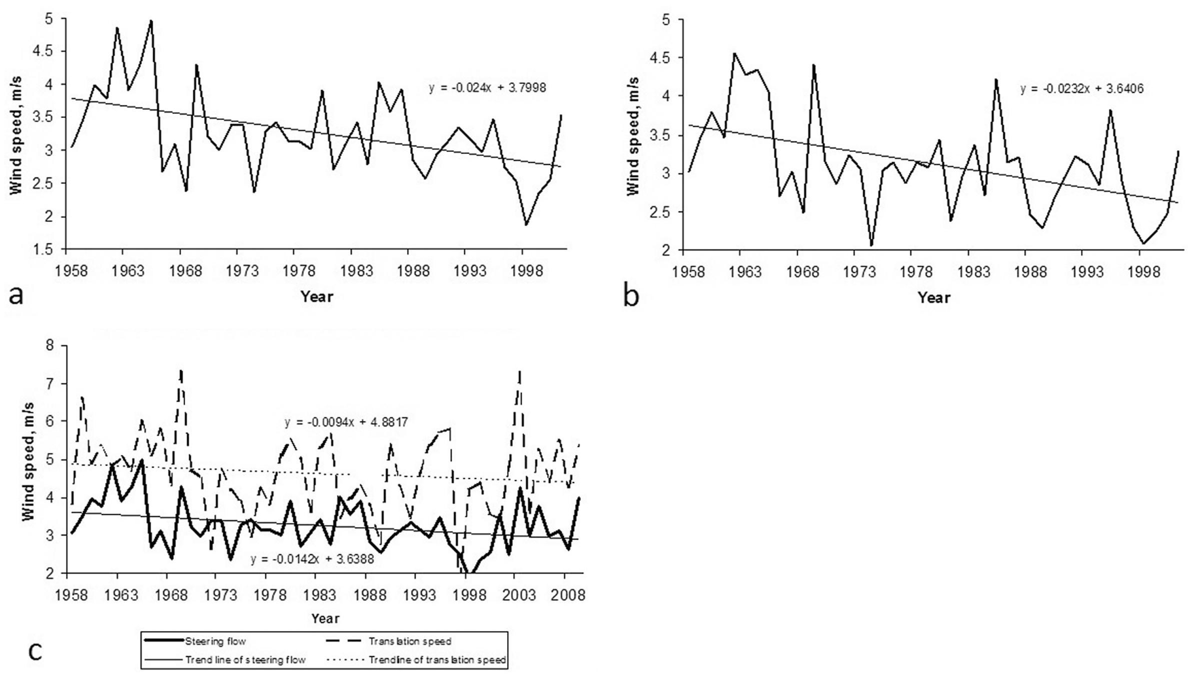

Figure 4. (a) Time series of area-averaged steering flows over the box indicated in Figure 3 from the NCEP/NCAR reanalysis data for July–September during 1958–2001. (b) Same as in Figure 4a but for the ERA reanalysis data. (c) Time series of area-averaged steering flows over the box indicated in Figure 3 from the NCEP/NCAR reanalysis data for July–September during 1958–2009 (solid line) and time series of area-averaged translation speed for the same period from the RSMC (broken line). Linear trends from steering flows and translation speed are also shown, respectively, as thin solid line and thin dotted line.

significant) and, after removing the trends, the correlation drops to 0.15.

4. Summary

[15] Traditionally, the impact of climate change on tropical cyclone activity has been focused on the intensity and frequency of the storm [e.g., *Emanuel*, 2005; *Webster et al.*, 2005; *Knutson et al.*, 2010]. For example, *Webster et al.* [2005] noted a large increase in the frequency for the strongest TC categories (4 and 5) in the western Pacific over the last three decades. However, this large trend has been challenged by the interdecadal variations of typhoon activity [*Matsuura et al.*, 2003; *Liu and Chan*, 2008] or possible measurement errors in the dataset [*Landsea*, 2005; *Klotzbach*, 2006]. Future projections based on high-resolution models and theory suggest that global warming would lead to stronger storms and a decrease in the frequency of TCs [e.g., *Knutson et al.*, 2010; *Murakami et al.*, 2011]. Along with intensity and frequency, there is a growing interest in knowing possible changes in TC tracks in a warming climate.

[16] For the WNP, a shift in typhoon tracks from historical observations was noted by *Wu et al.* [2005] and *Tu et al.* [2009]. Moreover, by objectively clustering TC tracks into eight distinct patterns, *Chu et al.* [2010a] found an increasing TC lifespan for most of these track patterns since 1970. Because longer storm days imply changes in steering flows, the motivation for this study is to examine whether steering flows have changed using a robust statistical trend analysis based on two commonly used reanalysis data sets. In the meantime, trends in translation speeds from RSMC and JTWC are also examined.

[17] Steering flows show a weakening trend during the peak typhoon season over the last 50 years. In particular, the decreasing flows are found to be statistically significant in both the western portion of the subtropical WNP and northern South China Sea. This decrease is seen in both NCEP and ERA reanalysis data sets. Independently, the translational speed of storms also exhibits a long-term decrease.

[18] The weakened easterly steering current observed over the subtropical western portion of the WNP in this study is in agreement with *Ho et al.* [2004]. *Wu et al.* [2005] also found westerly flow anomalies to the south of 25°N when the period 1965–1983 was compared to 1984–2003. *Tu et al.* [2009] likewise showed an eastward retreat of the WNP subtropical high since 2000, implying a weakened easterly steering flow although they did not present changes in steering currents. However, results presented in this study are at odds with *Wu and Wang* [2004] who projected stronger easterly currents in the tropics in the future. More recently, a study based on a very-high-resolution GCM suggested that in the future easterly steering flows will be weaker in the tropics [*Murakami et al.*, 2011], which is in contrast to the findings of *Wu and Wang* [2004]. Because the western subtropical WNP is commonly frequented by typhoons, the slow down of easterly steering flows will keep storms in the main track region longer in their lifetime and likely cause storms to recurve. Interestingly, *Wu et al.* [2005] and *Tu et al.* [2009] noted a northward shift of the prevailing typhoon tracks over the WNPEA region over the last 40 years, which corresponds to a recent increase in typhoon frequency observed over Taiwan, the East China Sea, and the sea to the south of Japan.

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