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Growing threat of intense tropical cyclones to East Asia over the period 1977–2010

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Abstract

The threat of intense tropical cyclones (TCs) to East Asia has increased in recent decades. Integrated analyses of five available TC data sets for the period 1977–2010 revealed that the growing threat of TCs primarily results from the significant shift that the spatial positions of the maximum intensity of TCs moved closer to East Asian coastlines from Vietnam to Japan. This shift incurs a robust increase in landfall intensity over east China, Korea and Japan. In contrast, an increase of TC genesis frequency over the northern part of the South China Sea leads to a reduction in the maximum TC intensity before landfall, because of their short lifetime; thus, there are no clear tendencies in the landfall intensity across Vietnam, south China and Taiwan. All changes are related to the strengthening of the Pacific Walker circulation, closely linked with the recent manifestation that the warming trend of sea surface temperature in the tropical western Pacific is much higher than that in the central to eastern Pacific.

Keywords: tropical cyclone, typhoon, typhoon intensity, landfall, East Asia

1. Introduction

The long-term change in the intensity of landfalling tropical cyclones (TCs) is a critical scientific and socio-economic issue, because TC landfalls result in numerous casualties and severe property losses. The socio-economic losses caused by TCs have increased markedly worldwide over the last few decades (Pielke *et al* 2008, Zhang *et al* 2009, Fengjin and Ziniu 2010); it has been argued that a large portion of the growing storm damage can be explained by the expanding social development (Pielke and Landsea 1998, Zhang *et al* 2009). Nevertheless, the intensity of landfalling TCs is a focal factor because the majority of losses arise from a few intense TCs (Landsea 1993, Pielke *et al* 2008). According to recent studies (Emanuel 2011, Mendelsohn *et al* 2012, Murnane and Elsner 2012), the increasing frequency of intense TCs can account for an upward trend in TC damage under conditions of global warming, regardless of economic growth.

Recent changes in oceanic and atmospheric environments over the western North Pacific (WNP) are likely to imperil coastal countries in East Asia with TCs, by inference from previous research (e.g. Park *et al* 2011, 2013). Park *et al* (2013) demonstrated that spatially distinct changes in dynamic environments have affected the corresponding pattern of changes in TC intensity in recent decades. As shown in figure 1, for the period 1979–2010, the sea surface temperature (SST) has warmed notably in the western Pacific, accompanied by weak cooling in the tropical central and eastern Pacific. This pattern of the Pacific SST trend occurred together with the strengthening of the Pacific Walker circulation (Cravatte *et al* 2009, Sohn and Park 2010, Zhang *et al* 2011). This ocean–atmosphere coupled phenomenon can be explained by the Bjerknes feedback (Bjerknes 1969). Even though it is still controversial whether this deepening of the zonal SST gradient over the tropical Pacific should be considered one of the global warming signals or the multi-decadal variations (Cane *et al* 1997, Latif *et al* 1997, An *et al* 2012, Kosaka and Xie 2013), it is evident that the enhanced Walker circulation subsequently increased low-level anticyclonic wind flows and strengthened

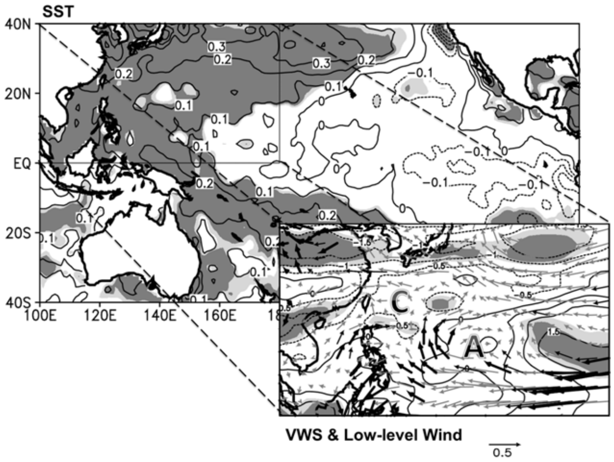

Figure 1. Linear trends in the SST (°C decade^{-1}) over the Pacific, the 850 hPa horizontal winds (vectors, m s^{-1} decade^{-1}) and the vertical wind shear between 850 and 200 hPa (contours, m s^{-1} decade^{-1}) over the WNP during the period 1979–2010. Light and dark gray shadings indicate that the trend is statistically significant at the 90% and 95% confidence levels there, respectively. Thin and thick black vectors denote statistically significant trends in horizontal winds at the 90% and 95% confidence levels, respectively. C and A mean that anomalous cyclonic and anticyclonic flows are observed there, respectively.

vertical wind shear over the eastern Philippine Sea. These atmospheric changes have suppressed TC development in this region, despite the general SST warming. Along the coastal sea extending from Vietnam to Japan, however, increased low-level cyclonic wind flows and weakened vertical wind shear, in combination with the warmer SST, have encouraged TCs to increase in strength. As a result, TCs may reach their maximum intensity more frequently closer to the East Asian continent; that is to say, TCs could intensify or sustain their strength up to the brink of landfall. This implies that there might be a significantly increasing trend of landfall intensity of TCs over recent decades along the East Asian coastlines.

Despite the above-mentioned spatially distinct environmental changes, previous studies focused on basin-wide averaged long-term changes in intensity-related parameters (e.g. power dissipation index, accumulated cyclone energy and maximum wind speed) over the WNP (e.g. Emanuel 2005, Webster *et al* 2005, Chan 2006, 2008). Although some researchers have examined the strength of TCs at landfall, either for two Northeast Asian countries (i.e. Korea and Japan) (Park *et al* 2011), or from a global perspective (Weinkle *et al* 2012), the increasing intensity of landfalling TCs over the extensive East Asian area in recent decades has yet to be investigated. This motivates the present study.

2. Data and methods

We utilized all four available TC best-track data sets in the WNP basin, issued by different agencies: Regional Specialized Meteorological Centers-Tokyo Typhoon Center (RSMC), Joint Typhoon Warning Center (JTWC), Hong Kong Observatory (HKO) and Shanghai Typhoon Institute (STI). The data sets commonly include the locations of TC centers and maximum sustained wind speeds at 6 h intervals. Furthermore, the reanalyzed TC data from the University of Wisconsin-Madison/National Climate Data Center (UW/NCDC), which are the most homogeneous data available at this time despite some biases reported in the WNP (Knapp and Kossin 2007, Kossin *et al* 2007, Park *et al* 2013), was also utilized to add confidence to the long-term changes in TC activity from the best-track data. The UW/NCDC data are only included in tables but not displayed in figures 2 and 3. The analyses only include TCs with a maximum sustained wind speed exceeding 17 m s^{-1} during the TC season in East Asia (July–November).

Previous studies have pointed out the inconsistency of historical trends in basin-wide total TC intensity over the WNP among different TC best-track data sets (Wu *et al* 2006, Kossin *et al* 2007, Song *et al* 2010). Consequently, it has been generally thought that it is premature to detect the reliable intensity trend from the best-track data. However, some recent studies found that there are subareas in which the intensity trends are consistent among the best-track data and therefore statistically more confident (e.g. Park *et al* 2011, 2013). Kim *et al* (2010) showed that to transform the raw intensity records into regular gridded data is informative for illustrating the spatially distinct trends. The present study followed their gridding method of the TC data. The gridded TC data with 1° × 1° horizontal resolution were constructed by shifting a 5° × 5° window in the zonal and meridional directions by 1°. That is, the value at a certain grid point includes the TC data in a 5° × 5° square box centered on that point. In addition, the differing units and averaging times of the maximum sustained winds among the different data sets were standardized to m s^{-1} and 10 min, respectively, following Park *et al* (2011, 2013). The long-term changes were calculated for the best-track data sets over the period 1977–2010 and for the UW/NCDC data over the period 1982–2006. The present study confined the analysis to this period because the geostationary meteorological satellites have been operated by Japan Meteorological Agency since 1977 in the WNP, making the data more reliable (Park *et al* 2011).

To estimate the time of TC landfall with greater accuracy, the TC data, generally recorded at 6 h intervals, were linearly interpolated with 1 h intervals. The intensity at landfall is defined as the wind speed of the TC when its interpolated center enters the landfall region for the first time (gray shaded area in figure 2(a)). The target landfall regions include Indochina, Hainan Island, Taiwan, mainland China, the Korean Peninsula and the Japanese archipelago. The land/sea information is based on the 0.25° horizontal resolution of data from the National Oceanic and Atmospheric Administration/National Climatic Data Center.

Atmospheric reanalysis and SST data, used in figure 1, were obtained from the European Centre for Medium-Range Weather Forecasts (the ERA interim; Dee *et al* 2011) and the UK Met Office Hadley Centre (the Hadley SST; Rayner *et al* 2003), respectively. The ERA interim offers various atmospheric variables, such as air temperature, horizontal/vertical winds and geopotential height, at 37 pressure levels and surface with 1.5° horizontal resolution for the period 1979–2010. The Hadley SST data, covering the period 1870–2010, has 1° horizontal resolution.

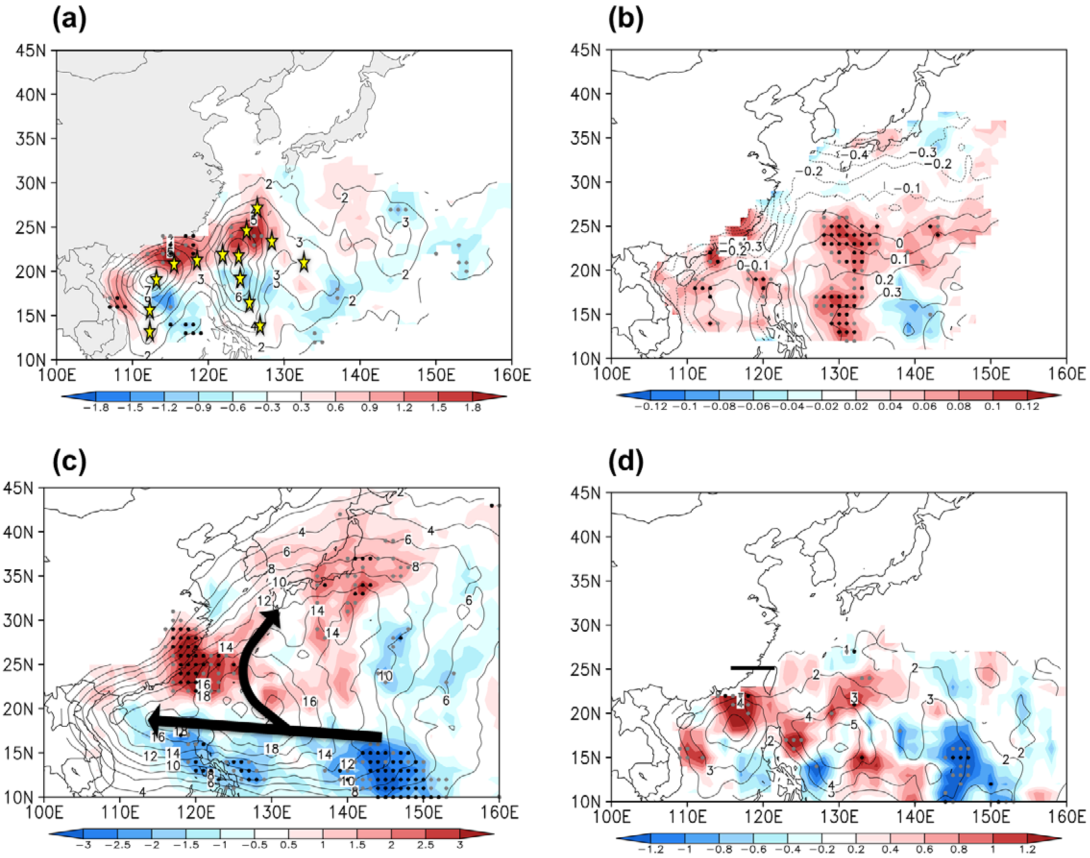

Figure 2. Climatology (contours) and linear trends (red and blue shading) in (a) the location of maximum intensity (climatology: %, trend: % decade^{-1}), (b) intensification rate (climatology: m s^{-1} h^{-1}, trend: m s^{-1} h^{-1} decade^{-1}), (c) track density (climatology: %, trend: % decade^{-1}) and (d) genesis locations (climatology: %, trend: % decade^{-1}) during the period 1977–2010. All values are averaged for the four best-track data. Gray and black dots are marked for grid points where the linear trends are statistically significant at the 90% and 95% confidence levels, respectively, for three or more best-track data. Yellow asterisks denote the ridges of the location of maximum intensity. Black arrows represent the main tracks of TCs (Tu *et al* 2009).

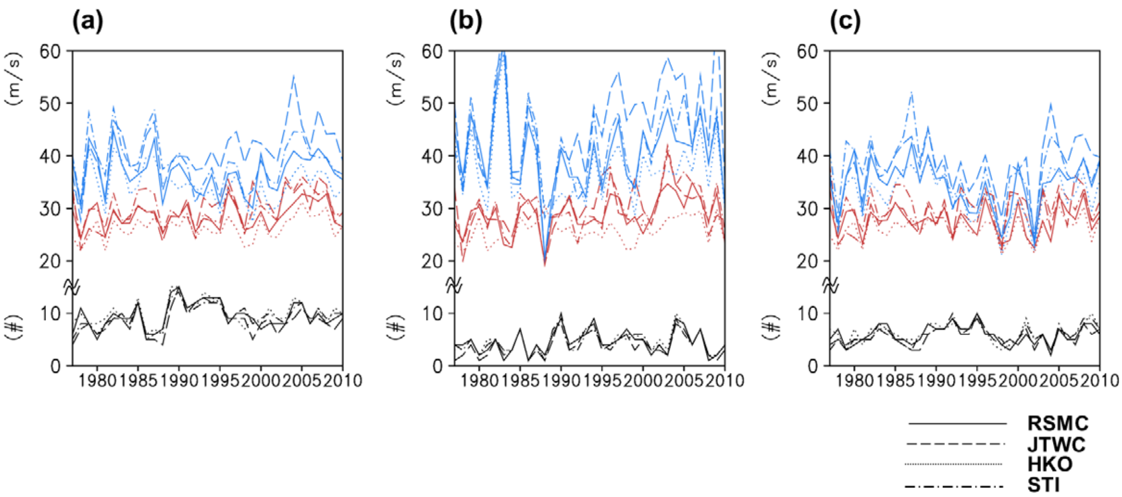

Figure 3. Time series of seasonal averages of maximum (blue lines) and landfall (red lines) intensity, and seasonal accumulation of landfall frequency (black lines) over (a) East Asia, (b) Northeast Asia and (c) Southeast Asia. Solid, dashed, dotted and dotted–dashed lines denote the RSMC, JTWC, HKO and STI data, respectively.

3. Results

As mentioned in section 1, the large-scale environmental changes over the WNP show noticeable regional differences in response to the distribution of the Pacific-wide SST change in recent decades (figure 1). Park *et al* (2013) demonstrated that the spatial distributions of these large-scale environmental changes facilitate the growth of TCs over near-coastal seas, but act to suppress TC growth over the eastern tropical Philippine Sea, despite the general SST warming there.

This change in large-scale climatic fields suggests that the principal region in which many TCs attain peak intensity during their lifetime might have been translocated. Figure 2(a) illustrates the climatology of the location of maximum intensity (contour) and its long-term change (shading), averaged for all best-track data, during the analysis period. Here, the location of maximum intensity represents the ratio of the number of TCs showing lifetime maximum intensity at a grid point to the total genesis count in the WNP. According to the climatology, the majority of TCs reached their maximum intensity within their lifetime at the western boundary of the Philippine Sea and the southern shore of China. The long-term change shows westward and northward shifts in the location of maximum intensity in a belt along the continental shoreline south of 30°N, while the corresponding decrement is predominant to the south and southeast of this increasing belt. The changes are statistically significant over the 90% confidence level for at least three best-track data in a considerable portion of the region where discernible tendencies are observed. These features confirm that the expected changes based on the large-scale environmental changes (figure 1) have indeed been occurring over the WNP basin.

The TC intensification rate and track density are helpful in interpreting the recent change in the location of maximum intensity. Figure 2(b) shows the climatology of the TC intensification rate (contour) and its long-term change (shading), averaged for all best-track data. Here, the intensification rate indicates the rate of change of wind speed in unit time at a grid point. Climatology of the intensification rate is negative along the coastal seas of East Asia and over the Philippines, meaning that TCs begin to decay after entering these regions. Thus, it is natural that the climatological ridges in the location of maximum intensity (asterisks in figure 2(a)) almost correspond to the zero lines of the intensification rate (figure 2(b)). The long-term change in the location of maximum intensity is also explained by the intensification rate which nearly corresponds to the large-scale environmental changes as shown in figure 1. Except for north of 30°N, a downtrend in the intensification rate is seen over the limited area of the southeastern Philippines (around 140°E and 15°N) while a significant uptrend is broadly distributed in the other regions south of 30°N over the 90% confidence level for at least three best-track data sets. In the midlatitudes, no apparent tendency of the intensification rate is detected, despite the increase in SST and the weakening of vertical wind shear (figure 1 versus 2(b)). Presumably, this is due to a weak anomalous anticyclonic flow that counteracts the positive effects of the SST and vertical wind shear on the intensification rate over Korea and Japan (figure 1). This hypothesis needs further verification, but this is beyond the scope of this study. The negligible change in the intensification rate in the midlatitudes is consistent with the results of Park *et al* (2011), who showed that only the growing intensity of landfalling TCs over Korea and Japan could bring about the longer duration of TCs in that region, since the local intensification rate has not changed significantly.

Figure 2(c) represents the climatology (contour) and long-term change (shading) for averages of the TC track density from all the best-track data. Climatology of the track density can explain two high cores in climatology of the location of maximum intensity near Hainan Island and Taiwan (contour of figure 2(a) versus 2(c)). It can be easily supposed that TCs have more chance to attain their maximum intensity in a grid if a greater number of TCs pass through that grid. Actually, the two high cores of location of maximum intensity lie on two main passing routes of the TCs, which are characterized by westward straight and northward curvy tracks from the eastern tropics of the WNP (black arrows in figure 2(c)) (Ho *et al* 2004, Wu *et al* 2005, Tu *et al* 2009, Kim *et al* 2011). Similar to this relationship, the long-term change in the track density could also account for the shift of the location of maximum intensity towards the East Asian continent. Comparable spatial patterns are observed between the track density and the location of maximum intensity; there are positive signs along the East Asian coasts and negative signs in the tropical WNP. However, the track density cannot fully explain the location of maximum intensity, since the changes are not exactly coincident with each other (shading of figure 2(a) versus 2(c)). For instance: (1) the largest increment in the track density is located over Taiwan, while the location of maximum intensity has noticeably increased over the east and southwest sides of Taiwan; and (2) there is the weak increasing trend in the track density along the eastern shoreline of Vietnam, but a significant positive sign in the location of maximum intensity exists there. Thus, climatology and the long-term change in the location of maximum intensity can be successfully understood when both the intensification rate and the track density are considered.

Given that TC intensity is highly affected by genesis location (Camargo and Sobel 2005, Park *et al* 2013), spatial changes in the main genesis locations should be examined. Figure 2(d) depicts climatology (contour) and long-term change (shading) in the genesis frequency for the averages of all best-track data sets. Climatologically, most TCs form over the South China Sea and the Philippine Sea. During the analysis period, there is a notable shift in TC genesis: an increase over the northern South China Sea and the northwestern Philippine Sea, with a decrease over the eastern Philippine Sea. Note that increasing genesis frequency in a certain region can reduce the average TC intensity over the local and surrounding regions because newly generated TCs usually have the weakest intensity, 17 m s^{-1}, that is the lower limit of TC intensity in this study. Therefore, the translocation of TC genesis toward East Asia may decrease landfall intensity over the southern coast of East Asia, including Vietnam, south China and Taiwan. To verify this genesis effect on landfall intensity, the East Asian coastlines were divided into two subareas, Northeast and Southeast Asia, to the north and south of 25°N, respectively (thick black line in figure 2(d)). Hereafter, landfall TCs over Northeast and Southeast Asia will be analyzed in addition to those over the entire East Asia.

Figure 3 displays the time series of maximum intensity prior to landfall, landfall intensity and landfall frequency for the analysis domains: East, Northeast and Southeast Asia. Notice that only landfall TCs are considered when calculating the maximum intensity, which gives the peak intensity prior

Table 1. Linear trend and its statistical significance of maximum and landfall intensity over East, Northeast and Southeast Asia for each data set. (Note: bold and italic types indicate that the long-term trends are statistically significant at the 95% confidence levels for the Student *t*-test and the Mann–Kendall test, respectively.) The units are m s^{-1} $decade^{-1}$.

		RSMC	JTWC	HKO	STI	UW/NCDC
East Asia	Max	−0.04	***+2.42***	−0.77	−0.62	+0.01
	Landfall	+0.58	***+1.81***	+0.92	**+0.79**	+0.56
Northeast Asia	Max	−0.08	***+3.47***	+0.25	−0.82	+0.62
	Landfall	***+1.30***	**+1.49**	***+1.83***	***+0.85***	***+1.92***
Southeast Asia	Max	−0.38	+1.28	−1.33	−0.54	−0.88
	Landfall	−0.10	+1.25	−0.08	+0.48	−0.50

Table 2. Correlation coefficient between frequency and intensity of landfall TCs over East, Northeast and Southeast Asia for each data set.

	RSMC	JTWC	HKO	STI	UW/NCDC
East Asia	−0.13	+0.14	−0.17	−0.15	−0.09
Northeast Asia	+0.17	+0.17	+0.08	+0.05	+0.25
Southeast Asia	+0.04	+0.19	−0.29[a]	+0.16	+0.17

[a] Denotes that the correlation is statistically significant at the 90% confidence level.

to landfall. Accordingly, landfall TCs may become stronger even if the maximum intensity before landfall does not change during the analysis period. This is because the maximum intensities of TCs more frequently occur nearer to East Asia (figure 2(a)). Table 1 furnishes this with the magnitude and statistical significance of each intensity trend in figure 3. To evaluate the statistical significances, the Mann–Kendall test was also applied with the Student *t*-test. The Mann–Kendall test is one of the non-parametric tests which is useful to evaluate trends for small samples because it is not necessary to hypothesize normal distribution (Chu *et al* 2012).

Figure 3(a) describes the case where the entire East Asia region is defined as a landfall domain. There are either upward or downward tendencies in the maximum intensity for all best-track data sets. The UW/NCDC also shows no clear long-term change that is +0.01 m s^{-1} $decade^{-1}$. As expected, the time series of landfall intensity, however, show notable increments. All of the best-track data sets consistently display positive changes though some of them are not statistically significant at the 95% confidence level. The UW/NCDC also displays a positive change, +0.56 m s^{-1} $decade^{-1}$, but it is not statistically significant. The insignificance of the increasing tendency can be attributed to the genesis effects that may reduce landfall intensity in Southeast Asia.

Since the number of landfall TCs may affect the landfall intensity, the landfall frequency is displayed in figure 3 and its correlation coefficients with landfall intensity are exhibited in table 2. It is likely that there is no connection between landfall frequency and intensity over East Asia; very weak correlations are observed for all data sets. In addition, the time series of landfall frequency represent a weak increase due to an upswing in the late 1980s and early 1990s, in contrast to the gradually rising landfall intensity. Here, the weak increasing tendencies in the landfall frequency over East Asia may be considered somewhat abnormal, because it has been shown that significantly more TCs have headed towards Taiwan and Japan over the analysis period (Wu *et al* 2005, Tu *et al* 2009). The cause of this weak trend in landfall frequency may be due to the notably decreased total TC genesis frequency after the mid-1990s (Matsuura *et al* 2003, Fengjin and Ziniu 2010, Liu and Chan 2013, Park *et al* 2013).

Figure 3(b) illustrates the time series for the case of TCs striking Northeast Asia including east China, Korea and Japan: the case that genesis effects may be negligible. As seen in table 1, mixed tendencies in the maximum intensity are still seen among the best-track data sets; yet the long-term change for UW/NCDC is not statistically significant (+0.62 m s^{-1} $decade^{-1}$). Contrariwise, the landfall intensity has notably increased for all data sets; most of their linear tendencies including estimates from the UW/NCDC data set pass statistical significance at the 95% confidence levels for both the Student *t*-test and Mann–Kendall test. This implies that the genesis effects have influenced the decrease in landfall intensity along the Southeast Asian coast in recent decades. Furthermore, the present result is consistent with Park *et al* (2011) who found stronger landfall TCs over Korea and Japan that are a part of the Northeast Asia region defined here. The landfall frequency still shows a weak relationship with the landfall intensity (table 2).

The time series for TCs landfalling on Southeast Asia, including Vietnam, south China and Taiwan, are illustrated in figure 3(c). The maximum intensity has consistently decreased for all data sets except for the JTWC, whose increment (+1.28 m s^{-1} $decade^{-1}$) is, however, much weaker than those in East and Northeast Asia (table 1). These changes may be due to the genesis effect; a greater number of TCs have formed near the south coast of China since 1977, but fewer over the southern part of the South China Sea (figure 2(d)). The shortened lifetimes of TCs over the ocean may have reduced the maximum intensity. Otherwise, the landfall strength of TCs was more weakly decreasing for most data sets (table 1). This may be because TCs could sustain their peak intensity nearer to land in the recent few decades (figure 2(a)). The landfall frequency also shows little change and is not a factor that influences the landfall intensity, showing no notable correlation coefficients between them except for the HKO data set that shows a negative correlation (table 2).

Interestingly, for all cases, the JTWC data exhibit a significant increase in both maximum and landfall intensity; the increments in maximum intensity are higher than those in landfall intensity (table 1). The results from JTWC, however, have minor influences on the overall conclusions of this study. It was already shown that TC intensification rate has been suppressed in the eastern Philippine Sea, whereas it has been encouraged in other subareas for all data sets (figure 2(b)). This leads to our main supposition that the maximum intensity has shifted towards East Asia and intensified landfall intensity. In this sense, the largely strengthened maximum intensity in the JTWC data can be simply explained by more rapid reintensification of TCs over the oceans close to land compared to the other data sets (figure 2(b)). Even though JTWC may be more reliable than the other best-track data sets (e.g. Chan 2008), it is believed that the intensity records of the JTWC after the late 1980s are likely to be overestimated due to the termination of aircraft reconnaissance (e.g. Kossin *et al* 2007, Wu and Zhao 2012). Thus, this study gives more confidence to the UW/NCDC data that are the most homogeneous data at the present.

There is additional clear evidence that the shifted location of maximum intensity is a main cause of the rising risk of TCs over East Asia; the landfall intensity does not exceed but just approaches its maximum prior to landfall in both Northeast and Southeast Asia. Except for the JTWC data, all of the long-term changes of the differences (i.e. the maximum minus landfall intensity) show substantial negative tendencies over Northeast (-1.7 to -1.3 m s^{-1} decade^{-1}) and Southeast (-1.2 to -0.3 m s^{-1} decade^{-1}) Asia though only a few of them are statistically significant (not shown). Thus, the recent increase in landfall intensity over East Asia is likely to depend on the translocation of maximum intensity.

4. Summary and discussion

Based on the analysis of five TC data sets, it was found that the location of maximum intensity of TCs has come closer to the East Asian coastline over the analysis period 1977–2010. This shift in the location of maximum intensity is related to the strengthened tropical Walker circulation, closely linked with the rising zonal SST gradient over the tropical Pacific during this period; there is the significantly increasing SST trend over the western Pacific while there are the weak increasing and decreasing trends over the central and eastern tropical Pacific, respectively. The enhanced Walker circulation strengthened low-level anticyclonic wind flows and vertical wind shear over the tropical eastern Philippine Sea, and vice versa along the East Asian coastlines extending from Vietnam to Japan. These counter-changes in large-scale environmental factors may directly result in the westward and northward shifts in the location of maximum intensity. A larger fraction of TCs heading for Taiwan and Japan is another possible reason for the shift of the location of maximum intensity towards East Asia. Consequently, the location of maximum intensity of TCs approaching East Asia can extensively strengthen the landfall intensity in Northeast Asia, even when the maximum intensity itself is nearly unchanged. In contrast, the landfall intensity in Southeast Asia has scarcely changed due to a substantial decrease in maximum intensity. This decrease in the maximum intensity is attributable to the enormous influence of the significant increase in newly generated weak TCs over the northern part of the South China Sea near Southeast Asia. Overall, the growing threat of intense TCs characterizes the recent change in the intensity of landfalling TCs over East Asia.

According to our result, the tropical circulation and related spatial pattern of tropical Pacific warming may be a very important factor for the landfall intensity of TCs over East Asia. This may suggest that TCs striking East Asia may continue to strengthen if climate change results in an increased zonal SST gradient in the Pacific Ocean. However, the spatial pattern of SST warming over the Pacific includes both global warming and various natural variations, such as El Niño–Southern Oscillation, Pacific Decadal Oscillation and other multi-decadal oscillations (Cane *et al* 1997, Latif *et al* 1997, Lee and McPhaden 2010, Kosaka and Xie 2013). It is difficult to objectively distinguish each variation from the SST changes. Thus, there has yet to be a consensus about the pattern of tropical Pacific warming in terms of an analogy with El Niño/La Niña in the future (Ashok and Yamagata 2009, Collins *et al* 2010, An *et al* 2012). Thus, it may be very hard to guess the exact future changes in landfall intensity of TCs over East Asia before the aforementioned problems are completely solved.

Acknowledgments

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