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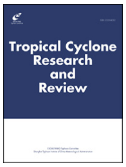

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Third assessment on impacts of climate change on tropical cyclones in the Typhoon Committee Region — Part I: Observed changes, detection and attribution

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Abstract

Published findings on climate change impacts on tropical cyclones (TCs) in the ESCAP/WMO Typhoon Committee Region are assessed. We focus on observed TC changes in the western North Pacific (WNP) basin, including frequency, intensity, precipitation, track pattern, and storm surge. Results from an updated survey of impacts of past TC activity on various Members of the Typhoon Committee are also reported. Existing TC datasets continue to show substantial interdecadal variations in basin-wide TC frequency and intensity in the WNP. There has been encouraging progress in improving the consensus between different datasets concerning intensity trends. A statistically significant northwestward shift in WNP TC tracks since the 1980s has been documented. There is low-to-medium confidence in a detectable poleward shift since the 1940s in the average latitude where TCs reach their peak intensity in the WNP. A worsening of storm inundation levels is believed to be occurring due to sea level rise-due in part to anthropogenic influence-assuming all other factors equal. However, we are not aware that any TC climate change signal has been convincingly detected in WNP sea level extremes data. We also consider detection and attribution of observed changes based on an alternative Type II error avoidance perspective.

Keywords: Tropical cyclones; Typhoons; Climate change; Typhoon Committee; Western North Pacific

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1. Introduction

Tropical cyclones (TCs) rank among of the most destructive natural disasters on Earth. The western North Pacific (WNP) is the most active TC basin in the world, with an average of about 26 named TCs affecting the region each year. Among the notably destructive TCs occurring in the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP) and the World Meteorological Organization (WMO) Typhoon Committee region in recent years were Washi in 2011, Haiyan in 2013, Rammasun in 2014, Soudelor in 2015, Nepartak and Meranti in 2016, Hato in 2017, and Jebi and Mangkhut in 2018. Against the background of global climate change, possible changes in TC activity and the associated impacts are topics of concern (Landsea et al., 2006; IPCC, 2013; Walsh et al., 2016). For the WNP, the Second Assessment Report (SAR) on the influence of climate change on tropical cyclones in the Typhoon Committee region (Ying et al.,

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2012a), concluded that while detection of any long term trends in TC activity in the WNP is still rather uncertain due to large inter-annual and inter-decadal variations and inter-agency inconsistency in the best track dataset, most of the available modeling studies projected an increase in TC intensity and precipitation rates in the WNP basin over the 21st century.

Since the publication of the SAR of the Typhoon Committee in 2012, the Members of Typhoon Committee and various research groups around the world have continued to investigate the connections between climate change and TCs, including homogenization of best-track datasets, attribution and detection studies, model projections, and impact assessments as recommended by the Typhoon Committee expert team in 2012 (Ying et al., 2012a). In 2014, the Typhoon Committee at its 46th Session in Bangkok, Thailand commissioned an expert team to update the SAR with the present assessment-a third assessment report (TAR)-for the Typhoon Committee Members' reference (Typhoon Committee, 2014).

This paper is the first part of a two-part series which summarizes the updated assessment contained in the TAR. The TAR reviewed evidence for past trends of TC activity in the WNP and identified and assessed possible influences of anthropogenic climate change on TC activities and impacts in the region. Section 2 will provide an updated assessment of past observed changes in TC activity and characteristics (including frequency, intensity metrics, and prevailing tracks). Section 3 will present the results collected from the survey of the observed trend and impacts of TC activity among Typhoon Committee Members and some related research findings. Section 4 will examine the latest findings on detection and attribution of changes of TC activities. Some relevant uncertainties of the assessment are discussed in Section 5. A summary of findings and recommended future studies is included in Section 6.

2. Observed tropical cyclone activity and characteristics

In this section, we review published results on the variability and trends in various tropical cyclone metrics in the WNP basin. In some cases, trends are reported as being statistically significant, which typically means that the trend is significantly different from zero at some significance level (e.g., $p = 0.05$) according to a particular trend test with associated assumptions. In cases where a statistically significant trend is found, this does not necessarily imply that the trend behavior over the given time period is significantly different from that expected due to natural processes alone. For example, trends of multi-decadal duration can be generated by low-frequency internal variability, and such internal variability must be assessed for a determination of whether a detectable (i.e., unusual compared to natural variability) change has been observed. The issue of climate change is addressed in detail in Section 4.

2.1. Tropical cyclone frequency

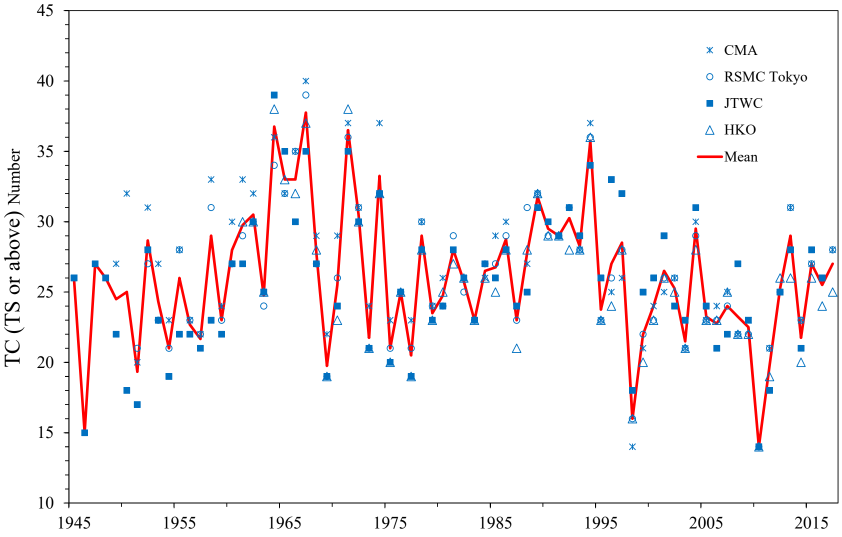
Studies of the variability and trends in tropical cyclone frequency in the WNP basin are reviewed in this subsection. For the WNP, four TC best track datasets are available, prepared respectively by China Meteorological Administration (CMA), Hong Kong Observatory (HKO), Joint Typhoon Warning Centre (JTWC), and Regional Specialized Meteorological Centre Tokyo (RSMC-Tokyo). These four datasets are commonly used by various research groups in TC analysis. In addition to these four datasets, Kossin et al. (2007, 2013) reanalyzed satellite imagery and constructed the Advanced Dvorak Technique−Hurricane Satellite dataset (ADT-HURSAT) for the purpose of having a more homogeneous satellite-based estimation of TC intensity for climate change analysis in all ocean basins. The ADT-HURSAT data, covering TCs from 1978 to 2009, was also used by some research groups for comparison studies to conventional best track data.

Analyses of long-term TC frequency variations were conducted for the first and second assessment reports based on the four datasets, namely RSMC-Tokyo, CMA, HKO, and JTWC (Lee et al., 2010; Ying et al., 2012a). An updated analysis of the TC frequency variations with data up to 2017 was conducted in the current assessment (Fig. 1). Amid the substantial inter-annual and inter-decadal variations, there is a statistically significant decreasing trend in annual counts of storms of at least tropical storm intensity or at least typhoon intensity, according to the CMA (1949−2017) and HKO (1961−2017) data sets. However, no statistically significant trends are found for the JTWC (1945−2016) or RSMC-Tokyo (1951−2017) data sets (Table 1). Table 2 shows that, using a common period across the data sets (1977−2017), all datasets show a decline in tropical storm/typhoon (and above) counts, although the trend is not statistically significant at the 5% level for most of the datasets.

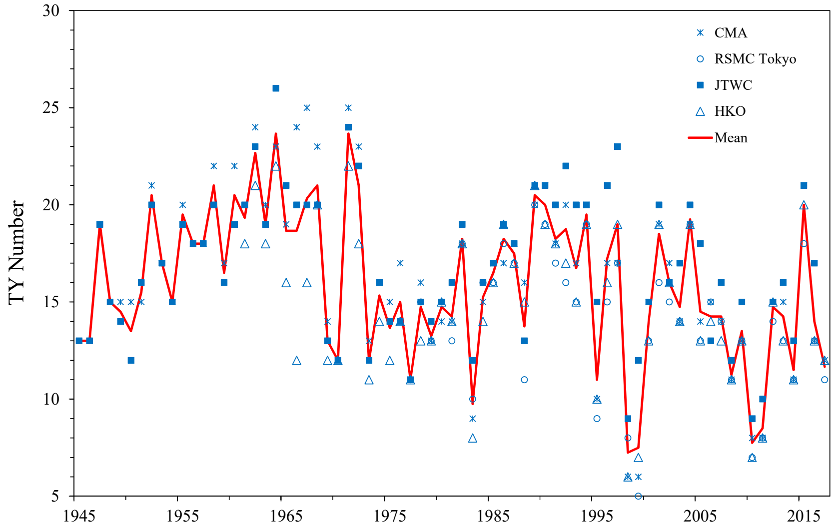
As for decadal changes, Choi and Cha (2015) studied the interdecadal variations in typhoons (categories 1−3) frequency over the WNP during the period of 1979−2011 and noted that the typhoon frequency has decreased since mid-1990s. Over the South China Sea, Li and Zhou (2014) concluded that there were two inactive periods (1979−1993 and 2003−2010) in the summertime (June −August) TC frequency in that region. Hu et al. (2018) also reported that there was a step-by-step interdecadal decrease in TC genesis frequency in the WNP from 1960 to 2014 in accordance with the phase of the Interdecadal Pacific Oscillation (IPO).

2.2. Tropical cyclone intensity and integrated storm activity metrics

Various research groups have adopted different approaches to reduce the uncertainty in TC intensity trend analysis due to wind speed conversion and intensity assessment methods. Kang and Elsner (2012) used a quantile method to construct a consensus trend of TC activity for the RSMC-Tokyo and JTWC datasets from 1977 to 2010. The most reliable consensus period is considered to be between 1984 and 2010, during which a statistically significant decreasing trend in the frequency and an increasing trend in intensity are both seen, implying fewer but stronger TCs in the WNP during the study



(a) storms of tropical storm intensity and above



(b) storms of typhoon intensity

Fig. 1. Annual storm counts in the western North Pacific from 1945 to 2017 based on the categories assigned according to reported maximum sustained winds converted into 10-min means for (a) storms of tropical storm intensity and above and (b) storms of typhoon intensity.

period. Moreover, Zhao and Wu (2014) examined the JTWC dataset and applied a downward adjustment to the maximum TC intensities prior to 1973. They detected a statistically significant shift in the frequency of Cat.4–5 TCs in the WNP in 1987 with the average number of Cat.4–5 TCs increasing from 5.1 per year during their first epoch (1965–1986) to 7.2 per year during their second epoch (1987–2010). Zhao et al. (2014) simulated Cat. 4–5 TCs frequency in a TC intensity model for 1948–2010 and concluded that there has been statistically significant decadal (12–18 years) variability of Cat. 4–5 TCs in the WNP and that changing TC track behavior is the most important factor behind the observed decadal variations in Cat. 4–5 frequency.

Using the International Best Track Archive for Climate Stewardship dataset (IBTrACS) and the ADT-HURSAT dataset over 1982–2009, Kossin et al. (2013) applied a quantile regression method to examine the trend in the quantiles of lifetime maximum intensity (LMI), considering only storms whose LMI was 65 knots or above. They reported that, for the best track data in the WNP, statistically significant positive trends are found in the mean LMI and in a range of quantiles. However, this result is not supported by the ADT-HURSAT data, which shows the highest quantile exhibiting a marginally statistically significant negative trend. As pointed out in their study, the 28-year length of the homogenized record of ADT-HURSAT

Table 1
Trends in annual numbers of TCs in WNP based on different datasets for all available data up to 2017. The trends are estimated by linear least squares regression. Results in bold indicate trends that are judged to be statistically significant at the 5% level.

Datasets	Data Period	Original intensity	
		All TC (tropical storm or above)	Typhoons
CMA	1949–2017	**−0.75/decade**	**−0.97/decade**
JTWC	1945–2017	+0.16/decade	−0.28/decade
RSMC-Tokyo	1951–2017	−0.44/decade[a]	−0.76/decade[b]
HKO	1961–2017	**−1.33/decade**	**−0.71/decade**
Datasets	Data Period	Adjusted Intensity (10-min mean)	
		All TC (tropical storm or above)	Typhoons
CMA	1949–2017	**−1.07/decade**	**−1.15/decade**
JTWC	1945–2017	−0.16/decade	**−0.42/decade**
RSMC-Tokyo	1951–2017	−0.44/decade[a]	−0.76/decade[b]
HKO	1961–2017	**−1.33/decade**	**−0.71/decade**

[a] The annual numbers from 1951 to 1976 are according to RSMC-Tokyo's assignment of TS category although the MSW data are not available.

[b] Period from 1977 to 2017 as MSW data in RSMC-Tokyo dataset only available since 1977.

Table 2
Trends in annual numbers of TCs in WNP based on different datasets from 1977 to 2017. The trends are estimated by linear least squares regression. Results in bold indicate trends that are judged to be statistically significant at the 5% level.

Datasets	Data Period	Original intensity	
		All TC (tropical storm or above)	Typhoons
CMA	1977–2017	−0.86/decade	−0.59/decade
JTWC	1977–2017	−0.63/decade	−0.42/decade
RSMC-Tokyo	1977–2017	−0.81/decade	−0.76/decade
HKO	1977–2017	−0.91/decade	−0.60/decade
Datasets	Data Period	Adjusted intensity (10-min mean)	
		All TC (tropical storm or above)	Typhoons
CMA	1977–2017	**−1.54/decade**	−0.86/decade
JTWC	1977–2017	−1.03/decade	−0.41/decade
RSMC-Tokyo	1977–2017	−0.81/decade	−0.76/decade
HKO	1977–2017	−0.91/decade	−0.60/decade

places strong constraints on the interpretation of the observed trends.

Kishtawal et al. (2012) used the IBTrACS dataset to assess the trends of TC intensification rate for TCs with peak intensity exceeding 80 knots (10-min mean) in different basins during the satellite era (1986–2010). Their results suggested that, in the WNP, there is a statistically significant positive trend for the intensification rate from tropical storm to typhoon stage, while the nominally positive trend in the rate from typhoon intensity to peak intensity is not statistically significant.

Using an Anthropogenic Climate Change Index (ACCI) defined by the difference between global surface temperatures from climate model ensemble simulations with and without anthropogenic climate forcing agents included, Holland and Bruyère (2014) reported clear relationships between ACCI and the observed proportion of very intense TCs (Saffir-Simpson categories 4 and 5) in the IBTrACS data from 1975 to 2010. While no change in global cyclone frequency or average intensity was found, they concluded there has been a substantial increase in the proportion of hurricanes/typhoons reaching category 4–5 levels, both globally and individually in all basins except for the eastern North Pacific. They also confirmed that an increase in proportion of category 4-5 storms is seen using the homogenized satellite-derived intensity data of Kossin et al. (2013), which begins in 1982.

On spatial variations, Park et al. (2013, 2014) investigated the spatial distribution of trends in TC intensity using five TC datasets (RSMC-Tokyo, HKO, CMA, JTWC and the ADT-HURSAT) from 1977 to 2010. All TC datasets depicted a spatially inhomogenous trend with weakening over ocean areas east of the Philippines (TP) and strengthening in the southern Japan and its southeastern ocean (SJ) regions. Moreover, there has been a statistically significant shift in the maximum intensity of TCs (maximum sustained wind speed over 17 ms^{-1}) close to East Asian coastlines during July–November, resulting in an increase in the intensity of TC's making landfall over East China, Japan and the Korean Peninsula. Cha et al. (2014) reported that while there is a decrease in the overall number of TCs that passed within the vicinity of Republic of Korea from 2001 to 2010, a statistically significant increase in the number of strong typhoons (maximum wind speed of 44 ms^{-1} or above) has been found. Mei and Xie (2016) applied cluster analysis to examine the intensification of landfalling typhoons (1-min maximum sustained wind of 33 ms^{-1} or above) over the WNP from 1977 to 2013 using the JTWC and adjusted RSMC-Tokyo datasets. The study stratified the typhoon tracks into four distinct clusters of which Clusters 1 and 2 contribute about 85% of the landfalling TCs in the basin. Cluster 1 typhoons form east of the Philippines, track north to northwestward and affect East Asia. Cluster 2 typhoons form slightly to the west of Cluster 1 over the South China Sea; they track west to northwest and affect Southeast Asia and southern China. The analysis of Cluster 1 typhoons suggested that the annual mean values of lifetime peak intensity of such storms have increased by about 15% during 1977–2013, along with a factor of four increase in the number Cat. 4–5 typhoons within the cluster. For Cluster 2 typhoons, the average intensity increased about 12% and the number of Cat.4–5 typhoons doubled over the 37-year period.

For rapid intensification, Zhao et al. (2018c) reported a statistically significant increase in the proportion of TCs undergoing rapid intensification at least once during their lifetime over the WNP during 1998–2015 compared to the period from 1979 to 1997. The study of Lin and Chan (2015), using the JTWC dataset from 1992 to 2012, reported that while there was some increase in TC intensity, decreases in frequency and duration dominated over the positive contribution of the intensity factor, resulting in a decreasing trend in the Power Dissipation Index (PDI) during the study period. Li et al. (2017) investigated changes in the destructiveness of landfalling TCs over China during 1975–2014 using the TC datasets of the four agencies (i.e. HKO, RSMC-Tokyo, CMA and JTWC) and found that TCs making landfall over East

China have tended to be more destructive in recent decades, with a statistically significant increase in PDI after landfall. Further analysis also revealed that such an increase in the PDI of TCs landfalling over East China is associated with concomitant enhancement in landfall frequency and intensity over East China.

2.3. Prevailing track and tropical cyclone exposure

Zhao and Wu (2014) reported a pronounced northwestward shift in TC tracks over the WNP between an early epoch (1965−1986) and a later epoch (1987−2010). This shift in the prevailing tracks between these two epochs led to a statistically significant decrease in TC occurrence over the South China Sea and a statistically significant increase from the Philippine Sea to the eastern coast of China and in the western part of the WNP. Park et al. (2014) also indicates that TC occurrence has a statistically significant decrease over the South China Sea and the eastern subtropical area of the WNP, with a statistically significant increase over oceanic areas around Taiwan, and marginally significant changes near the east coast of Japan. Kossin et al. (2016) analyzed TC exposure in the WNP using the TC datasets of the four agencies for 1980−2013. They found a poleward shift in the average latitude where TCs reach their peak intensity in the WNP. The poleward migration in the basin has coincided with decreased TC exposure in the region of the Philippines and South China Sea, while TC exposure has increased in the East China Sea region. Further analysis by Zhan and Wang (2017) suggested that this poleward migration over the WNP consists mainly of TCs with maximum sustained surface wind speed less than 33 $\mathrm{m s^{-1}}$. They concluded that this increase was linked to the greater SST warming at higher latitudes associated with global warming and its associated changes in the large-scale circulation, which favors greater TC formation in the northern WNP and fewer but stronger TCs in the southern WNP over the past 30 years. Knapp et al. (2018) found that the region prone to experiencing storms with discernible eyes expanded poleward globally from 1982 to 2015. Song and Klotzbach (2018) found that the poleward migration trends of the latitude of lifetime maximum intensity (LLMI) over the WNP vary on decadal timescales, with statistically nonsignificant and significant trends before and after 1980 respectively. Liu and Chan (2019) found that while the annual mean LLMI of TCs (considering storms of at least tropical storm intensity) shows a statistically significant increasing trend during 1960−2016, while for intense typhoons (category 4−5) they found no statistically significant trend but rather a pronounced interdecadal variation. A comparison of the spatial patterns of LLMI during the periods 1970−1990 and 1991−2011 shows that the LLMI location migrates from the southern to the northern part of East Asia from the first to the second period, with the frequency of intense typhoon landfalls and the average landfall intensities of the landfalling TCs increasing in Japan, the Korean Peninsula and east China but decreasing in southern China.

Kossin (2018a) analyzed the annual mean global and regional translation speeds of tropical cyclones based on the IBTrACS, NHC and JTWC data as well as 2-min Gridded Relief Data. They reported a statistically significant decreasing trend in the TC translation speed in the WNP, both for basin wide (about −20% or −0.07 $\mathrm{km\,h^{-1}}$ per year) and over land (about −30% or −0.12 $\mathrm{km\,h^{-1}}$ per year) over 1949−2016. Chu et al. (2012) also reported that translation speeds of TCs as well as steering flows show a weakening trend over the last half century in both the western portion of the WNP and northern South China Sea. Similar reductions in mean translation speeds for landfalling TCs in East China during 1975−2014 were also reported by Li et al. (2017). However, the robustness of the global decreasing trends in translation speed has been questioned by Moon et al. (2019) and Lanzante (2019), who suggest that the observed global trend reported by Kossin (2018a) may be influenced by changes in observing capabilities over time as well as natural variability.

Cinco et al. (2016) reviewed the trends and impacts of TCs in the Philippines from 1951 to 2013 and reported a decrease in the number of TCs landfalling in the Philippines, in particular during the last two decades of the study period. However, the number of extreme TCs (with 150 $\mathrm{km\,h^{-1}}$ maximum sustained winds or above) shows a slight increasing trend which is not statistically significant. Analyzing the JTWC dataset from 1945 to 2013, Takagi and Esteban (2016) reported a statistically significant increase in TC landfalling frequency in recent decades in the Leyte Island region of the Philippines (in the latitude zone between 10°N and 12°N). For TC activity around Japan, Grossman et al. (2015) reported that the number of years with greater numbers of TCs (wind speed greater than 17 $\mathrm{m s^{-1}}$) affecting the Japan Sea side and Pacific Coast side of Japan has increased since 1980.

3. Survey on tropical cyclone impacts in Typhoon Committee region

As a continued effort of the SAR (Ying et al., 2012a), the Expert Team conducted an update survey during 2016−2018 to gather regional information on the observed trends and impacts of TCs from the Members of the Typhoon Committee. This section briefly summarizes the information collected from the Members. In this section, we generally use TC to refer to cyclones originating over tropical ocean regions including all intensity classes (i.e., including tropical depressions). However, elsewhere in the paper, TC will refer to TCs of at least tropical storm (TS) intensity. Definitions of TC different from these conventions will be explicitly noted.

3.1. Frequency and intensity of landfalling and affecting tropical cyclones

The climatological mean annual frequency of TC genesis in the WNP for the period of 1971−2010 is 25.6 per year, while that of the previous three decades is 26.7. The number of landfalling/affecting TCs varies distinctly between Members. The climatological mean number of TCs/typhoons landfalling and affecting some of the Typhoon Committee Members are summarized in Table 3. The definitions of “landfalling” and “affecting” are also given in Table S1 of the supplementary information. China climatologically experiences nine landfalling TCs each year, the most by any of the 14 Members. The Philippines follows China as the second highest with about seven to eight per year. There are about 6.2 TCs and 2.3 typhoons coming within 500 km of Hong Kong, China each year. The number of TCs of at least tropical storm intensity making landfall in Japan is 2.7 per year. There was about only 0.8 landfalling TCs (maximum winds of 17.2 ms^{-1} or above) per year in Republic of Korea. In Macao, China, there is about one TC with TS intensity or above necessitating the issue of TC Signal No.8 and 0.6 landfalling typhoons per year. The number of TCs making landfall in Thailand is about 3 per year. Singapore was not directly affected by TCs apart from Tropical Storm Vamei in 2001. According to the SAR (Lee et al., 2012), there are about 1–2 landfalling TCs in Vietnam and about 18–20 TCs affecting the area of responsibility of Guam (Eq.–25°N, 130°E–180°E) each year. While detailed information on the literature review on TC frequency and intensity metrics is discussed in Section 2, further information on the long term variations of the frequency of landfalling/affecting tropical cyclones reported by some of the Members during the survey are summarized below:

(a) China

Trends in the number of TCs and typhoons landfalling in China are not statistically significant (Fig. 2), although a nominal decreasing trend in the number of landfalling TCs is observed (Yang et al., 2009).

(b) Hong Kong, China and Macao, China

The time-series of the number of TCs and typhoons entering within a 500 km range of Hong Kong both show a decreasing but not statistically significant trend since 1965 (Fig. 3), and there is no statistically significant trend for TCs coming within 300-km range of Hong Kong. There are also no statistically significant trends in the number of TCs (TS or above) affecting Macao, China (Fig. 4).

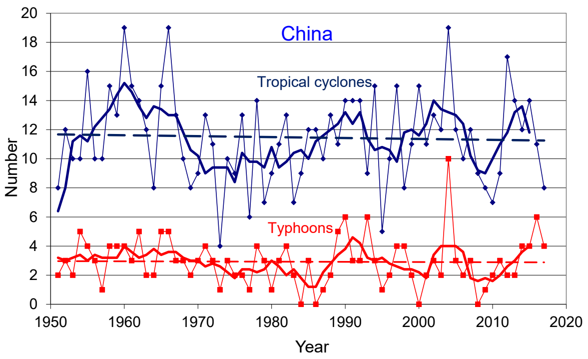


Fig. 2. Annual number of TCs (blue) and typhoons (red) landfalling in China (1949–2017). The solid, thick and dashed lines represent the annual numbers, 5-year running means and linear trends, respectively. (Courtesy of CMA).

Table 3
Climatological mean of landfalling/affecting tropical cyclones. (Note: Definitions of landfalling TCs and affecting TCs adopted by Members are summarized in Table S1 of supplementary information).

	Tropical Cyclones		Typhoons		Data Period
	Landfalling	Affecting	Landfalling	Affecting	
China	9 (7[a])	14	3	NA	1949–2017
Hong Kong, China	2.5[b]	6.2	1.4[b]	2.3	1961–2018
Japan	2.7	NA	1.4	NA	1981–2010
Macao, China	1.0	NA	0.6	NA	1990–2016
Republic of Korea	NA	NA	0.8[c]	3.1[c]	1977–2018
Singapore	Not directly affected by tropical cyclones, except TS Vamei in 2001				
Thailand	3	NA	0.005	NA	1951–2018

“NA” means Information not available from the survey results.

[a] TS or above.

[b] Landfalling within 300 km of Hong Kong, China (the number of landfalling tropical cyclones and typhoons with the center passing over Hong Kong are 0.3 and 0.2 respectively).

[c] TCs with maximum winds of 17 ms^{-1} or above.

(c) Japan

There is no statistically significant trend in the time series of TCs that approach within 300 km of Japan or make landfall (Fig. 5), although decadal and multi-decadal variations are observed. Longer-term analysis also shows no apparent trend over 115 years from 1900 to 2014 (Kumazawa et al., 2016). The record-breaking number of TC landfalls (10) in 2004 was more than three times greater than the climatological mean annual number of 2.7 (JMA, 2018).

(d) Republic of Korea

The numbers of TCs with maximum winds of 17 ms^{-1} affecting and landfalling in Republic of Korea have no long-term trend over 42 years from 1977 to 2018 (Fig. 6). While there was no very high impact landfalling or affecting typhoon from 2013 to 2017, the year 2018 was a highly active year, with five typhoons affecting Republic of Korea and two landfalling typhoons.

(e) Thailand

The frequency of TCs (most of which are tropical depressions) entering Thailand westward through Vietnam has a statistically significantly decrease after the mid-1960 (Fig. 7). However, the high frequency of TCs during 1960–1975 is considered to be a decadal variation.

3.2. Tropical cyclone induced precipitation

Zhao and Wang (2012) investigated the decadal variations of extreme TCs influencing China during 1949–2009 and

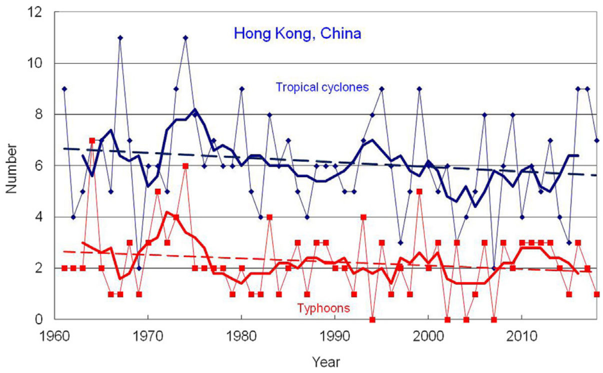


Fig. 3. Annual number of TCs (blue) and typhoons (red) coming within 500 km of Hong Kong, China (1961−2018). The solid, thick and dashed lines represent the annual numbers, 5-year running means and linear trends, respectively. (Courtesy of HKO).

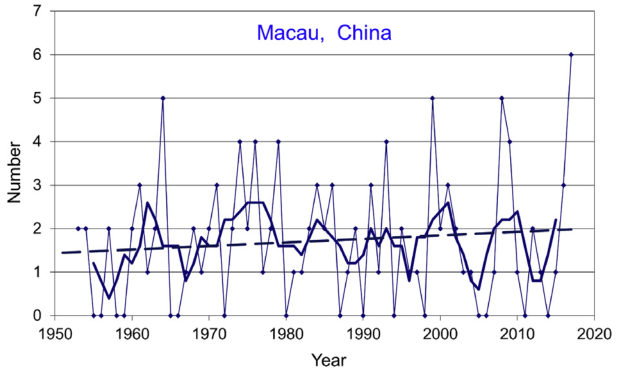


Fig. 4. Annual number of TCs (blue) (TS or above) necessitating the issuance of Tropical Cyclone No.8 in Macau, China (1953−2017). The solid, thick and dashed lines represent the annual numbers, 5-year running means and linear trends, respectively. (Courtesy of SMG).

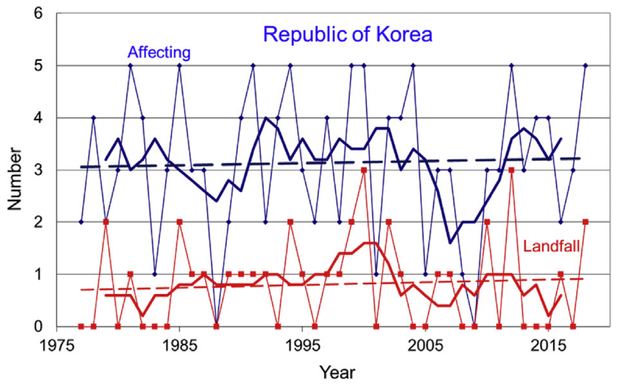


Fig. 6. The number of TCs with maximum winds of 17 m s^{-1} or above that approached Republic of Korea (blue) and those making landfall in Republic of Korea (red) from 1977 to 2018. The solid, thick and dashed lines represent the annual numbers, 5-year running means and linear trends, respectively. (Courtesy of KMA).

demonstrated that the decade when the maximum daily TC-induced precipitation occurred varies between areas and eras. Using daily precipitation observations at 514 meteorological stations during 1965−2009, Zhang et al. (2013) showed that the average rainfall per TC has a statistically significant increase in Southeast China during the study period, in particular south of the Yangtze River east of 110^{o}E from July to September. They suggested that this is in line with the reported shifts in prevailing TC tracks and increased times that systems remained as TCs after landfall. Chang et al. (2012) reported decreasing TC rainfall frequency and increasing TC rainfall intensity trends to the south of the China monsoon region from 1958 to 2010. Li and Zhou (2015) suggested that the frequency and intensity of TC rainfall over southeast China have undergone significant interdecadal changes during 1960−2009. Taiwan experienced a dramatic increase in typhoon-related rainfall in the beginning of the twenty-first century. Major contributing factors include slow-moving TCs and the location of their tracks relative to the meso-a-scale terrain (Chang et al., 2013). The typhoon rainfall shows a statistically significant increase for all intensities, while the non-typhoon rainfall exhibits a decreasing trend, particularly for lighter rain (Tu and Chou, 2013).

Li et al. (2015) pointed out that rainfall variability in Hong Kong is considerably affected by the TC rainfall which has a decreasing trend in both frequency and intensity in recent decades. The annual rainfall per TC and annual maximum

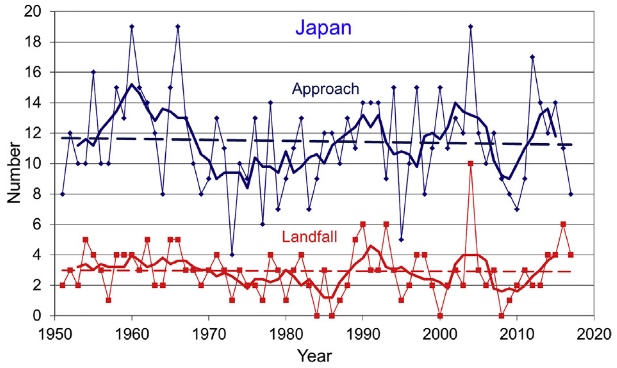


Fig. 5. The number of TCs with maximum winds of 17.2 m s^{-1} or above that approached Japan (blue) and those making landfall in Japan (red) from 1951 to 2017. The solid, thick and dashed lines represent the annual numbers, 5-year running means and linear trends, respectively. (Courtesy of JMA).

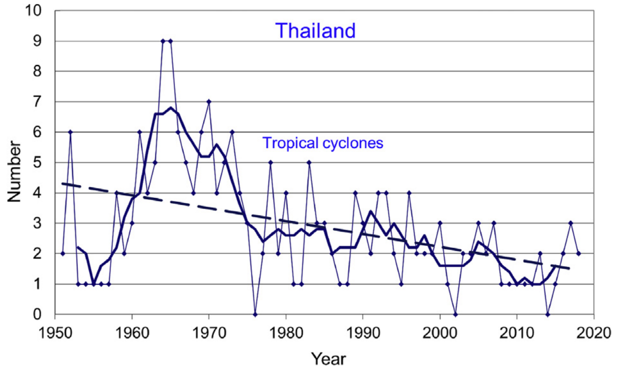


Fig. 7. The number of TCs (including TDs) making landfall in Thailand (blue). The solid, thick and dashed lines represent the annual number, 5-year running mean and linear trend, respectively. (Courtesy of TMD).

hourly TC rainfall within a 500 km range of Hong Kong from 1961 to 2018 has a slight decrease but without statistical significance at the 5% level (Fig. 8). In Macao, there is also no statistically significant trend in annual maximum precipitation per TC and mean total precipitation per TC (Fig. 9).

TC-induced one-day maximum precipitation shows a statistically significant increase in the Pacific Ocean east of Japan although a similar trend is not observed for the mean of the entire Japanese region and there is also a statistically significant decrease in the Philippines (Sato et al., 2012). Bagtasa (2017) investigated TC-induced rainfall in the Philippines using the RSMC-Tokyo TC dataset and the blended 64-year precipitation dataset which combines ground and satellite observations. An increasing trend since 2000 in TC rain and TC percentage contribution was observed in all four climate clusters adopted in this study.

In Vietnam, Nguyen-Thi et al. (2012) reported statistically significant increasing trends of TC rainfall and TC heavy rain days at most stations along the central coastline from 1961 to 2008. Wang et al. (2015b) conducted an analysis of autumnal (October and November) precipitation in Vietnam and revealed an intensification of precipitation over Central Vietnam since late 1990s. The interannual variation in precipitation over Indochina over a 33-yr period from 1979 to 2011 is analyzed from the view point of the role of westward-propagating TCs over the Asian monsoon region (Takahashi et al., 2015). Above-normal precipitation over Indochina occurred when enhanced cyclonic circulation with more westward-propagating TCs along the monsoon trough occurred.

3.3. Tropical cyclone-induced high winds

For mainland China, the TC high wind (TCHW) with the speeds ≥ 10.8 $\mathrm{ms^{-1}}$ frequency (intensity) shows a statistically significant downward (weakened) trend after the 1980s. The proportion of high wind events accounted for by TCHW decreased, although the trend was not statistically significant (Ni et al., 2015). The extreme maximum wind in China had the highest frequency in the 2000s during the period of 1949−2009 (Zhao and Wang, 2012).

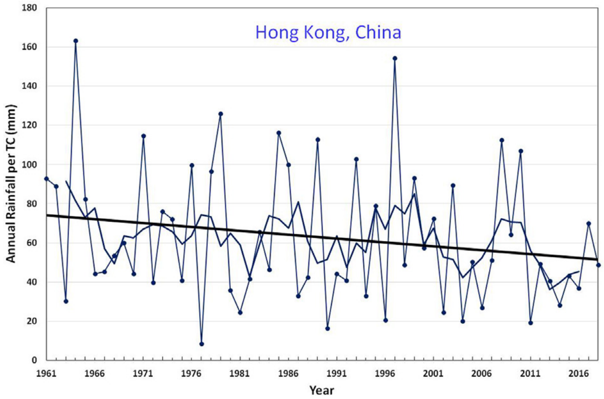


Fig. 8. Annual rainfall per TC associated with TCs entering within a 500 km range of Hong Kong, China from 1961 to 2018. Thin line represents the year by year statistics, bold line represents its 5-year running mean, and the straight line represents its linear fit. The trend is not statistically significant at the 5% level.

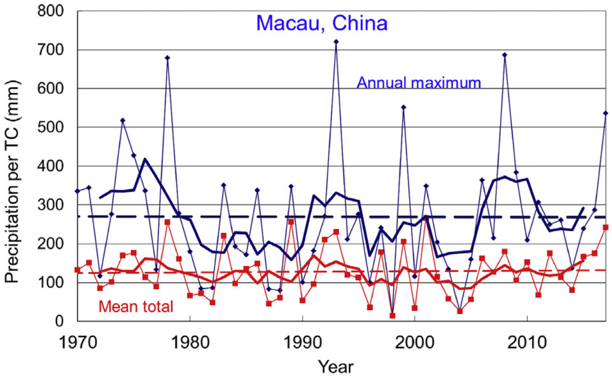


Fig. 9. Annual maximum precipitation per TC (blue) and mean total rainfall (red) per TC in Macau, China from 1970 to 2017. Thin line represents the year by year values, bold line represents its 5-year running mean, and the straight line represents its linear fit. The trend is not statistically significant at the 5% level. (Courtesy of SMG).

TC-induced annual maximum 10-min mean wind and maximum 1-sec gust as recorded at Waglan Island, an offshore island about 20 km southeast of Hong Kong, China, have slight statistically insignificant decreasing trends (Fig. 10(a)). However, the maximum 10-min wind at Kai Tak (an urban station) has a statistically significant decreasing trend from 1968 to 2018 (Fig. 10(b)). This decrease is attributed to continuous urban development and elevation in building height based on computational fluid dynamics simulations (Peng et al., 2018). Data from Macao shows periodic changes on a decadal time scale but no statistically significant trends in either the annual maximum gust or hourly average maximum wind speed (Fig. 11).

Fig. 12 shows the time series of the annual maximum wind speeds of all TCs occurring in the emergency zone (EZ; 28−40°N, 120−132°E) of Republic of Korea from 1977 to 2018. The largest maximum speeds were seen in 1983, resulting from Typhoon Forrest. The typhoon intensities over the EZ vary by year and a distinct trend is not seen from a long-term perspective (Cha and Shin, 2019). However, Cha et al. (2014) found that the number of strong typhoons that impacted the Republic of Korea, with maximum wind speeds exceeding 44 $\mathrm{ms^{-1}}$, has a statistically significant increase over the period 2001 to 2010. Park et al. (2014) reported an increase in landfall intensity over East China, the Korean Peninsula and Japan as well. Extreme TCs with high wind speeds in the Philippines have become slightly more frequent for the period of 1971−2013 (Cinco et al., 2016).

3.4. Storm surge and extreme sea levels

Needham et al. (2015) conducted a review of TC-generated storm surge data sources, observations, and impacts in different TC basins. They reported that the WNP observed the highest rate of low-magnitude storm surges, as the coast of

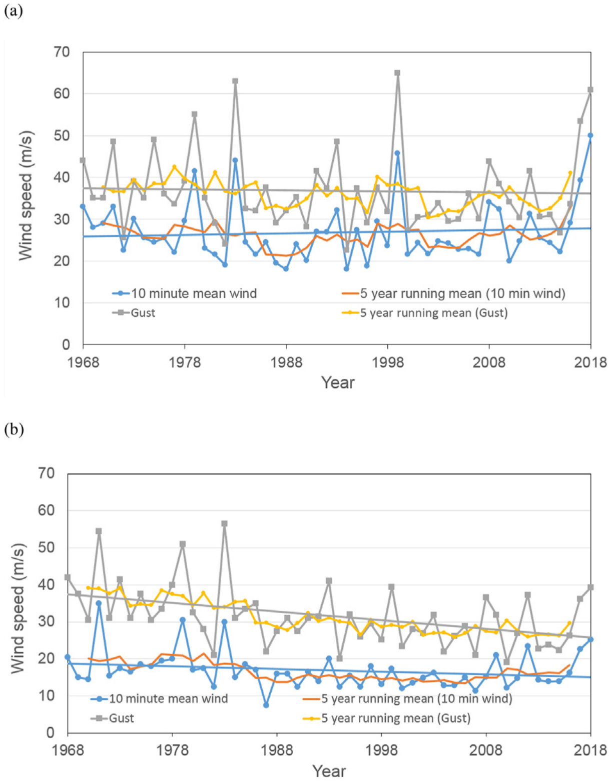


Fig. 10. Annual maximum 10-min mean wind speed and gust at (a) Waglan Island and (b) Kai Tak associated with TCs entering within a 500 km range of Hong Kong, China from 1961 to 2018. Thin lines represent the year by year statistics, bold lines represent 5-year running means, and the straight lines represent linear fits.

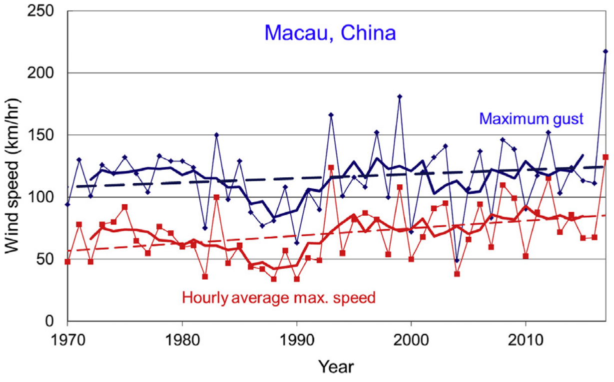


Fig. 11. Annual maximum gust and hourly average maximum wind speed of TCs in Macao from 1970 to 2017 (Courtesy of SMG).

China averages 54 surges $\geq$1 m per decade, and rates were likely higher in the Philippines. By forcing the Global Tide and Surge Model with wind speed and atmospheric pressure from a global atmospheric reanalysis from the European Centre for Medium Range Weather Forecasting (ECMWF), Muis et al. (2016) developed a global reanalysis of storm surges and extreme sea levels (Global Tide and Surge Reanalysis data set). They estimated that 1.3% of the global population is exposed to a 1 in 100-year flood. Three out of the 14 Members of the Typhoon Committee are listed among the 10 most-exposed countries: China, Vietnam, and Japan. China alone accounts for half of the global total exposure. By analyzing 64 years (1950−2013) of observations and storm surge model simulations, Oey and Chou (2016) found a statistically significant rise in the intensity as well as a poleward-shift of the location of TC-induced storm surges in the WNP after 1980s. They suggested that the rising and poleward-shifting trends of storm surges are mainly attributed to the slowdown of TC translation speed and the tendency for TC tracks to more readily recurve in recent decades which are in turn closely related to the weakening of the easterly steering flow over the tropical and subtropical WNP. However, according to the study by Hatada and Shirakami (2016) based on the TC-induced storm surges with 50-year return period (H_{50}) developed from an 80-year dataset covering 1934 to 2013, H_{50} estimated from the 30-year moving window shows no major trends in the WNP including most of Japan.

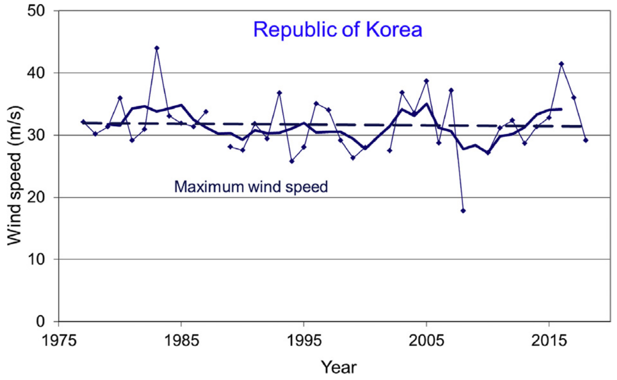


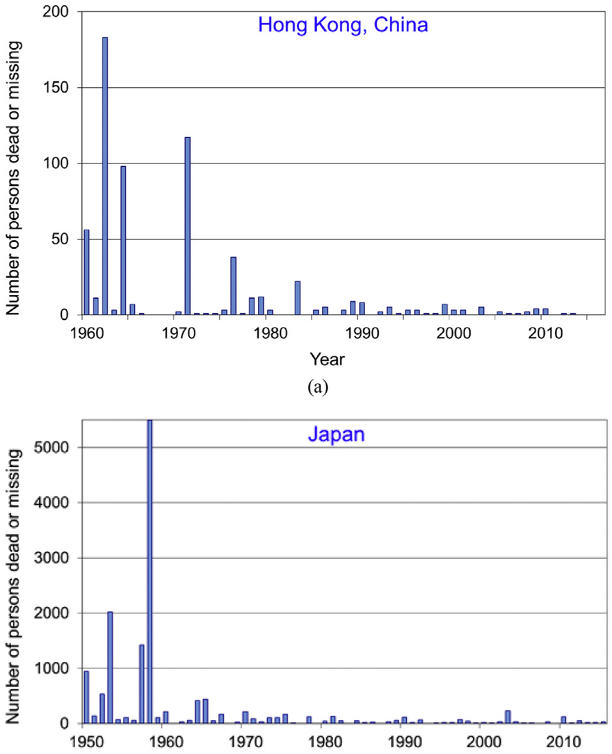
Fig. 12. Annual lifetime-maximum wind speeds of TCs (with 10-min average maximum wind speed of 17 m s^{-1} or above at 6-h intervals (00, 06, 12, and 18 UTC) over the emergency area of Republic of Korea (28−40°N, 120−132°E)) during the 1977−2018 period. The years of 1988 and 2009 did not have any such TCs, and were left blank. (Courtesy of KMA).

3.5. Casualties and economic losses

Climatological annual mean damages due to tropical cyclones in China include 505 fatalities and 5.6 billion USD accounting for 0.4% of annual GDP. Although there was little change over the past 25 years in the overall landfall frequency, landfall intensity and overland time, the annual total direct economic loss increased significantly presumably due to the rapid economic development during that time (Zhang et al., 2011). Chen et al. (2013) analyzed TC-induced damages for mainland China, including the number of fatalities and missing persons, affected crop area, destroyed houses, and rate of direct economic loss. No clear trend in damage per individual TC is found. The annual frequency of TCs causing heavy and catastrophic damage shows a clear decrease from 1984 to 2008 with no trend in the total number of damaging TCs. For Hong Kong, China, with continuous investment and strengthening of infrastructure and disaster risk reduction measures in the city over the past 50 years, the annual number of casualties due to TCs has decreased distinctly since 1960s (Fig. 13(a)).

In Japan, the number of casualties due to TCs has a statistically significantly decrease over 90 years (Fig. 13(b)) as infrastructure countermeasures have been developed, especially since 1961. Ushiyama (2017) analyzed casualties caused by storms and floods including TCs in Japan for the period of 1968−2014. A statistically significant decrease in casualties was identified for the period. The trend remains the same even after 1980s, although the damage to houses caused by other influences besides storms and floods do not show a statistically significant decrease. In the Republic of Korea, Typhoon Thelma in 1987 caused 345 casualties, and Typhoon Rusa in 2002 caused record-breaking property damage for the period since 1900. However, there is a decreasing trend in typhoon-induced damage, including casualties and economic loss, since 2000 (Cha and Shin, 2019).

Normalized cost of damages caused by TCs has increased in the Philippines since 1971 while there were no statistically significant trends reported in the frequency, intensity and landfall of TCs, (Cinco et al., 2016). Therefore, this increasing trend in the costs is presumably due to socio-economic factors such as land-use practices, living standards and policy responses. Typhoon Haiyan in 2013 caused historic record-breaking damages with socio-economical cost of 2 billion USD due to a devastating storm surge (Lagmay et al., 2015), with the cost of damages reaching twice the level of the second largest damage event in the historical record. A large number of TC fatalities occur in neglected low income regions such as those destroyed by Super Typhoon Haiyan, as inferred from an examination of 40-years of Australian tropical cyclone reports (Seo, 2015).



(a)

(b)

Fig. 13. Number of fatalities or missing persons due to tropical cyclones in (a) Hong Kong, China over the period 1960 to 2018 (Courtesy of HKO); (b) Japan from 1951 to 2017. (Data source: “White Paper on Disaster Management” published by the Cabinet Office of the Japanese Government).

4. Detection and attribution of tropical cyclone changes

4.1. The assessment approach

Against the background of climate change, the questions of whether there are detectable changes in TC activity in the Typhoon Committee Region and whether any changes in TC activity in the region can be attributable to human-induced climate change are prime concerns from both scientific and disaster risk reduction perspectives. This section generally adopted the detection and attribution assessment approach detailed in the assessment by the WMO Task Team on this topic at the global scale (Knutson et al., 2019) and a literature review stemming from the 9th International Workshop on Tropical Cyclones (Walsh et al., 2018), with our focus on those changes occurring in the Typhoon Committee Region. Much of our analysis and case studies are adapted from the WNP parts of that global assessment.

Some key terminology and points of note for the assessment approach are as follows:

(i) A “detectable change” refers to a change in TC activity that is highly unlikely to be due to natural variability alone. Some commonly used methods of assessing this issue include trend analysis and comparison of observed TC changes with changes obtained from model simulations of natural or internal variability.
(ii) A “detectable anthropogenic change” refers to a change that is both detectable and where the sign of an anthropogenic influence can be established with some degree of confidence.
(iii) “Attribution” refers to evaluating the relative contributions of different causal factors to an observed change, including an assessment of statistical confidence (Hegerl et al., 2010).

It should be noted that attribution can be made either for changes that have been established as detectable or for changes which have not been shown to be detectable. In the latter case, the attribution claim is of a type known as “attribution without detection”, which typically have relatively low confidence, although such information may be useful for risk assessment and for early identification of changes that are expected to later emerge as detectable changes. Descriptions of the meanings of different confidence levels used in our assessment are given in Table 4.

The anthropogenic component of change for attribution studies is normally estimated using a climate model historical forcing run. Future projections from climate models can give some broad expectation of the nature of historical anthropogenic influence, but should be used with great caution, if at all, for this purpose, since historical climate forcings will differ

Table 4
Illustrative description of the different confidence levels used or potentially used in this report. The characteristics were adopted in part from U.S. Fourth National Climate Assessment (NCA4; USGCRP, 2018).

Confidence Level	Description of Characteristics
Very High	Very strong evidence (established theory, multiple sources, very confident results, well-documented and accepted methods, etc.), high degree of physical understanding of mechanisms, strong consensus, established evidence of predictive skill of models.
High	Strong evidence (established theory, multiple sources, confident results, well-documented and accepted methods, etc.), good physical understanding of mechanisms, high consensus
Medium	Moderate evidence (several sources, good consistency, methods vary and/or documentation limited), fair physical understanding of mechanisms, good consensus
Low-to-Medium	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), some physical understanding of mechanisms, competing schools of thought
Low	Inconclusive evidence (some published evidence, but: extrapolations, inconsistent findings, poor documentation or data or methods, untested methods), poor physical understanding of mechanisms, disagreement among experts

substantially from expected future climate forcings (such as the relative mix of aerosols and greenhouse gas forcings).

Observed changes in TC activity which we consider here can include long-term changes such a trend over many decades, or in some cases a particular event (storm case or unusually active season). In the latter instance, we consider cases where a particular "event attribution" study has been published that makes claims about whether anthropogenic climate change either changed the probability of occurrence of an event over some threshold level or whether it altered the intensity of the event in a given direction. This recognizes recent developments in the field of event attribution (e.g., NAS, 2016).

In assessing whether a TC change is detectable or whether anthropogenic forcing contributed in a certain direction to the change, different types of errors can be considered. Following the conventions discussed in Lloyd and Oreskes (2018), if we conclude that a change is detectable or that anthropogenic forcing contributed, and this turns out not to be the case, we have made a Type I error (overstating of anthropogenic influence). On the other hand, if we do not conclude a change is detectable or that anthropogenic forcing contributed to it when in fact the change is detectable and anthropogenic forcing did contribute to it, we are making a Type II error (understating anthropogenic influence).

Previous TC/climate change assessments typically have focused on avoiding Type I errors. Here we will separately consider two complementary viewpoints: emphasis on avoiding Type I error and emphasis on reducing the occurrence of Type II error. To achieve this goal, we will nonetheless require *substantial evidence* and require that at least the *balance of evidence* supports the conclusion of detectable change or anthropogenic influence. We recognize in advance that this approach will result in more speculative statements with a higher expected occurrence rate for Type I errors (e.g., false alarms for detectability or anthropogenic influence), and so any statements arising out of the goal of "Type II-error reduction" will be stated separately from typical Type I error avoidance statements in our summary, in order to clearly distinguish the different types of statements.

Before commencing with the assessment of detectable/attributable changes in TCs, we note that there is published evidence of detectable and attributable climate change for some climate variables in the WNP. One example of this is Gillett et al. (2008) who found evidence for attributable anthropogenic warming of SSTs in the tropical cyclogenesis region of the basin using detection/attribution fingerprinting techniques. A second example is the regional surface temperature trends analysis of Knutson et al. (2013) who present maps (their Fig. 10(e) and (f)) indicating a number of areas in the basin where a century-scale detectable warming trend is observed, with a contribution from anthropogenic forcing, according to their grid-point based assessment using SST observations and CMIP3/CMIP5 models.

4.2. TC-climate change case studies

In this section, several case studies of possible detectable influence or anthropogenic influence on either a particular TC event (storm or season) or the climatology of a particular TC metric (e.g., global mean TC intensity) are considered. We examine cases where a conclusion about such influence have been published in the peer-reviewed literature. The conclusions are similar to those given by the WMO Task Team report (Knutson et al., 2019). Brief discussions of the case studies are presented below.

a. Case study: Poleward migration of latitude of maximum intensity (western North Pacific)

As discussed in Section 2.3, the latitude of lifetime-maximum intensity (LLMI) of TCs has moved northward in the WNP since the 1940s (Kossin et al., 2014, 2016; 2018b). This poleward migration appears to be statistically most robust in the WNP. It is thought to be related to the global poleward expansion of the tropics in general (Lucas et al., 2014; Sharmila and Walsh, 2018). Studholme and Gulev (2018) and Tennille and Ellis (2017) reported relatively small poleward migration of LLMI in the basin, but both used much shorter analysis period. Song and Klotzbach (2018) infer that both the Interdecadal Pacific Oscillation and basin SST warming and related potential intensity increase are factors affecting the poleward migration in the WNP, by influencing the genesis latitude (Daloz and Camargo, 2018) and the latitudinal distance from genesis to the LLMI, respectively.

Some follow up studies also provide independent supporting evidence for a poleward shift in TC tracks in the region (Liang et al., 2017; Altman et al., 2018). For example, Altman et al. (2018) used analysis of tree-rings in the basin to infer that TC-induced damage to forests has increased in the more poleward regions, comparing pre- and post-1920 periods. This supports the notion of a long-term poleward shift of TC activity in the region and lends support to the notion that the observed changes are unusual compared to natural variability.

The LLMI changes in the basin may be related to changes in steering flows and shifts in TC occurrence of tracks from the South China Sea toward the East China Sea in recent decades as shown in a number of studies (Park et al., 2014; Kossin et al., 2016; Choi et al., 2016), leading to increased TC landfall intensity over east China, Korean Peninsula and Japan. Zhan and Wang (2017) suggest that the poleward movement of LLMI in the region is most pronounced for weaker TCs. The observed decadal shifts in TC activity in the region will be further discussed in a separate case study below.

Exploring the potential causes of the LLMI trends, Kossin et al. (2016) performed linear trend analysis on the poleward shift of LLMI in the western North Pacific since the mid-1940s. While the trend through 2016 is only marginally statistically significant in the full time series, they found that when they removed (via linear regression) the influence of key modes of multidecadal variability in the region (i.e., El Niño/ Southern Oscillation and the Pacific Decadal Oscillation), the trend in the residual series became even more statistically significant than in the original series. The statistical significance of the trend is also robust when the Atlantic Multidecadal Oscillation (AMO) or Interdecadal Pacific Oscillation signal is removed (J. Kossin, personal communication 2018). Zhang et al. (2018) had found that the AMO could be related to WNP TC activity. The statistical significance of the trend in the residuals is also robust when different TC datasets are used (Kossin et al., 2016), or with the use of either annually or seasonally (July−November) averaged climate indices (J. Kossin, personal communication 2018) (Fig. 14).

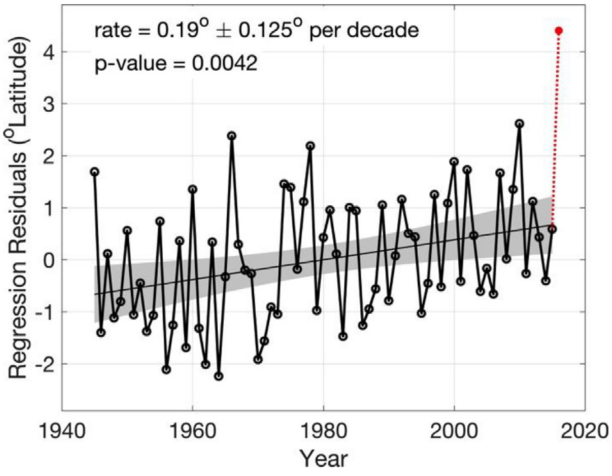


Fig. 14. Average (July−November) latitude of tropical cyclones in the western North Pacific at the time of their maximum intensity based on surface winds. Shown is the residual time series obtained after regressing the original time series onto the Pacific Decadal Oscillation and El Nino/Southern Oscillation indices and then removing those components from the time series. The trend statistics in the panel include the rate of poleward migration (degrees latitude per decade) and two-sided 95% confidence intervals for the trend. The p-value indicates the statistical significance of the trend based on a calculation that does not include the large positive outlier for 2016 (red) which would make the trend even more significant. From Kossin (2018b), licensed under CC BY 4.0.

Modeled trends in WNP LLMI were analyzed based on CMIP5 historical runs and 21st century projections (Kossin et al., 2016). TC simulations of CMIP5 models have a number of limitations in the basin, with some models simulating 20% or less of the climatological frequency of TCs there. The CMIP5 historical run ensemble mean shows a nominally positive, but not statistically significant, trend in LLMI over 1980−2005, while there is a statistically significant poleward trend in the Representative Concentration Pathway 8.5 (RCP8.5) scenario for the CMIP5 models analyzed by Kossin et al. (2016). The pattern of track density changes in the CMIP5 historical simulations is qualitatively similar to that in the observations, which supports the notion of some anthropogenic influence on the observed track density changes.

In another modeling study, Oey and Chou (2016) explored multidecadal changes of historical storm surge events for the region by simulating surge events, driving an ocean model with observed estimated wind forcing from TCs in the WNP basin. Their study suggests an increase in the intensity of simulated surges since 1950 and a poleward shift of the latitude of intense surge events since about 1980. However, the linkage of these changes to anthropogenic forcing was done only in relatively general terms, and they did not estimate this effect through direct climate forcing experiment nor demonstrate that the changes were outside the range of natural variability.

Based on the above discussion, we conclude, following Knutson et al. (2019a), that from a Type I error perspective, that there is *low-to-medium confidence* that the observed poleward migration of the WNP basin LLMI is detectable compared with the estimated natural variability of TC activity in this basin. However, because the simulated change in the CMIP5 historical runs is not statistically significant, we have only *low confidence* that the observed change has a positive anthropogenic contribution. Alternatively, from a Type II error perspective, where we are attempting to reduce cases of overlooked detection or underestimated anthropogenic influence, we find that the balance of evidence suggests that the observed poleward migration of latitude of maximum TC intensity in the WNP basin is both detectable and that it has a positive contribution from anthropogenic forcing.

b. Case study: Landfalling TC trends

A relatively long record of landfalling TC activity is the century-scale time series of TC landfalls for Japan, extending back to 1901 (Fig. 2 from Kumazawa et al., 2016). This time series shows no prominent trend since 1901. Similarly, as depicted in Section 3.1 and a previous assessment (e.g. Lee et al., 2012), the (shorter) available landfalling time series from a number of other subregions of the Typhoon Committee region generally do not show consistent pronounced increasing trends but a mixture of different changes. For example, there is a statistically significant increase for the Korean Peninsula, but most of the other regional TC landfalling series show no change or decreasing trends. To date no study has made a clear demonstration that any observed landfalling TC trends in the region are unusual compared to natural variability. Given this lack of detectable trends and the finding from Kossin et al. (2016) of a lack of statistically significant poleward displacement of TCs in the basin in the CMIP5 historical runs, we conclude there is *low confidence* in any detectable anthropogenic influence on landfalling TC frequency to date in the Typhoon Committee region, and no detection or attribution of change to anthropogenic forcing from a Type II error perspective.

c. Case study: Event attribution for Super Typhoon Haiyan (2013)

Event attribution studies can examine individual TC events for evidence of anthropogenic influence. This influence can be either on the probability of occurrence of an event beyond some threshold value or on the intensity of an observed event. As discussed in a U.S. National Academy of Sciences (NAS) 2016 report, one approach is to use an "ingredients-based" methodology, re-simulating an event using a model (e.g., a TC forecast model), but altering the large-scale environmental conditions (e.g., sea surface temperatures and atmospheric temperatures) based on an estimate of pre-industrial-to-current anthropogenic climate change.

Takayabu et al. (2015) used this approach to re-simulate Super Typhoon Haiyan's (Philippines, 2013) intensity, using an estimated anthropogenic SST change signal characterized by relatively strong SST warming near the Philippines, with atmospheric boundary conditions from a lower resolution global model, and using a very high resolution (~2 km grid) nested regional model. They found that the imposed anthropogenic changes to the environment strengthened the present-day storm compared to the pre-industrial version of the storm. On the other hand, by using a lower resolution model—a global domain with grid spacing locally as fine as 8 km in the WNP, Wehner et al. (2018) simulated a moderating anthropogenic influence on Haiyan's intensity. These ingredients-based studies start by assuming the existence of a particular storm and synoptic situation and thus do not address whether anthropogenic forcing altered the storm's probability of occurrence. The Takayabu et al. (2015) study does not incorporate possible anthropogenic influence on circulation features that could affect the storm's track (steering flow) or intensity changes (via environmental wind shear), whereas these circulation change influences are included in the Wehner et al. approach.

These event attribution studies do not attempt to provide evidence that an observed change in TC activity is detectable (i.e., that an observed climate change signal in TC intensity in the region is highly unusual compared to natural variability alone). Therefore, in the above studies, any cases of inferred anthropogenic attribution are examples of attribution without detection which we assess as having *low confidence*. From the perspective of avoiding Type II errors, we find that the evidence from available studies is inconclusive on whether anthropogenic forcing contributed to the intensity of Super Typhoon Haiyan in the WNP.

d. Case study: Event attribution for recent anomalous TC seasonal activity

Event attribution studies can examine groups of events (e.g., individual TC seasons or even groups of seasons) for evidence of anthropogenic influence. The influence can be either on the probability of occurrence of a number of events beyond some threshold value or on the total number of events in the season. Model simulations of pre-industrial-to-current anthropogenic climate change are typically used to re-simulate entire seasons or multiple seasons of activity under pre-industrial vs. modern day conditions.

Analyzing the causes of the unusually active WNP TC season of 2015 using model simulations, Zhang et al. (2016) infer an anthropogenic contribution to high Accumulated Cyclone Energy (ACE) in the basin in that season. Using a purely statistical approach, Yang et al. (2018) infer a contribution of global warming to record-setting (1984−2015) TC intensity in the WNP in 2015. This study used global temperature as a statistical predictor, rather than estimating an anthropogenic contribution from climate model simulation.

The above studies are examples of event attribution studies. Neither of these studies provides convincing evidence that an observed change in TC activity in the WNP is detectable (i.e., an observed climate change signal that is highly unusual compared to natural variability alone). Therefore, in the above studies, any cases of inferred anthropogenic attribution are examples of attribution without detection, and we have *low confidence* in the attribution. From the perspective of avoiding Type II errors, we conclude that the balance of evidence suggests an anthropogenic contribution to the highly active 2015 WNP TC season. We do not conclude that the observed changes are detectable, or unusual compared to natural variability, based on the balance of available evidence.

e. Case study: Increase in proportion of Category 4−5 TCs

Holland and Bruyère (2014) analyzed changes in TC frequency for various storm categories, assessing IBTrACS/JTWC intensity data and a shorter homogenized satellite-based intensity data (Kossin et al., 2013). Using the satellite-based data, they conclude that the global proportion of hurricanes reaching Category 4 or 5 intensity has increased by 25−30% per degree Celsius of global warming in recent decades. They found a similar though weaker trend signal using Kossin's (2013) homogenized global satellite TC intensity record.

Their globally focused analysis contains some information on the WNP basin and finds a statistically significant positive trend in category 4−5 proportion for the WNP using data from 1975 to 2010. However, they did not report results for the WNP using the shorter, homogenized ADT-HURSAT (Kossin et al., 2013) satellite-based record. For landfalling TCs globally, they find a statistically significant increase in category 4−5 proportions based on the data of Weinkle et al. (2012), but they reported only a weak, negative trend in this metric for the WNP, which they attributed to a shift in recent decades of the main genesis location in the basin toward the equator and eastward.

The potential importance of data homogeneity for this problem was noted by Klotzbach and Landsea (2015). Their trend analysis of category 4−5 percentages used JTWC data for the years 1970−2014. Their results for the WNP indicate statistically significant increasing trend for 1970−2014, but not for 1970−2004 or for 1990−2014. They recommend that global trend studies begin around 1990 owing to data homogeneity concerns (which presumably refers to the JTWC data, but not necessarily to the satellite-based data of Kossin et al. (2013)).

These analyses did not compare the observed trends to expected internal climate variability on various multi-decadal timescales from climate model control runs. Holland and Bruyere's linkage to anthropogenic forcing as a mechanism is statistical in nature as there is no explicit comparison between observed storm metrics and those derived from simulations using historical forcings. They inferred that the observed increase may be reaching a saturation point soon and may not continue increasing over the coming century, which would hinder its detectability, although they noted that this saturation point may be higher for the WNP basin than other basins.

Considering this evidence from a WNP focus and from a Type I error perspective, we conclude that there is only *low confidence* in detection of any anthropogenic climate change signal in historical proportion of category 4−5 TCs in the WNP. Alternatively, from the perspective of reducing Type II errors (where we require l convincing levels of evidence), the studies of Holland and Bruyère (2014) and Klotzbach and Landsea (2015) provide conflicting interpretations for the WNP, and neither study presented clear evidence of a detectable trend there using the shorter, homogenized satellite-based intensity record of Kossin et al. (2013). Therefore, we do not conclude that the balance of evidence supports the notion of a detectable increase in the proportion of Category 4-5 storms in the WNP, nor that it supports an anthropogenic forcing influence on the proportion of Category 4-5 storms.

f. Case study: Slowdown of TC translation speeds

Kossin (2018a) found a statistically significant decreasing trend in TC translation speed over the WNP over 1949−2016, a change seen in a number of other basins, but which was especially pronounced over land regions near the WNP (21% decrease). However, follow-on analyses by Moon et al. (2019), Lanzante (2019) suggest that the observed global trend reported by Kossin (2018a) may have been influenced by changes in observing capabilities over time, casting some doubt on the robustness of the reported global trends, which we infer likely applies in the case of reported trends in the WNP since 1949 as well. A previous study by Chu et al. (2012) had also found a statistically significant decline in TC translation speeds (1958−2009) in the WNP and South China Sea regions, accompanied by a decrease in steering flows. Considering these available studies, we assess the confidence in a detectable decreasing trend in observed TC translation speed in the WNP as low. There are very few modeling studies of anthropogenic influence on TC propagation speeds in the WNP (e.g., Kim et al., 2014), and none in historical simulation mode, and so we conclude that it is premature to ascribe these observed changes to anthropogenic influence.

In summary, from a Type I error avoidance perspective, we have *low confidence* that there has been a detectable decrease in WNP TC translation speeds since 1949 or that anthropogenic forcing has contributed to the observed decrease. Alternatively, from the perspective of reducing Type II errors, the balance of evidence is inconclusive on whether there has been a detectable decrease in TC translation speeds over land regions near the WNP since 1949, nor is there a balance of evidence that anthropogenic forcing contributed to such an observed decrease.

g. Case study: TC frequency changes

Analyses of time series of TC frequency in the WNP were presented in Section 2 for both tropical storms and storms of typhoon intensity. These analyses show some evidence for statistically significant decreasing trends, but the results are dependent on the dataset used and the period examined. The longest records examined (from JTWC, extending back to 1945) show no statistically significant trends in either tropical storms or typhoons. Zhao et al. (2018a) conclude that internal variability (the Interdecadal Pacific Oscillation) contributed to the lower TC frequency observed in the WNP basin after 1998.

We conclude that there is no substantial evidence (i.e., *low confidence*) for a detectable anthropogenic influence on tropical storm or typhoon frequency in the WNP.

h. Case study: TC intensity changes

The question of whether there has been any detectable anthropogenic influence on TC intensities in the basin can be characterized in terms of two issues: whether the data are reliable enough for trend analysis, and if a trend is found, whether the trend can be distinguished from natural variability and can any changes be causally attributed to anthropogenic forcing.

Trend analyses of past change in TC intensity in the WNP (Section 2) have produced conflicting results. Some studies have reported increasing trends of intensity and related metrics (e.g. Kang and Elsner, 2012; Mei et al., 2015; Zhao and Wu, 2014; Kishtawal et al., 2012). These studies were based on use of the conventional best track intensity data, in some cases with adjustments for homogeneity issues. Significant problems with historical records of TC intensity in the basin were noted by Knapp et al. (2013), based on analysis of central pressure data, and they particularly noted low confidence with wind-based estimates in older parts of the best track data. To address the data homogeneity problems using objective intensity estimation from satellite data, Kossin et al. (2013) analyzed intensities using both best track data (IBTrACS) and the ADT-HURSAT satellite-based record over 1982–2009. Statistically significant increases were found for some quantiles of the data in the best track data, but these were not supported in the ADT-HURSAT data, which had some negative trends at higher quantiles.

Clearly there are data quality issues to be addressed with intensity data in the basin, and trend results will depend on the nature and quality of adjustments made to the data to attempt to correct for time-dependent biases which can introduce spurious trends. In addition to these data concerns, while a number of the above studies link intensity changes to surface temperature metrics, there are not clear demonstrations in the published studies that observed trends in TC behavior are outside the range of expected natural variability in the basin, or that the observed changes have been caused by anthropogenic forcing. For example, changes in the proportion of TCs in the basin undergoing rapid intensification was observed to increase, beginning in 1998, but this change was linked to decadal changes in large-scale atmosphere-ocean conditions, and was not linked to anthropogenic forcings (Zhao et al., 2018c). Concerning landfalling TC intensity, Mei and Xie (2016) found increased intensity and intensification rates of landfalling typhoons since the 1970s. They estimate that landfalling typhoons that strike East and Southeast Asia have intensified by 12–15% over the past 37 years, which they attributed to locally enhanced surface warming. While data quality issues for landfalling TCs are presumably not as severe as for the basin-wide data, their study links the intensity changes to surface warming but does not claim to have detected an anthropogenic climate change signal.

In summary, we conclude that, while there are observed changes on TC intensity in the basin especially since 1980s, there is *low confidence* in a detectable anthropogenic influence. From a Type II error perspective, there is not a balance of evidence to support the notion of a detectable anthropogenic influence in this aspect.

i. Case study: Spatial variations in TC activity within the WNP basin

In addition to the poleward shift of the latitude of maximum intensity discussed above, other examples of spatially varying trends in TC activity have been documented for the WNP basin (see Section 2). Among these changes are a spatially varying pattern of TC intensity trend (Park et al., 2013) with weakening over an oceanic region east of the Philippines and increases further north; TC occurrence changes with a northwestward shift of TC occurrence after the mid-1990s; and a northwestward shift in TC tracks over the period 1977–2013 (e.g. Zhao and Wu, 2014; Mei and Xie, 2016). The changes have produced a decreased TC exposure in the Philippines and South China Sea, including the Marianas, Philippines, Viet Nam, southern China; and increased TC exposure in the East China Sea, including Japan, Republic or Korea, and parts of East China (see also He et al., 2015; Li et al., 2017; Zhao et al., 2018b).

There is not yet compelling evidence linking such changes to anthropogenic forcing nor a demonstration that the observed changes are unusual compared to expected natural variability. The analysis of Kossin et al. (2016) provides some evidence of climate change detection and weak evidence of anthropogenic influence, but their analysis focused mainly on the poleward migration of the latitude of maximum intensity. Oey and Chou (2016) attribute the shift in TC occurrence in the basin in recent decades to a weakening of easterly steering flows, while Liang et al. (2017) attribute it to a weakening and eastward shift of the subtropical high. However, these circulation changes were not shown to be distinct from natural variability or to be caused by anthropogenic forcing. In one modeling study of potential anthropogenic influence on decadal TC variations in the basin, Takahashi et al. (2017) inferred that changes in sulfate aerosol emissions caused more than half of the observed decline in TC frequency in the southeastern part of the WNP during 1992–2011. However, given the high degree of uncertainty in modeling aerosol influence on climate (e.g., Malavelle et al., 2017), more studies of this phenomena are needed,[1] including an exploration of the model dependence of results, before firmer conclusions can be made.

We conclude that for the examples of spatial variation of TC activity discussed above and in Section 2, there is *low confidence* in any detectable anthropogenic influence, and from a Type II error perspective, there is not a balance of evidence to conclude that the observed changes are either unusual compared to natural variability or that they contain a substantial anthropogenic contribution.

j. Case study: TC rainfall changes

Observational studies of TC rainfall changes in the WNP are reviewed in Section 3. Some examples of statistically significant trends in some TC rainfall-related metrics are given. However, some of the observed changes are relatively regional in scale (e.g., Tu and Chou, 2013; Li et al., 2015; Nguyen-Thi et al., 2012) and appear related to such factors as tropical cyclone frequency (i.e., more/fewer TCs in a region leading to more/less TC-related rainfall (Zhang et al., 2013)), or regional slowing of TC propagation speeds (Tu and Chou, 2013), and in some cases TC rainfall intensity (Li and Zhou, 2015). Lau and Zhou (2012) reported a reduction in rainfall energy per storm over the WNP for 1998–2007 compared to

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[1] Concerning aerosols and TCs, anthropogenic aerosols could conceivably be directly affecting TC behavior in the basin apart from an influence through anthropogenic climate change (e.g., Wang et al., 2014), but this aspect is relatively unstudied and is not covered in detail in our assessment.

1988−1997 using Tropical Rainfall Measurement Mission (TRMM) and Global Precipitation Climatology Project (GPCP) datasets, but noted that the relatively short data record length and other limitations of the rainfall data prevented their making any definitive conclusions about long-term changes in TC rain rates.

The influence of multiple factors on TC precipitation can confuse the interpretation or attribution of such changes in a climate change context (Chang et al., 2012). Trends over relatively short periods may well have predominant natural variability components that need to be distinguished from any anthropogenic influence (e.g., Bagtasa, 2017). While some statistically significant trends were noted in the above studies, none of the observational studies of TC rainfall reviewed provide clear evidence for observed changes (e.g., long-term trends) in TC-precipitation metrics that are detectable, or highly unusual compared to expected levels of natural variability. Possible influence of decadal to multidecadal variability of likely natural origin (e.g., the Pacific Decadal Oscillation, or Interdecadal Pacific Oscillation) on the observed trends has not been explicitly addressed.

Additionally, most studies show mixtures of results across stations, and it remains unclear whether the fraction of stations passing certain significance thresholds exceeds the fraction expected by chance (i.e., field significance). Wang et al. (2015b) suggest that anthropogenic warming has probably contributed to increased precipitation and TC activity over central Vietnam since 1970, but this was not an attribution conclusion based on quantitative (modeling) analysis.

In addition to limitations of linear trend analysis and available datasets, another complication with detection and attribution with regard to TC rainfall changes is that such changes can be influenced by a large number of factors, including: changes in track or frequency of occurrence of TCs altering total TC rainfall in a region; changes in size or propagation speed of TCs affecting accumulated rainfall in given locations; changes in storm duration affecting storm-total precipitation; and changes in the average rainfall rate out of a TC, which considers the flux of precipitation, averaged over some region, in a coordinate system that moves along with the storm. We note that it is the latter type of change (TC rainfall rate in the storm-relative context) that climate models and downscaling studies are consistently projecting will likely increase with global warming (e.g., Knutson et al., 2010; Knutson et al., 2015) since there are changes in this Lagrangian precipitation rate that are most closely related to the higher water vapor content of air in a warmer climate.

Concerning modeling studies, Wang et al. (2015a) examined the water budget of two landfalling typhoons on Taiwan using cloud-resolving model simulation case studies. They artificially modified the large-scale environment to reflect the long-time-scale change in the region between 1950−69 and 1990−2009, based on reanalysis data. They showed that in the slightly cooler and drier conditions of the 1950−1969, the TC precipitation rates were slower, due mainly to reduced atmospheric moisture content. This study quantitatively demonstrated the importance of the increased water vapor content for producing enhanced precipitation rates in typhoons under warmer climate conditions. However, since the changes between the two time periods they studied must be considered as some combination of anthropogenic and natural changes, their study does not constitute an anthropogenic forcing attribution study.

We conclude that for TC rainfall rates in the basin, there is *low confidence* in a detectable anthropogenic influence, and from a Type II error perspective, there is not sufficient evidence or a balance of evidence to conclude that any observed changes or trends are either unusual compared to natural variability or that they contain a substantial anthropogenic contribution.

5. Uncertainties

At least three factors, including data quality, methodology and physical understanding, may potentially impact the uncertainties of historical trend analyses. Physical understanding potentially affects all parts of the climate change assessment, and here we refer especially to those aspects of physical understanding associated with specific problems of data and methodology.

5.1. Data completeness and homogeneity

The data quality issue refers to the completeness and homogeneity of historical data (Landsea, 2007; Walsh et al., 2016; Ying et al., 2014). The completeness of data is an important issue for a number of reasons, including the fact that TC activity is an important component of the global energy and moisture cycles (e.g., Jiang and Zipser, 2010; Rodgers et al., 2000; 2001; Jullien et al., 2012; Ying et al., 2012b). The completeness of data, which is closely tied with temporal and spatial inhomogeneities, is highly dependent on the development of the global observation system and data analysis techniques. Temporal and spatial inhomogeneities can exist in various historical TC datasets (e.g., Landsea and Franklin, 2013). Such data limitations can potentially make it very difficult to distinguish long-term trends due to climate change, or multidecadal internal variability, from spurious changes associated with changes in observing methods. To improve the data homogeneity, it may be imperative to reanalyze the historical TCs using consistent techniques and sufficient data, although there may exist various practical problems (Emanuel et al., 2018) with achieving the goal of data homogeneity.

Despite some efforts in TC dataset homogenization, the four best-track datasets in the Typhoon Committee region show significant disagreements in details and even in long-term trends as discussed in previous Sections. For example, the Typhoon Committee project on "Harmonization of Tropical Cyclone Intensity Analysis" compared the current intensity (CI) numbers of TC satellite analyses and found that the major causes of large discrepancies may be associated with specific details in the analysis process (Koide, 2016), such as analysis during rapid intensification, length of sampling time used, interpretation of parameters based on cloud patterns, and CI-intensity rules. Similar causes were also mentioned in Barcikowska et al. (2012). Therefore, trends in intensity-related metrics based on the best track datasets must be treated with caution. An objective and standardized analysis system may avoid some of these problems, and improvements in the general rules used in analysis procedures as well as physical understanding on special problems (e.g. rapid intensification, wind-pressure relationship, etc.) may also help to improve the data analysis techniques.

5.2. Methodologies for homogenization and trend detection

The methodology issues discussed here concern mainly the appropriateness of homogenization methods, trend detection techniques, and the methods used to attribute changes to natural and anthropogenic changes.

Unlike other atmospheric metrics such as temperature, it is difficult to find appropriate statistical homogenization approaches for TC best track data due to the very complex conditions of the data (e.g. Koide, 2016; Ying et al., 2011a; Ying et al., 2014). An alternative choice is to reconstruct a new and homogenized dataset specifically for trend analysis based on existing observations such as the ADT-HURSAT intensity dataset of Kossin et al. (2013). Another (hybrid observation-modeling) approach is to simulate the historical TC intensity using dynamical downscaling methods (Wu and Zhao, 2012). Using the TC best tracks, SST and vertical wind shear as driving parameters, TC intensities were derived using a simple air-sea coupled model with an axisymmetric atmospheric component and one-dimensional oceanic component. This method implicitly assumed that the data quality of the driving environmental parameters was high enough to introducing minimal inhomogeneities into the results, and that the dynamical downscaling framework was capable of accurately reproducing TC intensity variability given the input environmental driving parameters. This approach thus aims to identify inhomogeneities in historical TC data by comparison with homogeneous samples of TC data as derived from models, under the assumption of perfect models and homogeneous environmental inputs.

Regarding trend detection, uncertainty may be introduced by approaches that do not robustly identify climate changes. In a statistical sense, climate change is defined as distinct change of the characteristics of a probability distribution function (PDF), such as parameters of scale, shape and location (IPCC, 2001; Meehl et al., 2000). This suggests the importance of assumed distribution of samples. Since TCs are extreme events with non-normally distributed metrics such as wind (i.e., intensity) and precipitation, important changes may occur in central values (median, mean) or tails of the PDF. Methods that assume a normal distribution should be used with caution since the unbiased estimates of PDF parameters highly depend on the prior assumption of the distribution form. For example, it may not be appropriate to apply normal distribution-assuming methods on samples from only the tails of a PDF to examine the change of extreme events. A better choice may be non-parametric methods, which are independent of the distribution. For example, quantile regression (Koenker, 2005; Koenker and Hallock, 2001) can used to assess trends in various quantiles (i.e., all parts of PDF) and has been used to assess climate trends (Elsner et al., 2008; Haugen et al., 2018; Murnane and Elsner, 2012; Ying et al. 2011b, 2011c). However, both parametric and non-parametric methods typically require the samples to be temporally independent. For TCs, interannual and decadal variabilities were identified in some metrics (e.g., He et al., 2015; Klotzbach and Gray, 2008; Zhang et al., 2018; Zhao et al., 2018d). Such fluctuations suggest that the data are serially correlated, which will introduce uncertainties into tests of significance of long-term trends (e.g., Douglas et al., 2000; Hamed, 2008; Kam and Sheffield, 2016). To address this issue, the influence of the sample's autocorrelation needs to be considered (Douglas et al., 2000; Hamed, 2008; Kam and Sheffield, 2016). In this sense, investigations that consider quasi-periodic variations of in the climate system (e.g., the Interdecadal Pacific Oscillation or Pacific Decadal Oscillation) and their role in TC variability, either using statistical regression (e.g., Kossin et al., 2016) or control model simulations (Bhatia et al., 2019) can help distinguish long-term externally forced TC climate trends or changes from internal (intrinsic) variability of TC activity, with associated confidence levels.

In summary, for attribution of observed changes in TC activity, historical climate model simulations using observationally based estimates of past changes in climate forcing agents can be used, although these techniques have been used relatively rarely for TC activity in the WNP basin (see Section 4). The reliability of such methods depends on the reliability of the climate models and the historical climate forcing agents. The former refers to the ability of models to simulate the TC metric in question as well as the historical changes in a variety of TC-relevant environmental parameters (e.g., SSTs, wind shear, atmospheric circulation, moisture, atmospheric and oceanic vertical temperature profiles), given adequate historical climate forcing estimates.

6. Summary

6.1. Observed changes

Using data updated to 2017, four best track datasets continue to show significant interdecadal variations in basin-wide TC frequency and intensity in the WNP. While most of the best track datasets depict a decreasing trend in basin-wide TC frequency, the observed trend and its statistical significance are still highly dependent on the best track dataset used, the analysis period chosen, and other analysis details.

Observations from the Members did not reveal statistically significant trends in the frequency of landfalling or affecting TCs for China; the vicinity of Hong Kong, China; Macao, China; Japan (TC or above); the Philippines; or the Korean Peninsula.

For TC intensity analysis, there has been encouraging research progress in improving the consensus between best track datasets and increasing use of the homogenized ADT-HURSAT dataset to investigate intensity trends. Increases in the number and intensification rate for intense TCs, such as Cat. 4–5s, in the WNP since mid-1980s was reported by a number of studies using various statistical methods to reduce the uncertainty in intensity assessment among best track datasets. But comparison of ADT-HURSAT and best track datasets intensity trends suggests there may be remaining homogeneity issues in the best track datasets. Moreover, spatial and cluster analysis of TC intensity depicts inhomogenous trends in different subregions of the WNP. The intensity of TC landfall over East China and Japan has shown a statistically significant increase while that of south China, the Philippines and Vietnam has not changed significantly.

A statistically significant northwestward shift in TC tracks and a poleward shift in the average latitude where TCs reach their peak intensity in the WNP have also been reported based on data since the 1980s. The prevailing track changes have also resulted in an increase in TC occurrence, including TC landfalls, in some regions, including East China, Japan, and the Korean Peninsula in recent decades. Moreover, a statistically significant decreasing trend of average TC translation speeds in the WNP from 1949 to 2016 has been reported. Poleward-shifting trends of storm surges in the WNP after 1980s were also reported in a study using observations and model simulated storm surge data. Another study finds no statistically significant trend in 50-year return period TC-induced storm surges in the WNP.

TC rainfall trends can be significantly influenced by changes in TC frequency and prevailing tracks and may vary between regions. Statistically significant increases in TC-induced precipitation vary with time-scale and area, but include: annual maximum daily precipitation in Japan, annual precipitation in the Philippines and the central coastline of Vietnam, and the annual number of days with TC-induced daily precipitation ≥ 50 mm along the central coastline of Vietnam. Annual TC-induced precipitation varies in China by region and on a decadal time scale. Average precipitation per TC has a statistically significant increase in southeast China. Annual TC-induced precipitation in Hong Kong, China affects the total precipitation amount and interannual variability, and non-TC-induced daily precipitation has an increasing trend.

Regarding TC-induced high winds, there is a significant decreasing trend in the frequency of TC-induced high winds in mainland China since 1980s. In Hong Kong, China, there is also a statistically significant decreasing trend in TC-induced high winds in urban areas since 1960s, mainly attributed to urban development. The impact of typhoon intensities over Republic of Korea varies by year, but with no significant long-term trend over the period examined. The Philippines also reported a slight increase in frequency of extreme TC high winds during 1971–2013.

While some studies reported that the TC-induced annual total direct economic losses have a statistically significant increase in China and the Philippines due to rapid economic development, another study using a comprehensive assessment index suggest that there is no statistically significant trend in the annual damage per TC in China from 1984 to 2008. In Japan and Hong Kong, China, there is a statistically significant reduction in TC-related casualties in the past few decades, mainly attributed to improvements in infrastructure and disaster prevention measures.

6.2. Detection, attribution and uncertainties

For the detection and attribution aspects, the assessment approach of the WMO Task Tram was adopted. Using the conventional perspective of avoiding Type I error (i.e., avoiding overstating anthropogenic influence), the strongest case for a detectable change in TC activity in the WNP is the observed poleward migration of the latitude of lifetime maximum intensity (LLMI). There is *low-to-medium confidence* that the observed poleward migration of the WNP basin LLMI is detectable compared with the estimated natural variability of TC activity in this basin. However, there is only *low confidence* that anthropogenic forcing had contributed to this poleward shift. There is *low confidence* that any other observed TC changes in the WNP are detectable or attributable to anthropogenic forcing.

From the perspective of reducing Type II errors (i.e., avoiding understating anthropogenic influence), a number of further tentative TC detection and/or attribution statements can be made. We caution that these may have potential for being false alarms (i.e., overstating anthropogenic influence), but they nonetheless may be useful indicators of evolving risk. With this caveat, the balance of evidence suggests: i) detectable anthropogenic contributions to the poleward migration of the latitude of maximum intensity in the WNP; and ii) an anthropogenic influence (but without detection) on the unusually active TC season in the WNP in 2015.

While we are not aware that any TC climate change signal has been convincingly detected to date in sea level extremes data in the WNP basin, a widespread worsening of storm surge inundation levels is believed to be occurring due to sea level rise associated with anthropogenic warming, assuming all other factors equal.

There are a number of reasons for the relatively low confidence in detection and attribution of TC changes in the basin. These include data homogeneity concerns (observation limitations, including the short time interval when reliable satellite observations were available), the small signal to noise ratio for expected anthropogenic changes, and uncertainties in estimating background natural variability levels and the response of TC activity to historical forcing agents, including greenhouse gases and aerosols. Concerning the forced response, it is possible that past aerosol forcing has offset much of the influence of greenhouse gas warming on TC intensities to date, yet aerosol forcing is not be likely to continue to offset this influence during the coming century (e.g., Sobel et al., 2016). We strongly recommend continued monitoring of various TC metrics in the basin for signs of emerging anthropogenic influence.

6.3. Recommendations for future work

6.3.1. TC observed data and trend analysis

The Typhoon Committee should encourage and continue to coordinate efforts by Members and the research community for the further development and improvement of homogenous climate-quality TC datasets. Some examples include:

(i) Sharing of observations/data between meteorological services and warning centers as well as IBTrACS;
(ii) Analysis of new TC-related metrics (LLMI and TC translation speed are examples of metrics since the SAR);
(iii) Assessing impact of changes in observing capabilities over time (e.g., satellite vs. pre-satellite; ship tracks; aircraft reconnaissance vs. no aircraft reconnaissance);
(iv) Conducting further research on observed trends in TC-induced high winds, heavy rain and storm surge and inundation levels; and
(v) Enhancing collaboration and coordination of aircraft reconnaissance in the basin.

6.3.2. Detection and attribution

With a view to further enhancing the detection and attribution studies, Typhoon Committee Members and research community are also encouraged to conduct further research to:

(i) Expand the use of detection and attribution techniques in studies of past TC variations to improve understanding of the causes of past changes and confidence in future projections.
(ii) Develop better estimates of expected levels of internal (natural) decadal to centennial scale variability of TC activity for use in climate change detection and attribution studies.
(iii) Develop better estimates of expected TC responses to historical climate forcing agent changes such as increases in greenhouse gases and regional to global changes in aerosol forcing

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Appendix A. Supplementary data

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