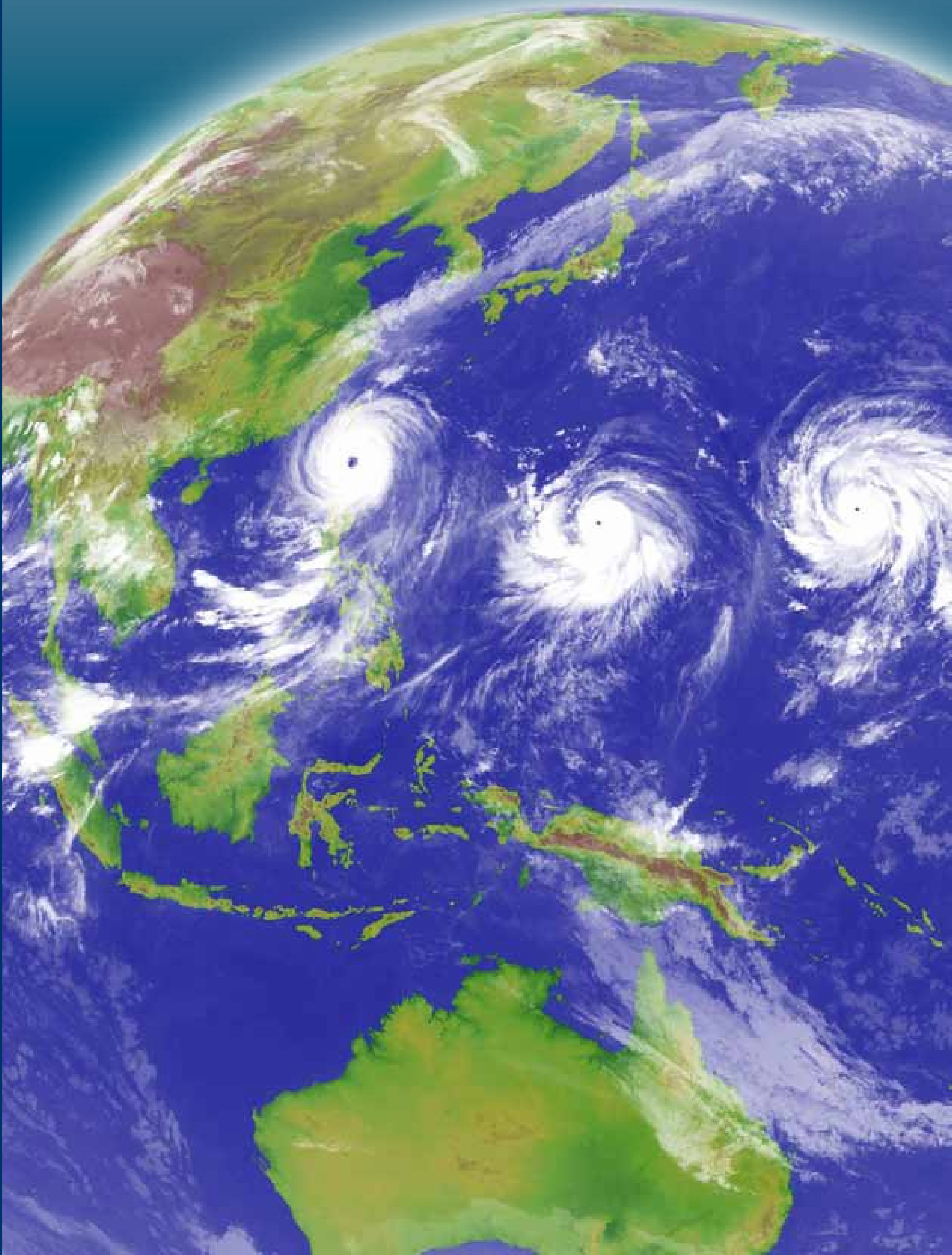
ASSESSMENT REPORT ON IMPACTS OF CLIMATE CHANGE ON TROPICAL CYCLONE FREQUENCY AND INTENSITY IN THE TYPHOON COMMITTEE REGION

DECEMBER 2010

ESCAP/WMO
Typhoon Committee



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ON THE COVER

Infrared satellite imagery of JMA's GMS-3 taken at 00 UTC on 9 Sept 1987. Three strong typhoons found in the western North Pacific, Gerald (8714), Freda (8713) and Holly (8715) from left to right. Courtesy by RSMC Tokyo.

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Authors
Tsz-Cheung LEE (Hong Kong Observatory, Hong Kong, China)
Woo-Jin LEE (APEC Climate Center, Republic of Korea),
Tetsuo NAKAZAWA (Meteorological Research Institute – MRI/JMA, Japan)
James C. WEYMAN (NOAA's National Weather Service, RSMC Honolulu, USA)
Ming YING (Shanghai Typhoon Institute, CMA, China)

Coordination of the Report
Tin-Ngai TONG (Macao Meteorological and Geophysical Bureau, Macao, China)

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ESCAP/WMO Typhoon Committee Secretariat
Avenida 5 de Outubro, Coloane
Macao, China
Tel.: (+853) 88010531   Fax: (+853) 88010530
E-mail: info@typhooncommittee.org

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NOTE FROM THE EDITOR

Since 2007, year in which its Secretariat was transferred to Macao, China, the ESCAP/WMO Typhoon Committee (TC) has taken several measures to strengthen its identity. For the first time, its Secretariat has its own premises, an emblem was created and a song was composed for the TC. Following these steps, the Committee, at its 42nd Session, approved a method and procedures to publish TC publications under a TC numbering system.

Before the adoption of these rules, the following publications of the Committee have been published in conformity with the sequential numbering system of the World Meteorological Organization (WMO):

I. **Typhoon Committee Expert Mission Report**
WMO/TD-No. 1448 - August 2008

II. **Typhoon Committee Disaster Information System Manual**
WMO/TD-No. 1449 – August 2008

III. **Guidelines for Reservoir Operation in Relation to Flood Forecasting**
WMO/TD-No. 1471 – December 2008

IV. **General Guidelines for Setting up a Community-Based Flood Forecasting and Warning System (CBFFWS)**
WMO/TD-No. 1472 - December 2008

V. **Report on UN ESCAP/WMO Typhoon Committee Members Early Warning System**
WMO/TD-No. 1475 - January 2009

VI. **Report on UN ESCAP/WMO Typhoon Committee Members Disaster Management System**
WMO/TD-No. 1476 - January 2009

VII. **WEB GIS Based Typhoon Committee Disaster Management System Manual**
WMO/TD-No. 1508 – September 2009

VIII. **Final Report on Flood Hazard Mapping Project**
WMO/TD-No. 1519 December 2009

IX. **Sediment-Related Disaster Forecasting Warning System Project**
WMO/TD-No. 1520 – December 2009

The TC Secretariat takes this opportunity to thank the members of the Expert Team for their generous and dedicated work that made possible the preparation of this Report.

Olavo Rasquinho
Secretary of ESCAP/WMO Typhoon Committee

FOREWORD

In recent years, attention of the public has been brought increasingly to "abnormal" tropical cyclone activities in the different ocean basins. In later 2001, Typhoon Vamei rapidly intensified near the coastal region to the southeast of the Malay Peninsula and became the first tropical cyclone formed near the equator. The hurricane season in 2003 in the North Atlantic reached 9 months in contrast to the historical average of 6 months. The first hurricane in the South Atlantic occurred in 2004 in recorded history and hit Brazil. In the same year, 10 typhoons made landfall over Japan in contrast to about 3 in climatological mean. In 2004 and 2005, there were 14 and 27 hurricanes in the North Atlantic basin, respectively, well above normal (about 10). In 5 weeks in February-March 2005, as many as 5 tropical cyclones threatened to hit the Cook Islands in the South Pacific.

The world has also witnessed record-breaking damages from the tropical cyclones in many countries. In August 2005, category 5 Hurricane Katrina hit Louisana and Mississippi in the United States. About 80% of New Orleans was flooded, with some parts under 15 feet (4.5 m) of water. In March 2006, Category 5 Tropical Cyclone Larry threatened the east coast of Australia and the maximum wind speed of 54 m/s was recorded when it made landfall in the coastal region of Queensland. Larry brought a great disaster to agriculture and a total economic loss of about US$0.5 billion (http://www.bom.gov.au/qld/cyclone/tc_larry/Larry_report.pdf) due to strong winds, heavy rainfall, and storm surge. In June 2007, Super Cyclonic Storm Gonu in Arabian Sea hit Oman and the Islamic Republic of Iran, causing the total economical loss of US$3.9 billion(http://www.netxplica.com/documentos/2007_catastrofes.pdf). In November 2007, Super Cyclonic Storm Sidr over the Bay of Bengal affected 8.9 million people and caused more than 3000 causalities, with 1001 missing, and 55,282 injured in Bangladesh (http://www.cdmp.org.bd/cdmp_old/reports/Draft-Sidr-Report.pdf). In May 2008, Very Severe Cyclonic Storm Nargis over the Bay of Bengal hit Myanmar and resulted in 138,366 death(the International Disaster Database EM-DAT). In 2009, Typhoon Morakot brought about extremely heavy rainfall to 10 counties in South Taiwan, China, and the resultant landslides led to more than 600 deaths (http://research.eerc.berkeley.edu/projects/GEER/GEER_Post%20EQ%20Reports/Taiwan_2009/Morakot_KCJ.pdf).

Whether do these abnormal storms imply climatic change in tropical cyclone activities (including length of season, frequency, intensity, tracks, and winds and rainfall of landfalling storms) over all the ocean basins? Are there any relationships between those storms and global warming? These questions have been raised by scientists as well as the general public with growing attention.

In response to the wide concerns, a special session was devoted to the potential impact of global warming on the activity of tropical cyclones at the Sixth WMO International Workshop on Tropical Cyclones (IWTC-VI) held in Costa Rica in November 2006, which released a "Statement on Climate Change and Tropical Cyclones". In February 2007, IPCC published its Fourth Assessment Report (AR4), which also included the assessment of the possible impact of global warming on tropical cyclone activities. Both discussed this issue from a primarily global perspective and concluded that (i) no clear trend was found in tropical cyclone activities in the climate record, however, (ii) it is likely that future tropical cyclones will become more intense.

Western North Pacific is the most active basin of tropical cyclones in the world. Countries in this basin are frequently affected by tropical cyclones which account for one-third of the total annual occurrences of cyclones around the globe. Therefore, change in the climatic characteristics of tropical cyclone activities would have a great deal of relevance to the disaster prevention and preparedness and the socio-economic development in this region. In view of this, ESCAP/WMO Typhoon Committee, the intergovernmental organization to mitigate impacts and risks of typhoon-related disasters, decided to conduct an assessment on the tropical cyclone activities in the western North Pacific through a more regionally oriented approach for the purpose of providing a professional view to the governments and the public in the region.

This assessment report was prepared by the Assessment Expert Group of the Meteorological Working Group of the Typhoon Committee. The Expert Group consists of Tsz-Cheung LEE (Hong Kong Observatory, Hong Kong, China), Woo-Jin LEE (APEC Climate Center, Republic of Korea), Tetsuo NAKAZAWA (Meteorological Research Institute – MRI/JMA, Japan), James C. WEYMAN (NOAA's National Weather Service, RSMC Honolulu, USA) and Ming YING (Shanghai Typhoon Institute, CMA, China). Tin-Ngai TONG from Meteorological and Geophysical Bureau, Macao, China, served as the Team Coordinator.

This report was prepared based on careful assessment and analysis of the available operational and research results collected from the Members of the Typhoon Committee, together with examinations of the original datasets created by the Expert Group. The report provides a review on the genesis and landfall frequency and intensity changes of the tropical cyclones in the western North Pacific. We tried to make it detailed and easy to read. Meanwhile, the report also identifies areas that require further studies by the Typhoon Committee and its Members regarding the climatic changes in tropical cyclone activities in this region.

This report is expected to serve as a reference for decision makers as well as the general public in regard to "climate change impact on typhoon activities". On the occasion of publication of this report, on behalf of the Meteorological Working Group, I would like to thank all the members of the Assessment Expert Group for their hard-working and excellent outcomes and the Typhoon Committee Members for their great support and cooperation.

Working Group on Meteorology
of the Typhoon Committee
Chair: Xiaotu Lei
January 2010

PREFACE

A tropical cyclone is a huge rotating column of warm, moist air with a very low sea-level pressure near the centre and is one of the most destructive forces of nature. With wind speeds often exceeding typhoon strength and usually accompanied by torrential rain, a mature tropical cyclone can significantly impact areas over a thousand kilometers from its centre. The climatological conditions under which tropical cyclones occur have been well established over decades of research. These include a requirement for warm sea surface temperatures, low vertical wind shear and high values of large scale relative vorticity in the lower layers of the troposphere.

In 2007, the United Nations Intergovernmental Panel on Climate Change (IPCC) clearly indicated in its Fourth Assessment Report that the warming in the climate system is unequivocal. In addition, it stated the increases in the atmospheric greenhouse gas concentration due to human activities are very likely responsible for most of the observed global warming since the middle of the 20th century. The IPCC found clear observational evidence that the sea surface temperatures over most of the ocean basins have increased over the last few decades. Looking into the future, global climate model simulations suggested that the tropical sea surface temperatures will increase by an even greater amount in the 21st century than during the 20th century.

Against the background of climate change and a continuous increase in economic damage and disruption by tropical cyclones, there is a growing concern on the possible impacts of climate change on the frequency and intensity of tropical cyclones. In last few years, a large body of research on the potential impacts of climate change on tropical cyclones has been conducted. With a view to assessing the change in frequency and intensity of tropical cyclones in the ESCAP/WMO Typhoon Committee region and inform policymakers and public on this matter, the Typhoon Committee formed an Expert Team in 2009 to conduct a review of the best available publications/information at the time. This report summarizes the assessment of the Expert Team, including the observed changes in the tropical cyclone frequency, intensity, and landfalling; results of climate model projections for the future tropical cyclone activity given by various research groups; and the uncertainty associated with the assessment.

ACKNOWLEDGEMENTS

The work was led by the ESCAP/WMO Typhoon Committee. The authors would like to thank all the staff of the Typhoon Committee Secretariat (TCS) for their assistance in both logistic and editorial aspects, in particular for arranging the Expert Team Meeting in Macao, China in December 2009. The authors are also grateful to Koji Kuroiwa of WMO, Xiaotu Lei of CMA and Derek Leong of TCS for their valuable comments. Last but not the least, the authors wish to thank the WMO Expert Team, including Thomas Knutson, John McBride, Johnny Chan, Kerry Emanuel, Greg Holland, Chris Landsea, Isaac Held, James Kossin, A. K. Srivastava, and Masato Sugi, for kindly sharing their draft assessment results for the authors' reference.

EXECUTIVE SUMMARY

There have been significant interdecadal and interannual fluctuations in the frequency of tropical cyclone (TC) formation and occurrence over the Western North Pacific (WNP) in the last 50 years. Different interpretations on the trend of TC frequency over WNP have been reported, depending upon the best track dataset, analysis period, TC classification, etc.. Thus, based on available publications, we cannot conclude whether there is a long term trend in the TC frequency over WNP. In view of this, an additional analysis utilizing 5 different best track datasets with data up to 2008 and allowing adjustments for the difference in averaging period between datasets has been conducted. The results suggest that most of the best track datasets depict either a decreasing trend or no trend in the annual number of TCs (tropical storm or above) and typhoons in WNP.

It should be noted that there exist significant differences between the available TC best track datasets for WNP. Such discrepancies could be due to the difference in the implementation of analysis techniques and the definition of the maximum wind as well as the limitation in in-situ observations.

For TC intensity, differences in best track datasets available for WNP do not allow for a convincing detection of a long term trend in TC intensity change in this basin when compared with variability from natural causes.

The trend of the number of landfalling tropical cyclone varies from one region to the other. There is no significant linear trend in the frequency of landfalling TCs in Japan, the Philippines and within 300km of Hong Kong, China. The trends of landfalling TCs in China and Thailand are decreasing. The trend of TC influencing the Republic of Korea is increasing in recent years, but it is not conclusive.

In China, there is a decreasing trend in the maximum intensity of landfalling TCs in recent years but the mean intensity of landfalling TCs has no trend. The extreme wind induced by tropical cyclone affecting China has a decreasing trend and the total amount and intensity of TC precipitation has no significant trend.

Looking into the future, the majority of the climate models projects a reduction in the number of TCs in the WNP in different future greenhouse gas scenarios. While there are fewer studies on the change of TC intensity, some of the model projections suggest an increase in the number of intense TCs in the WNP in a warmer climate. Although climate models could provide us with projections for future changes in TC activity, a variety of uncertainties and limitations in the climate modeling and associated downscaling methods may affect the reliability of the projections, in particular in regional scale.

1. INTRODUCTION

Climate change has become a hot topic of discussion in recent years. Besides global warming patterns, the possible change in tropical cyclone activity is also a matter of great concern to the public and decision-makers.

Tropical cyclone is one of the most destructive weather systems on earth. The Western North Pacific (WNP) is the most active tropical cyclone basin in the world with an annual average of about 30 tropical cyclones. To understand the possible changes in the tropical cyclone activity in the WNP under the climate change situation is a high priority issue in the Typhoon Committee region from both scientific and socio-economical viewpoints.

The Typhoon Committee is an intergovernmental body established in 1968 under the auspices of the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP) and the World Meteorological Organization (WMO). The Committee's purpose is to promote and coordinate planning and implementation measures required for minimizing the loss of life and material damage caused by typhoons. It is currently composed of 14 Members: Cambodia; China; Democratic People's Republic of Korea; Hong Kong, China; Japan; Lao People's Democratic Republic; Macao, China; Malaysia; the Philippines; Republic of Korea; Singapore; Thailand; United States of America and Viet Nam.

At its Forty-first Session held in Chiang Mai, Thailand (19 to 24 January 2009), the TC decided to form an Expert Team to assess the change in frequency and intensity of tropical cyclones in the region and inform policymakers and public on this matter. This decision was based on the information provided by Members, the outcomes of the Working Group on Meteorology parallel session, and the "Integrated Workshop on Coping with Climate Change in the Typhoon Committee Area" held in Beijing, China (22 - 26 September 2008).

An Expert Team which consisted of five experts from China; Japan; Republic of Korea; United States of America; and Hong Kong, China as well as a coordinator from Macao, China was formed in mid-2009 under the Working Group of Meteorology. The Expert Team conducted a series of literature review and assessment work in 2009 and met during the Expert Team Meeting held in Macao, China (14-15 December 2009) to discuss the findings and assessments.

In this report, the assessments on the observed changes in the tropical cyclone frequency, intensity, and landfalling are discussed in Sections 2, 3 and 4 respectively. Results of climate model projections for the future tropical cyclone activity given by various research groups and the uncertainty associated with the assessment are respectively reported in Sections 5 and 6. The recommendations for future work on the subject are included in Section 7. Moreover, for readers' easy reference, Annex I provides a comparison of the tropical cyclone classification and Annex II lists the acronyms used in the report.

It should be noted that the review and assessment by the Expert Team were conducted within a limited time period. While the Expert Team Members have strived to conduct the assessment based on the best available publications/information, the literature review process does not mean to be completely exhaustive. There is the possibility that certain findings and publications have not been covered in this assessment.

2. TROPICAL CYCLONE FREQUENCY

There were significant interannual and interdecadal fluctuations in the tropical cyclone (TC) frequency in the Western North Pacific (WNP) over the past 50 years (Yumoto and Matsuura, 2001; Yeung et al., 2005; Chan et al., 2009). As far as trend analysis is concerned, previous studies have shown divergent results (i.e. increasing, decreasing and no trend) depending on the best track dataset, analysis period, and TC classification. Thus, based on available publications, it is difficult to conclude whether there is a long term trend in the TC frequency over WNP. In view of this, an additional independent analysis utilizing latest available data up to 2008 from five best track datasets, allowing adjustments for the difference in averaging period between datasets, has been conducted to assess the possible trend of TC frequency in this basin. Trend analysis results reported by various researchers for different TC classifications are summarized in the Sections 2.1 to 2.3. It should be noted that the maximum sustained wind in the RSMC-Tokyo and HKO datasets have been averaged over a 10-minute period, while it is averaged over a 2-minute period in the CMA dataset and over a 1-minute period in the JTWC dataset. TC classifications and wind averaging periods adopted by different centers are tabulated in Annex I. The results of the independent analysis using the latest best track datasets from 1945 to 2008 are discussed in Section 2.4.

2.1 Intense typhoon

Using the tropical cyclone best track data of Joint Typhoon Warning Center (JTWC), Webster et al. (2005) found that between the two consecutive 15-year periods of 1975-1989 and 1990-2004, the percentage of intense typhoons (maximum sustained wind (1-minute average) > 114 kts, i.e. equivalent to Cat. 4 to Cat. 5 hurricanes in the classification of the Atlantic basin) in the WNP has increased from 25% to 41%. However, Wu et al. (2006) noted that the same analysis using the best track datasets of the Hong Kong Observatory (HKO) and Regional Specialized Meteorological Center Tokyo (RSMC-Tokyo) showed a decrease in the proportion of intense typhoon between the two periods. Wu et al. (2006) also pointed out that there was a noticeable difference in the number of intense typhoons between the best track datasets of JTWC, HKO and RSMC-Tokyo during the period from 1977 to 2004. The study of Song et al. (2009) using the datasets of JTWC, RSMC-Tokyo and China Meteorological Administration (CMA) showed that, for TCs simultaneously recorded by these three datasets from 1977 to 2007, JTWC dataset showed an increasing trend for the frequency of intense typhoons in WNP but the datasets of CMA and RSMC-Tokyo revealed a decreasing trend and no trend respectively.

2.2 Typhoon

Wu et *al*. (2006) and Yeung et *al*. (2005) noted that, between 1961 and 2004, there was no linear trend in the number of typhoons in WNP using the best track data of HKO. Similarly, no trend was found in the study conducted by Japan Meteorological Agency (JMA) using RSMC-Tokyo data between 1977 and 2008 (JMA, 2009). However, Ma and Chen (2009) reported a decreasing trend using a longer period of data from CMA (1949-2008).

2.3 Other tropical cyclone categories

By analyzing HKO's best track data, Yeung et al. (2005) suggested that the annual number of TCs (all TCs, including tropical depressions) occurring over the WNP has been decreasing from 1961 to 2004. A similar trend for TCs (all TCs, excluding tropical depressions) has also been identified in the analyses carried out by Ma and Chen (2009) using the best track data of the CMA. Ma and Chen (2009) also analyzed the trends of each TC category using the CMA dataset and showed that the number of typhoons and severe tropical storms has been decreasing, but the number of tropical storms has been increasing slightly.

The study of Yuan et al. (2008) revealed that, based on the best track data of JTWC, the number of tropical storms in WNP has an increasing trend from 1945 to 2006, but the number of TCs in other categories did not exhibit any significant trend.

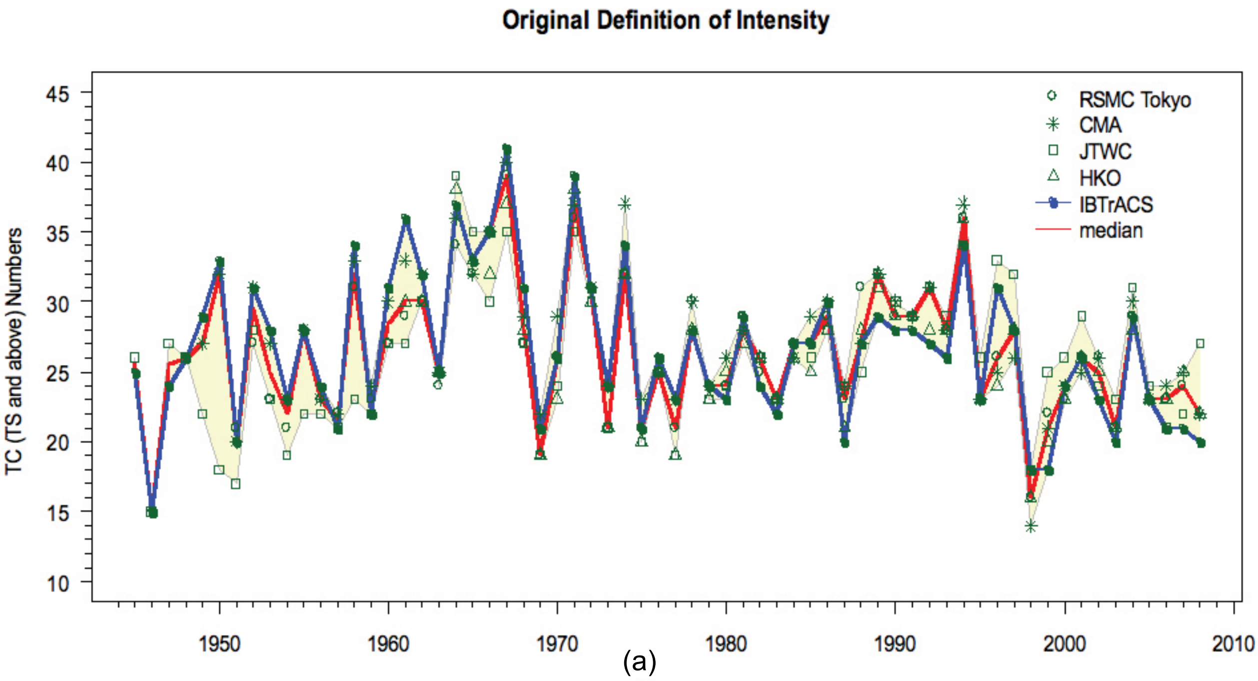
2.4 Independent assessment on TC frequency in WNP

Figure 2.1(a) shows the variation in the annual number of TCs with intensity reaching tropical storm or above from 1945 to 2008 based on the best track datasets of JTWC, RSMC-Tokyo, HKO, CMA and International Best Track Archive for Climate Stewardship (IBTrACS). To account for the differences in the definition of maximum wind averaging period between datasets (CMA uses 2-minute average, JTWC uses 1-minute average, other centers use 10-minute average), an adjustment was also performed to align the TC intensity of these two datasets to 10-minute average based on the maximum wind speed conversion factors for different averaging periods documented in the relevant WMO guidelines (Harper et al., 2009). Figure 2.1(b) also shows the TC (tropical storm or above) frequency variation for the 10-minute average adjusted datasets. Similar plots for the frequency of typhoons are given in Figures 2.2(a) and (b). T-test has also been conducted to check the statistical significance (at 5% level) of each trend. The linear trends of the annual number of TCs (tropical storm or above) and typhoons for the five datasets based on all available data (1945-2008) are tabulated in Table 2.1. A similar trend comparison based on the same data sets for the period from 1977 to 2008 is given in Table 2.2.

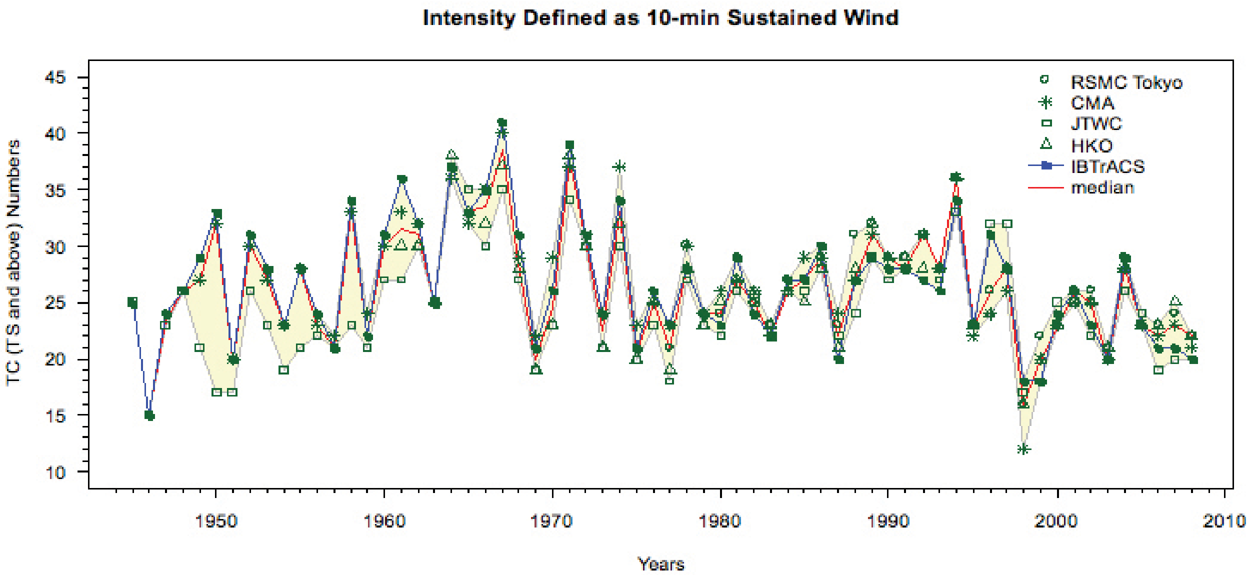
As shown in Table 2.1, for statistically significant trends, CMA dataset shows a decreasing trend for all four combinations, HKO dataset has a decreasing trend for “All TCs”, and IBTrACS dataset shows a decreasing trend for “Typhoons”. JTWC and RSMC-Tokyo datasets have no statistically significant trend (at 5% level) for all combinations.

For the trend analysis based on a common period from 1977 to 2008, all datasets and combinations have no statistically significant trend (see Table 2.2).

As such, based on the available data from 1945 to 2008 and after adjusting for the difference in the maximum wind averaging period between datasets, most of the best track datasets depict either a decreasing trend or no statistical significant trend in the annual number of TCs (tropical storm or above) and typhoons in WNP.

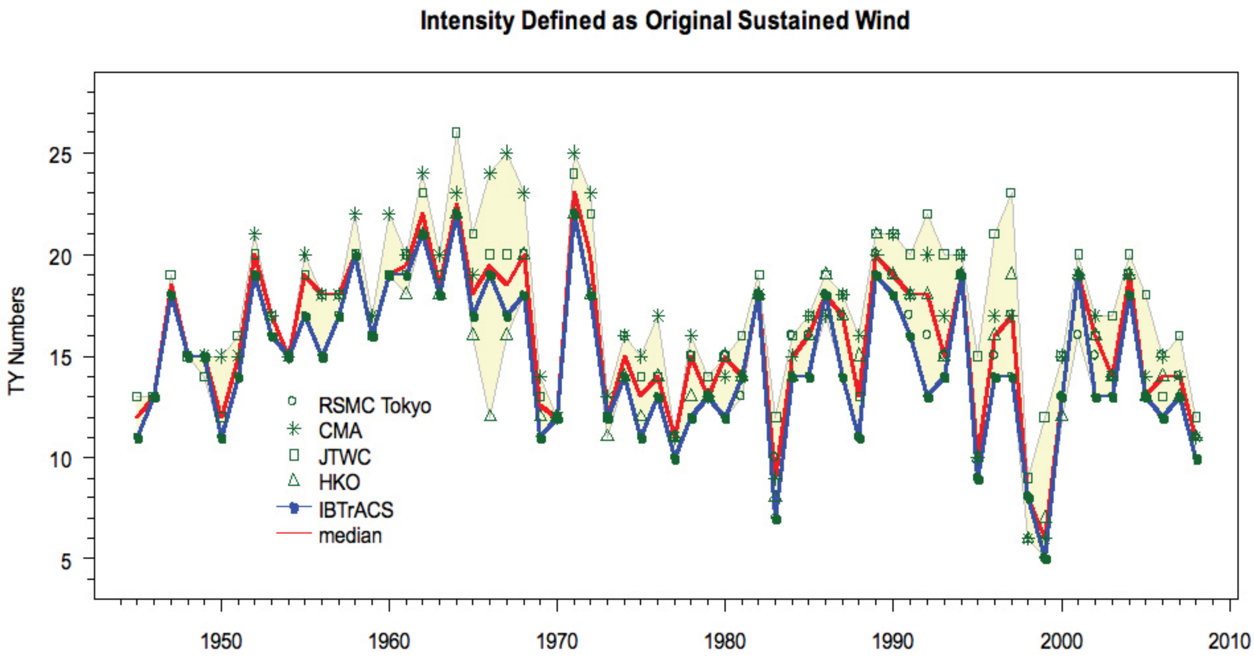


(a)

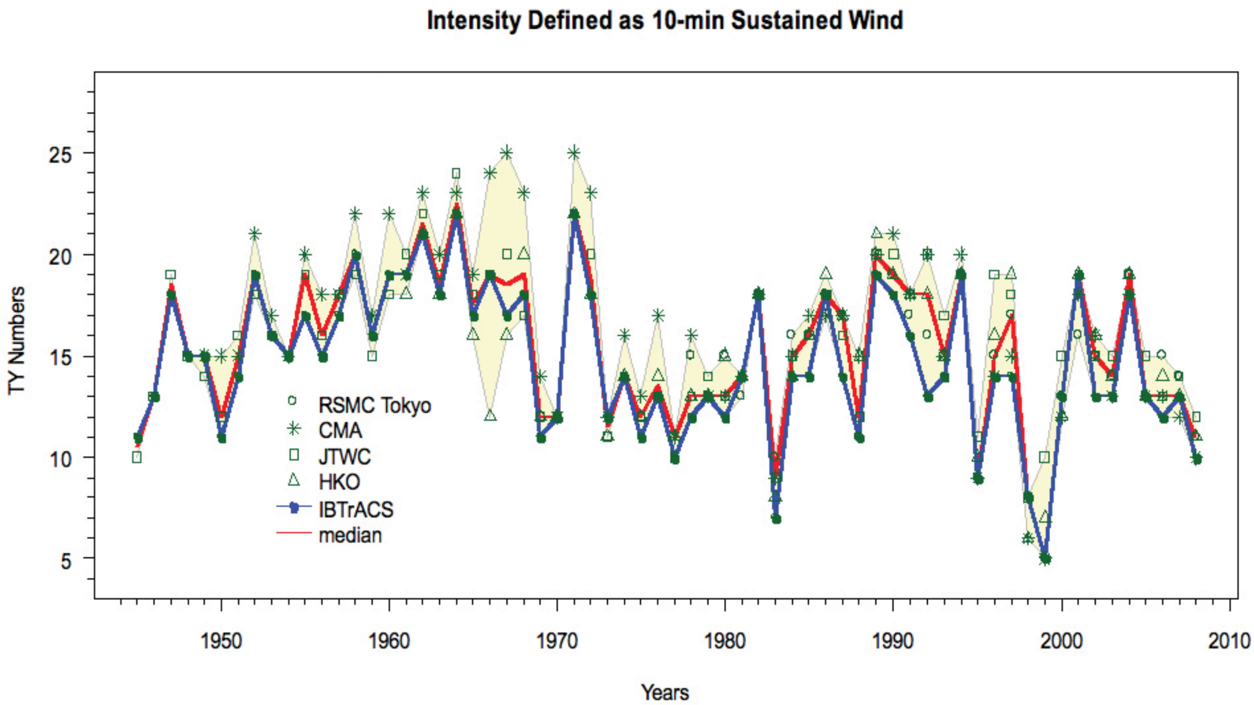


(b)

Figure 2.1 Variation in the annual number of TCs (tropical storm and above) in WNP for different best track datasets as computed based on (a) original wind speeds of various best track datasets, (b) the 10-minute average adjusted datasets. The shaded area between grey lines denotes the range of frequency differences among different datasets.



(a)



(b)

Figure 2.2 Same as Figure 2.1, but for annual number of typhoons in WNP.

Table 2.1 Trends of annual no. of TCs in WNP based on different datasets for all available data up to 2008. Data in bold indicates the trend is statistically significant at 5 % level.

Datasets	Data Period	Original intensity		10-minute averaging adjusted intensity	
		All TC (tropical storm or above)	Typhoons	All TC (tropical storm or above)	Typhoons
CMA	1949-2008	**-0.77/decade**	**-0.89/ decade**	**-0.98/decade**	**-1.15/ decade**
JTWC	1945-2008	+0.55/decade	-0.06/ decade	+0.19/decade	-0.25/ decade
RSMC-Tokyo	1951-2008	-0.34/decade	-0.39/ decade*	-0.34/decade	-0.39/ decade*
HKO	1961-2008	**-1.35/decade**	-0.59/ decade	**-1.35/decade**	-0.59/ decade
IBTrACS	1945-2008	-0.67/decade	**-0.62/ decade**	-0.67/decade	**-0.62/ decade**

* period from 1977 to 2008 as maximum sustained wind data in RSMC-Tokyo dataset only available since 1977

Table 2.2 Trends of annual no. of TCs in WNP based on different datasets from 1977 to 2008. No trend is statistically significant at 5 % level.

Datasets	Original intensity		10-minute averaging adjusted intensity	
	All TC (tropical storm or above)	Typhoons	All TC (tropical storm or above)	Typhoons
CMA	-1.18/decade	-0.22/decade	-1.59/decade	-0.79/decade
JTWC	+0.08/decade	+0.26/decade	-0.69/decade	+0.26/decade
RSMC-Tokyo	-1.00/decade	-0.39/decade	-1.00/decade	-0.39/decade
HKO	-0.63/decade	-0.22/decade	-0.63/decade	-0.22/decade
IBTrACS	-1.22/decade	-0.15/decade	-1.22/decade	-0.15/decade

3. TROPICAL CYCLONE INTENSITY

By using the homogeneous record of the University of Wisconsin-Madison/National Climatic Data Center (UW/NCDC), Kossin et al. (2006) indicated that there was no significant trend in the power dissipation index (PDI) in the WNP from 1983 to 2004. The study by Wu et al. (2006) also found no trend in PDI or intense typhoons in WNP from 1965 to 2004 using best track datasets of HKO and RSMC-Tokyo. However, a similar analysis conducted by Wu et al. (2008) using the best track data from JTWC indicated an increasing trend in PDI over WNP from 1975 to 2004. Such a discrepancy due to the choice of dataset and analysis period reduces our confidence in the assessment of TC intensity trend.

Similar dependency on dataset was also observed in the analysis of TC days. Kamahori et al. (2006) found that, based on RSMC-Tokyo best track dataset, there was a substantial decrease in the number of TC days for intense typhoons over the WNP between the periods 1977-1990 and 1991-2004. However, this result differed from the one using the JTWC dataset which showed an increasing trend in the number of TC days for intense typhoons. Such a disagreement among dataset in WNP could be attributed to different implementation of the Dvorak technique based on satellite-based measurements and maximum wind definition (Kwon et al., 2006; Yu et al., 2007).

The study of Chan (2009) indicated that, in WNP, the thermodynamic factors such as maximum potential intensity (MPI) do not seem to have any appreciable contribution towards the variability of the annual occurrence of intense typhoons. Dynamic factors such as vertical wind shear may be the determinant in this basin. This implies that although global warming could likely increase the thermodynamic energy available in the atmosphere, such an increase does not necessarily imply a concomitant increase in the number of intense TCs. Until we can demonstrate that the dynamic factors will also become more favourable for TC intensification, it remains uncertain whether the frequency of occurrence of intense TCs will increase under a global warming scenario.

The other metrics of intensity such as TC precipitation still require further research, even though there is general support on the increasing tendency of moisture and associated precipitation in a warming climate on a global scale scenario (Trenberth, 1999 and 2008).

4. LANDFALLING

4.1 Landfalling TC frequency

Chan *et al.* (2009) conducted a study on TC (TS and above) landfalling trends of 3 different sub-regions in East Asia, namely South (south China, Viet Nam and the Philippines), Middle (east China), and North (Korean Peninsula and Japan) by using the JTWC best track data. Their results showed that none of the time series of annual number of landfalling TCs shows a significant linear trend. They also suggested that global warming has not led to a higher frequency of landfalling TCs or typhoons in any of these regions in Asia.

The trends for landfalling TCs in different countries/places vary from one to the other. The frequency of TCs that hit Thailand had a decreasing trend since mid-1960s (Thai Meteorological Department, 2009). In the Philippines, the number of landfalling TCs possessed an increasing trend in Visayas, a decreasing trend in Mindanao, and no significant trend in Luzon (PAGASA, 2008). There was no significant trend in the number of landfalling TCs in Japan (JMA, 2009). The annual number of TC making landfall within 300 km of Hong Kong also had no significant trend (Ginn *et al.*, 2010).

Park *et al.* (2006) showed that the frequency of typhoons influencing Korea peninsula was increasing in recent years, but not conclusive due to limited time record of 50 years (1954-2003).

For China, several studies have been conducted to investigate the trends of landfalling TCs. Their results showed that the number of TCs landfalling in China was decreasing (Wang and Ren, 2008; Hu *et al.*, 2008; Yang *et al.*, 2009). The study of Yang et al. (2009) pointed out that the TC landfalling frequency in southern China was decreasing but the frequency trend of those landfalling over East China was not obvious. There was no trend in the total number of typhoons landfalling over all of China. Yang et al. (2009) also found that the locations of landfalling TCs over China were tending to approach the area of 23~35°N (Figure 4.1), which are consistent with Cao et al. (2006), who suggested that the locations of landfall were tending to approach the central part of the China's coastline.

Regarding the interannual and interdecadal variations in TC tracks, Kim *et al*. (2005) examined the variation in TC tracks in summertime (July-September) over WNP by analyzing the TC passage frequency with empirical orthogonal function (EOF) analysis method. They identified three leading modes. Two tropical modes represented the long term trend and the relationship with ENSO, while the other mode oscillated between south of Korea and southeast of Japan with interannual time scales (so-called East Asia Dipole Pattern (EADP)). Liu and Chan (2008) also studied the TC occurrence pattern over WNP and found a significant interdecadal variation.

4.2 Landfalling TC intensity

The study of Yang *et al*. (2009) showed that the percentage of intense typhoons landfalling in China showed an increasing trend from 1949 to 2006. However, Wang and Ren (2008) suggested that maximum landfall intensities in China were stronger during 1950s~1970s but decreased in recent years. Wang and Ren (2008) also showed the mean landfall intensity didn't depict any linear trend during 1951~2004.

Ying *et al*. (2010a) and Ying and Chen (2009) examined the changes of tropical cyclone impact on China and different areas of China (south China, East China, Northeast China and China inland) using the CMA's best track and TC wind and precipitation observation datasets. They found that there was no trend in the frequency of TCs affecting China and these four sub-regions. On the regional scale, the extreme wind induced by TCs affecting China had an overall decreasing trend but the total amount and intensity of TC precipitation had no significant trend. However for individual stations, those with a decreasing trend of storm winds were mainly located near the southern part of China's coastline, and those stations with increasing trends in rainfall intensity were mainly located in the southeastern area of China.

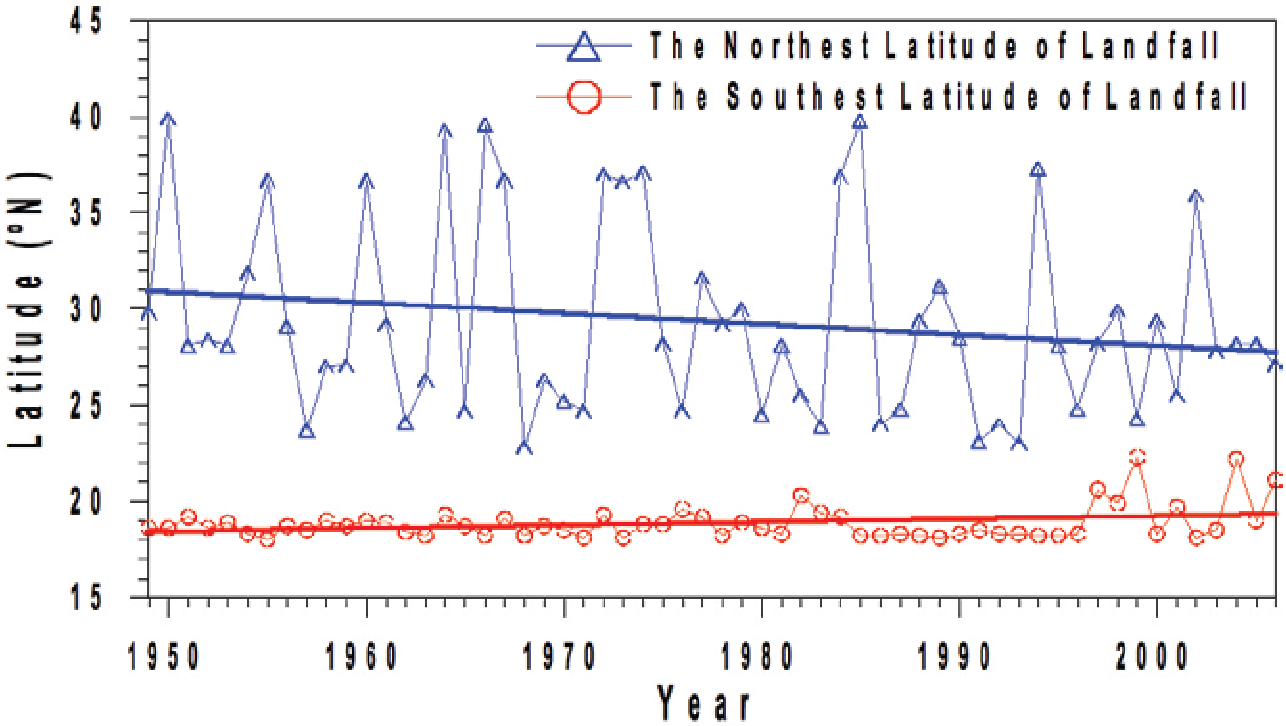


Figure 4.1 The south most (red line) and north most (blue line) locations of TCs making landfall in China (in latitudes) (Yang *et al.*, 2009).

5. FUTURE PROJECTIONS

Different research groups have conducted climate model simulations based on different future greenhouse gas and sea surface temperature rise scenarios, to project the future change in tropical cyclone activities in the 21st century.

5.1 Frequency

The projections given by the studies of Sugi *et al.* (2002), McDonald *et al.* (2005), Gualdi et al (2008) and Sugi *et al.* (2009) using the atmospheric general circulation models revealed that there would be a significant reduction in the frequency of TCs in the WNP basin under the global warming situation. Simulations using high resolution climate model (Oouchi et al, 2006; Bengtsson *et al.*, 2007) also suggested a significant decrease in the number of tropical cyclones in WNP. Moreover, Yokoi and Takayabu (2009) have examined the global warming impacts on TC genesis frequency over WNP projected by five CMIP-3 atmosphere-ocean coupled general circulation models which could realistically simulate horizontal distribution in tropical cyclogenesis over the WNP. All five models projected increasing trends of frequency in the central North Pacific and decreasing trends in the western part, with a maximum drop over the South China Sea (see Figure 5.1).

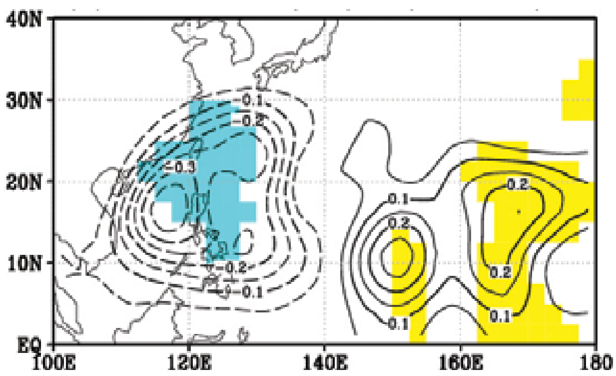


Figure 5.1 Multi-model ensemble of projected global warming impact on the genesis frequency. Yellow (blue) tone: all 5 models project increase (decrease) trends. (extracted from Yokoi and Takayabu, 2009)

However, Caron and Jones (2008) indicated that annual frequency in WNP would increase. The study of Stowasser *et al.* (2007) also projected the total number of cyclones in WNP would be slightly higher in the global warming climate than at present, but the overall increase is not statistically significant. This contrasts with the results from the above mentioned high resolution global model projections which found substantial reduction in the number of tropical cyclones in the global warming climate.

Zhao *et al.* (2007) has conducted a review on the projections of TC activity over WNP in the 21st century provided by 11 different global climate models under different greenhouse gas emission scenarios. They indicated that most of the models projected that the number of TCs in the WNP may decrease in the 21st century.

Summary of the projections of TC frequency change is given in Table 5.1.

5.2 Intensity

For TC intensity projections, fewer studies have been conducted for WNP when compared with TC frequency projections. Stowasser *et al.* (2007) found that, in the 21st century, the average intensity and the number of intense storms over the entire WNP region rise significantly in the global warming simulation. The study of Knutson and Tuleya (2004) also projected the mean TC intensity would increase in WNP. Bengtsson *et al.* (2007) found an increase in the number of intense TCs for the Northern Hemisphere. Oouchi *et al.* (2006) depicted that TC intensity in WNP would increase slightly in the future greenhouse-warmed climate, but the increase is not statistically significant. The review by Zhao *et al.* (2007) suggested that the TC intensity may increase in the 21st century.

However, the result from Sugi *et al.* (2002) indicated no significant change in the intensity in WNP in the 21st century. Hasegawa and Emori (2005) found that TC intensity would decrease on average but the tropical cyclone precipitation would increase due to the increase in atmospheric moisture content.

Summary of the projections of TC intensity change is given in Table 5.2.

Table 5.1 Summary of results for some of the climate model projections of TC frequency in the 21st century

Study Reference	Model Type / details	GHG	Global	WNP
Sugi *at al.*, 2002	T106 AGCM	2xCO2	Decrease (-34%)	Decrease (- 66%) 105°E to 135°W
McDonald *et al.*, 2005	N144 HadAM3	IS95a	Decrease (-6%)	Decrease (-30%)
Hasegawa and Emori, 2005	CCSR/NIES/ FRCGC AGCM, T106	2xCO2	---	Decrease (-4%)
Yoshimura *et al.*, 2006	T106 AGCM	2xCO2	Decrease (-9 to -18%)	---
Oouchi *et al.*, 2006	TL959 (20km mesh)	A1B	Decrease (-30%)	Decrease (-40%) 0-45°N, 100-180°E
Stowasser *et al.*, 2007	Downscaling NCAR CCSM2	6xCO2	---	Increase slightly, but not statistically significant.
Bengtsson *et al.*, 2007	ECHAM5 T213 (60km) T319 (40km)	A1B	---	Decrease (-20 to -28%)
Gualdi *et al.*, 2008	SINTEX-G (SXG) AOGCM, T106	2xCO2; 4xCO2	Decrease (-16 to -44%)	Decrease (-20%)
Caron and Jones, 2008	CMIP-3 multi-model Yearly Genesis Parameter (YGP)	A1B, A2, and B1	---	Increase (7 to 22%)
Sugi *et al.*, 2009	TL959 (20km mesh) TL319 (60km mesh) 8 experiments	A1B	7 experiments decrease (-20 to -30%)	5 experiments decrease (-26 to -38%) 2 experiments increase (28 to 64%)
Yokoi and Takayabu, 2009	CMIP-3 multi-model	A1B, A2, and B1	---	Increase in the central North Pacific (5–20N, 150E–180; CNP) Decreasing in the western part, with a maximum decrease over the South China Sea (10–25N, 110–120E; SCS).

Table 5.2 Summary of results for some of the climate model projections of TC intensity in the 21st century

Study Reference	Model Type / details	GHG	Global	WNP
Sugi *at al.*, 2002	T106 AGCM	2xCO2	No significant change	---
Knutson and Tuleya, 2004	CMIP2	+1%/yr CO2	---	Increase (5 to 14%)
Hasegawa and Emori, 2005	CCSR/NIES/ FRCGC AGCM, T106	2xCO2	---	Decreases on average, but precipitation increase
Oouchi *et al.*, 2006	TL959 (20km mesh)	A1B	Increase (11%)	Increase (4%)
Stowasser *et al.*, 2007	Downscaling NCAR CCSM2	6xCO2	---	Average intensity and the number of intense storms rises significantly
Bengtsson *et al.*, 2007	ECHAM5 T213 (60km) T319 (40km)	A1B	30% more TC with maximum wind speeds above 50 ms−1 (the Northern Hemisphere)	---

6. UNCERTAINTIES

6.1 Best track datasets

Assessments on climate change and TC activity always encounter data problems, such as the inhomogeneity of data, validity of statistics or indices, and inconsistency between different data or phenomena. As suggested by Landsea *et al.* (2005), the quality of global TC best track data may be not good enough for assessing the trends. According to the comparison conducted by Yu *et al.* (2007), there was a large discrepancy in the best track data set between different national meteorological services and warning centres in WNP. Yu *et al.* (2007) suggested that the intensity differences among CMA, RSMC Tokyo and JTWC data sets were significant when the three are compared at the same maximum sustained wind averaging period (10-minute average). For 1988-2003, the mean difference between CMA and RSMC Tokyo were 0.6 m/s, and the difference between CMA and JTWC was 1.7 m/s. However, the maximum difference in the strength of the same TCs was more than 30m/s, and the number of typhoons in CMA best track datasets was greater than that of RSMC-Tokyo and JTWC (Zhang and Ying, 2009). Moreover, Nakazawa and Hoshino (2009) examined the tropical cyclone datasets of the RSMC-Tokyo and JTWC from 1987 to 2006 and identified significant differences in Dvorak parameters (CI and T numbers) in 1992-1997 and 2002-2005 (see Figure 6.1).

Ying *et al.* (2010b) evaluated the differences of the annual cycle of TC activities as revealed by JTWC, RSMC-Tokyo, and CMA datasets. As shown in Figure 6.2, the differences in the power spectra of pentad storm frequency among the three best track datasets increased in decadal and longer time periods. That is to say, significantly different long term variations will occur when different datasets are used to construct indices such as PDI and ACE. Song *et al.* (2009) also compared the best track datasets of JTWC, CMA and RSMC-Toyko and indicted that, for TCs simultaneously recorded by all three datasets from 1977 to 2007, JTWC dataset had more “intense typhoons” than that of the other two datasets, leading to an increasing trend in the annual frequency of intense typhoons and PDI.T

he difference in best track data could be due to:

(i) different implementations of the Dvorak technique, the basis for TC intensity estimation at major centres after the deactivation of aircraft reconnaissance after 1987 (Kamahori et al., 2006; Nakazawa and Hoshino, 2009);
(ii) difference in the maximum wind definition. JTWC uses one-minute sustained wind, CMA uses 2-minute sustained wind and most of the other centers use 10-minute mean wind;
(iii) limited in-situ observations available for validating TC intensity; and
(iv) data inhomogeneity resulting from technological advancements, such as observational techniques, changes in equipment, increase in station number, etc.

6.2 Model uncertainties

The advance in climate modeling in the last decade has provided us with a useful tool to project the future climate changes under various greenhouse gas and aerosol emission scenarios. However, there still exist a variety of uncertainties and limitations in the climate modeling and associated downscaling methods which may affect the skill and reliability of the projections of TC activities. Some of these uncertainties and limitations include:

(i) Future greenhouse gas and aerosol emission scenarios;
(ii) Physics of climate modeling (e.g., including model parameterizations, model response to greenhouse gases and aerosols, projections of sea surface temperature in different regions, air-sea interaction simulation capability, etc.);
(iii) Downscaling techniques (e.g., boundary conditions for dynamic downscaling, assumptions for statistical downscaling approach, etc.); and
(iv) Model resolution, model-scenario combination and criteria for selecting simulated TC.

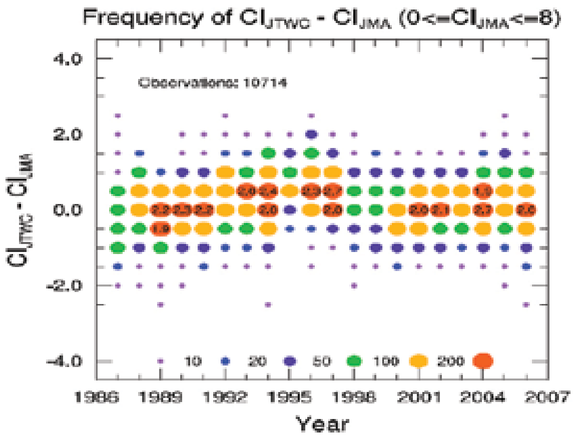


Figure 6.1 Temporal changes in the frequencies of the difference in CI-number between JTWC and JMA for 1987-2006. The color circles indicate the occurrence number at each estimated Dvorak parameters and the numbers in the red circles show the percentage of the occurrence at the point (Nakazawa and Hoshino, 2009).

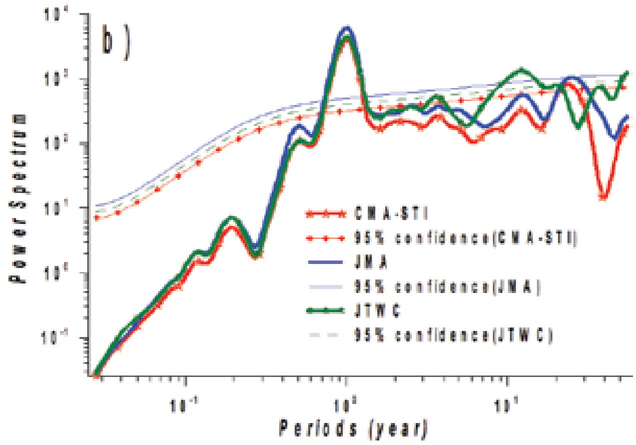


Figure 6.2 The power spectra for pentad storm frequencies that derived from the CMA, RSMC Tokyo (JMA) and JTWC datasets with original wind speeds (Ying *et al.*, 2010a).

7. RECOMMENDATIONS FOR FUTURE WORK

The following areas could be considered for future research on the subject in the Typhoon Committee region:

- Explore the feasibility of setting up or adopting a homogenous and unified TC best track dataset for WNP.

- Conduct more detailed studies on the observed TC activity in coordination with the Typhoon Committee's Training and Research Coordination Group, including the standardization of metrics, such as maximum sustained winds/minimum central pressure and station observed wind/pressure/precipitation, which have not been covered in past studies.

- Understand and validate the projections of future TC activities given by the global climate models or coupled general circulation models.

- Study the future TC impacts (e.g., wind, precipitation, storm surge, landfalling process, etc.) using high resolution global climate models and formulate relevant climate change adaptation and mitigation strategies.

- Use sophisticated statistical methods instead of the normal distribution approach to study the changes in TC activities.

- Promote sharing of knowledge and expertise with other Tropical Cyclone regional bodies and programmes.

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ANNEX I

Comparison of the Tropical Cyclone Classification

Maximum Sustained Wind Speed at the centre of the tropical cyclones			Hong Kong (10-minute average)	Mainland China (2-minute average)	Japan (10-minute average)	US Pacific (1-minute average)	US Atlantic (1-minute average)
kts	km/h	m/s					
< 34	< 63	<17.1	Tropical Depression (TD)	Tropical Depression	Tropical Depression	Tropical Depression	Tropical Depression
34 – 47	63 – 87	17.2-24.4	Tropical Storm (TS)	Tropical Storm	Tropical Storm	Tropical Storm	Tropical Storm
48 – 63	88 – 117	24.5-32.6	Severe Tropical Storm (STS)	Severe Tropical Storm	Severe Tropical Storm		
64 – 80	118 – 149	32.7-41.4	Typhoon (T)	Typhoon	Typhoon 64 – 84 kts	Typhoon 64-129kts	Hurricane categories 1: 64 – 82 kts
81 – 99	150 – 184	41.5-50.9	Severe Typhoon (ST)	Severe Typhoon	Very Strong Typhoon 85 – 104 kts		2: 83 – 95 kts
>=100	>=185	>=51	Super Typhoon (SuperT)	Super Typhoon	Violent Typhoon >=105 kts	Super Typhoon >= 130 kts	3: 96 – 113 kts 4: 114 – 135 kts 5: >135 kts

Note : the conversion between kts to km/h and kts to m/s may vary slightly subject to rounding practices and conversion factor decimal places.

ANNEX II

Acronyms

Acronyms	Full Name
ACE	Accumulated Cyclone Energy
AGCM	Atmospheric General Circulation Model
AOGCM	Atmosphere-Ocean Coupled General Circulation Model
APEC	Asia-Pacific Economic Cooperation
CMA	China Meteorological Administration
CMIP	Coupled Model Intercomparison Project
TC(s)	Tropical Cyclone(s)
EADP	East Asia Dipole Pattern
ESCAP	Economic and Social Commission for Asia and the Pacific
GHG	Greenhouse gas
HKO	Hong Kong Observatory
IBTrACS	International Best Track Archive for Climate Stewardship
JMA	Japan Meteorological Agency
JTWC	Joint Typhoon Warning Center
MPI	Maximum Potential Intensity
NOAA	National Oceanic and Atmospheric Administration
PAGASA	Philippine Atmospheric, Geophysical & Astronomical Services Administration
PDI	Power Dissipation Index
RSMC-Tokyo	Regional Specialized Meteorological Center Tokyo
TRCG	Training and Research Coordination Group
WMO	World Meteorological Organization
WNP	Western North Pacific

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Secretariat of ESCAP/WMO Typhoon Committee
Avenida 5 de Outubro, Coloane
Macao, China
Tel.: (+853) 88010531
Fax: (+853) 88010530
E-mail: info@typhooncommittee.org

ESCAP/WMO TC/TD-No. 0001