THE SECOND ASSESSMENT REPORT ON THE INFLUENCE OF CLIMATE CHANGE ON TROPICAL CYCLONES IN THE TYPHOON COMMITTEE REGION

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ON THE COVER

This photograph of Super Typhoon Bopha was taken on Sunday, Dec. 2, 2012 from the International Space Station, by Astronaut Ford as Bopha bore down on the Philippines with winds of 250 km/h. Credit: NASA ISS

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FOREWORD

With the continued attention on the issues of global climate change, the impact of climate change on the tropical cyclone has been becoming one of the most important topics in the field of climate change research. Due to the lack of long sequential observational data, the non-uniformity of the observational data and the limitations on the techniques on the analysis of tropical cyclone intensity, which makes the detection of impact of climate change on tropical cyclones and its prediction more challenging and uncertain.

In recent years, international agencies and academic groups have been continuing to update their assessment report on the impact of climate change on tropical cyclone, with the aim to reduce the uncertainties on its detection and prediction. In fact, Intergovernmental Panel on Climate Change (IPCC) will soon have its thematic elaboration on the impact of climate change on tropical cyclone in its 5th Assessment Report, and International Workshop on Tropical Cyclones (IWTC) will soon update its statement on the impact of climate change on tropical cyclones as well.

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As we all know, the Asia-Pacific is the world's most active tropical cyclone region, the variation of this region's tropical cyclone activities is pivotal to the global variation of tropical cyclone activities. As an official body of the international collaboration on the mitigation of impacts of tropical cyclones in the Asia-Pacific Region, ESCAP / WMO Typhoon Committee attaches great importance to the impact of climate change on tropical cyclones. Since 2008 the Working Group on Meteorology of Typhoon Committee has initiated the project on the assessment of the impact of climate change on tropical cyclone as one of its major tasks and planned to publish the serial assessment reports on this topic. Unlike the IPCC assessment reports and IWTC statement, the Typhoon Committee's Assessment Report not only attaches great importance to the published papers, it also places more emphasis on the analysis of the tropical cyclone activities and the assessment of disasters on Members' states provided by the Typhoon Committee Members' authorities. The first Assessment report with the focus on the impact of climate change on tropical cyclone frequency and intensity in the Typhoon Committee Region was officially released in January 2010, which has hence aroused widespread attention in the international community.

With the joint effort of the Typhoon Committee expert team and the support of the official meteorological agencies in Asia-Pacific regions, the second Typhoon Committee assessment report with the focus on identifying any possible influences of anthropogenic climate change on tropical cyclone track and impact area in this region has also been completed. This report will be officially released at the forty-fifth Typhoon Committee Session in January 2013. I truly believe that the publication of this report is able to raise the awareness of general public as well as providing the information and analysis to the professionals on the impact of climate change on tropical cyclones and hence be able to promote and coordinate Members' long-term strategy on minimizing the loss of life and material damages caused by tropical cyclones. On the occasion of the release of this report and on behalf of Working Group on Meteorology, I would like to thank the members of the expert team for their dedicated work and significant contribution to this report. I would also like to thank ESCAP, WMO and the Member States for their strong support as well as the assistances provided by Typhoon Committee Secretariat on the preparation of the report.

Working Group on Meteorology is planning to initiate the project on the third Typhoon Committee assessment report with the focus on the impact of tropical cyclone unusual behaviors on the local and regional climate change which is expected to be published in early 2016.

Working Group on Meteorology of ESCAP/WMO
Typhoon Committee
Chair: Dr. Xiaotu Lei
Shanghai Typhoon Institute of CMA
January 2013

PREFACE

It is well known that the ESCAP/WMO Typhoon Committee region (i.e., the western North Pacific basin) is a unique region in the world for tropical cyclone activity. The tropical cyclone activity in this region is the most intense of any basin, and tropical cyclones can bring great disasters to Members of the Typhoon Committee. A series of reports have been commissioned by the Committee to assess the influence of climate change on tropical cyclone activity in this region.

In December 2010, the ESCAP/WMO Typhoon Committee published the first assessment report entitled "Assessment Report on Impacts of Climate Change on Tropical Cyclone Frequency and Intensity in the Typhoon Committee Region", which focused on the frequency and intensity changes of tropical cyclones in the western North Pacific basin. We are pleased to now present this second assessment report. This second report comprehensively reviewed the tropical cyclone climate in the region and its changes over time, not only updating time series of cyclone frequency and intensity, but also assessing possible changes of track pattern, genesis location and impacts of tropical cyclones. In particular, with the support of the Members of the Typhoon Committee, new survey results about the influence of landfalling tropical cyclones on some of the Members were included in this report. These surveys addressed possible changes in the frequency of landfall, in tropical cyclone-induced severe wind and heavy rainfall, and in related casualties and economic losses. As in the first assessment report, an assessment was also made for trend detection and projections for the late 21st century, including discussion of uncertainties. Some important issues related to current and future operational practices or research were stated along with recommendations. It is our hope that this report will give rise to more studies on the influence of climate change on tropical cyclone activity in this region, leading to improved scientific understanding, and better information for decision-makers, on this important issue.

ACKNOWLEDGEMENTS

We sincerely thank members of ESCAP/WMO for kindly providing materials for section 3 and thank Mr. Koji Kuroiwa, Drs. Sangwook Park, Chuho Chu, and Yu-Kyung Hyun, and other experts from members of Typhoon Committee for their valuable comments. This work was sponsored by the ESCAP/WMO Typhoon Committee Annual Operating Project. We also wish to thank Dr. Xiaotu Lei, Mr. Weng Kun Leong, and Mr. Derek Leong for coordinating various affairs during implementing the project. Sincerely thanks are also given to all staff of Typhoon Committee Secretariat for their assistance during the project and arranging the expert team working meeting, and to STI/CMA for providing web-based information exchange platform and hosting the working meeting of the expert team in Shanghai, China in 2011.

EXECUTIVE SUMMARY

This report assesses the current state of the science on the relationship between climate change and tropical cyclone (TC) activity in the Western North Pacific (WNP) basin. The report will focus in particular on identifying any possible influences of anthropogenic climate change on tropical cyclone track and impact area in this region.

Two central questions that are addressed through the report are the following:

- Is there a detectable human influence on any TC metric in the Typhoon Committee region?
- What changes in TC activity are expected in the region over the 21st century as a consequence of climate warming as projected by IPCC (Intergovernmental Panel on Climate Change)?

Assessment of past changes in basin-wide TC activity

Existing datasets show pronounced interdecadal variations in a number of TC metrics in the WNP basin, such as storm frequency, intensity, and power dissipation index (PDI). Two of four Best Track data sets show significant decreasing trends in in the TC (tropical storm or above) frequency over the last five decades or so, while two other Best Track sets show only a nominally decreasing trend which is not statistically significant. In general, multi-decadal trends in WNP basin-wide TC (tropical storm or above) frequency are highly dependent on which Best Track data set is used, on the analysis period chosen, and other analysis details.

Trends in intense typhoon frequencies, such as Category 4 to 5, are particularly divergent in recent decades, and remain uncertain. Satellite-based intensity trends since 1981 show only modest evidence for significant trends and their utility is limited by the relatively short record length together with uncertainty about natural variability levels. PDI series show some low-frequency correlation with SST and a rising tendency since 1950 but key uncertainties remain about both data homogeneity and the potential role of natural variability. In general, uncertainties in observed TC datasets, as reflected for example in the differences between records from different centers in the basin, as well as uncertainties about the potential role of natural variability on TC trends and other changes in the basin, limit our ability to make a confident attribution of the observed changes in these TC metrics to human influences.

Climatologically, most TCs in the WNP are generated in the Philippine Sea or the South China Sea, within a latitude band of 10°N to 25°N. There are three prevailing tracks of TCs: a westward moving track, a recurving track that continues toward Japan or the Korean Peninsula, and a recurving track to the northeast, mostly east of 140°E. There are indications that the most important factor for TC track change is a change in the large scale TC steering flow, while the change in genesis position is of secondary importance. Observations indicate a decreasing trend in TC occurrence in part of the South China Sea and an increasing trend along the east coast of China during the past 40 years. This change is related to local circulation change in the eastern Asia and WNP. One modeling study suggests that this change has a large contribution from radiative forcing, but further studies are needed to understand the relative contributions of natural variability and anthropogenic forcing to these observed changes in TC occurrence.

In summary, it remains uncertain whether there has been any detectable human influence on tropical cyclone frequency, intensity, precipitation, track, or related aggregated storm activity metrics in the WNP basin.

Assessment of past changes in landfalling TC activity

Tropical cyclone frequency

Analysis of time series of landfalling TCs indicates no significant trend in the number of landfalling TCs for China, Japan (tropical storm or above), the Philippines, the Korean peninsula and in the vicinity of Hong Kong and Macao. Although not statistically significant, the trends are negative for China and in the vicinity of Hong Kong and positive for the Korean peninsula.

The number of typhoons landfalling in /crossing the Philippines has a significant decreasing trend. The frequency of TCs (mostly tropical depressions) entering Thailand also has a significant decreasing trend, although there is a slight increasing trend in the number of TCs of tropical storm strength reaching Thailand. According to a change point analysis, the number of TCs affecting the vicinity of Taiwan increased significantly in the last decade.

The variations of the landfalling TCs in this region are likely related to the shift of TC tracks as observed in the last few decades as a result of the changes in the large scale steering flow. However, with significant inter-decadal variations in the TC activity being evident in this region, the data period may be too short to confidently determine whether any of these changes are outside the range of natural variability. More research will also be required to further our understanding of the natural variability in this basin and the relative contributions of natural variations and anthropogenic forcing to the observed changes.

High winds and precipitation

The maximum sustained winds of TCs affecting the near-coastal China and off-shore sub-regions have a decreasing trend, with a prominent decreasing trend at the coastline of southeast China including the urban areas of Hong Kong. There is no significant trend in maximum wind speed due to tropical cyclones in Macao.

For precipitation, while the annual TC induced precipitation in China has a statistically significant decreasing trend for some of the stations along the coast, the changes in TC induced precipitation *per TC* and maximum 1-hour precipitation have significant spatial variations in China with increasing trend at a number of stations, especially over coastal areas of southeastern China.

A significant increase has been reported in the TC-induced rainfall for TCs landfalling in the Korean peninsula and Japan and the summer rainfall related to TCs (TS or above) affecting Taiwan. There is no significant trend in the TC-induced rainfall in Hong Kong and Macao.

It remains to be demonstrated that whether any of these reported sub-basin-scale changes have a substantial contribution from anthropogenic forcing.

Casualties and economic losses

In terms of casualties, there is no significant trend in China and the Republic of Korea. The number of casualties in Hong Kong and Japan has decreased. However, the economic losses due to TCs have an increasing trend in China, the Republic of Korea and the Philippines. Analysis available for China suggests that the increase in economic losses there is likely due mostly to the economic development.

Assessment of late 21st century projections of TC activity

According to the WNP tropical storm frequency projections from twelve available studies based on dynamical models having a grid spacing finer than about T106 or 120 km, more models suggest a decreasing trend than an increasing trend over the 21st century. The projected changes for the late 21st century range from about -70% to +60%. Other studies using statistical/dynamical methods (one study) or empirical genesis parameters (three studies) tend to have more mixed projections, with three of four suggesting an increase in frequency.

According to nine available studies, using either dynamical models with 50 km or finer grid spacing, or evaluations by potential intensity theory, most of the studies projected an increase in TC intensity over the WNP, although several studies projected a mix of positive and negative intensity changes depending on the model downscaled. Studies with quantitative results suggested changes ranging from -3% to +18% for maximum wind speeds.

Six available studies, reporting TC precipitation rate projections either for all basins, northern hemisphere basins, or the WNP, all projected increases with quantitative projections ranging from roughly +5% to +30%.

A common general feature of several projection studies is that the track/occurrence of TCs may shift eastward or northward in the WNP. However, this finding requires further studies to assess the robustness of this result.

The vulnerability of coastal regions to storm surge flooding is expected to increase with future sea-level rise and coastal development, although this vulnerability will also depend on future storm characteristics.

Globally, a recent study concludes that projected increases in future income and demographic pressure over the next 20 years may increase the number of people exposed to TC threat per year and exacerbate disaster risk, despite potential progress in development and governance. Projected global increases in TC intensity and decreases in TC frequency are projected to have opposing effects on TC exposure, though these effects are generally smaller than the projected influence of societal changes.

CHAPTER 1. INTRODUCTION

This report assesses the current state of the science on the relationship between climate change and tropical cyclone (TC) activity in the Western North Pacific (WNP) basin. The report will focus in particular on identifying any possible influences of anthropogenic climate change on TC track and impact area in this region. Two central questions that are addressed through the report are the following:

- *Is there a detectable human influence on any tropical cyclone metric in the Typhoon Committee region?*

- *What changes in TC activity are expected in the region over the 21st century as a consequence of climate warming as projected by IPCC (Intergovernmental Panel on Climate Change)?*

As outlined in the IPCC 4th assessment report (IPCC 2007), warming of the climate system is now unequivocal and is evident for example in increased globally averaged sea surface temperatures. Moreover, the IPCC concluded that most of the increase in globally averaged temperatures since about 1950 is very likely due to human-caused increases in greenhouse gas concentrations. Gillett et al. (2008) conclude that an anthropogenic warming signal can be identified in sea surface temperatures (SSTs) in the Western North Pacific tropical cyclogenesis region.

Tropical cyclones form and intensify in the warm tropical oceanic regions in the present climate. Historically, these storms have ranked among the most destructive of all natural disasters. The WNP basin experiences more TCs on average in a given year than any other basin, (~30 per year, comprising roughly one third of the global total and about 40% of the global total accumulated cyclone energy, as estimated by the ACE Index (Maue 2011)). TCs in this basin appear to be larger in size on average than in other basins (e.g., Yuan et al. 2007; Chavas and Emanuel 2010), and the strongest recorded storms in terms of lowest central pressure have occurred in this basin. Thus it is of great interest and societal importance to understand how climate warming could affect TC activity in the basin.

While a continued warming of the tropical oceans on the century time scale appears highly likely under typical 'business as usual' future emission scenarios, the relationship between greenhouse gas-induced surface temperature increases and TC activity is much more uncertain than the surface temperature change itself. For example, a recent WMO expert team global assessment (Knutson et al. 2010) concluded that it remains uncertain whether past changes in TC activity are highly unusual compared with the variability expected from natural causes. That report also concluded that a decrease (or little change) in global TC frequency was likely during the coming century, and that an increase in the globally averaged TC intensity was also likely. The report further concluded that the frequency of the most intense TCs would more likely than not increase, at least in some basins. In terms of regional changes, the report concluded that future TC projections were even more uncertain for individual basins than for the global averages.

In the western North Pacific and the South China Sea, likely modulating by the El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) as well as the sea surface temperature anomaly in the East Indian Ocean (e.g. Liu and Chan, 2008; Chan, 2008; Yeh et al., 2010; Zhan et al., 2011), the TC activity exhibits significant interannual and interdecadal variations in this basin. Against the background of global climate change, model simulations suggested that the long term change of SST and associated atmospheric conditions due to future greenhouse gas scenarios could have impact on the genesis locations, frequency and prevailing tracks of the TCs in this basin (see Chapter 5 for more detailed discussions). Moreover, the warming of the SST and lower troposphere could, theoretically, favor the formation of more intense TCs and enhance the precipitation associated with the TC activity (Emanuel, 2008). However, with considerable interannual and interdecadal variations in the TC activity in this basin, the detection of anthropogenic influence on TC activity based on about five decades of available TC data is still a major challenge to the research community. Also, the issues on homogeneity and consistency of best track data sets in the WNP further add uncertainty to relevant research studies.

An assessment report focusing on tropical cyclone frequency and intensity in the ESCAP/WMO Typhoon Committee[1] region (WNP basin) (Lee et al., 2010) reported that the majority of climate model studies project a reduction in TC frequency in this basin over the coming century with some model projecting an increase in the number of intense TCs. The large uncertainties and limitations of such modeling studies were noted. The ESCAP/WMO Typhoon Committee commissioned the present (2nd) assessment report at its 42nd Annual Session in Singapore (25-29 January 2010), requesting in particular that the new report focus attention on the TC track and impact area issues.

In the current report Chapter 2 will provide an updated assessment of past observed changes in TC frequency, and intensity (including aggregated activity measures), as well as precipitation for the WNP basin. Chapter 3 will examine TC genesis, tracks, and duration for the basin as a whole. In response to the Typhoon Committee's request that the 2nd assessment report focus more attention on the TC track and impact area issues in particular, our expert team surveyed each of the Typhoon Committee Member concerning the climatology and observed trend behavior of TC activity and related impacts in their respective countries. Chapter 4 will focus on the results from these surveys as well as published scientific papers on TC impacts in the Typhoon Committee region. Chapter 5 will update the 21st century TC activity projections material from the team's first assessment report. Uncertainties will be discussed in Chapter 6, and recommendations for future work will be given in Chapter 7.

While this report does not provide an exhaustive literature review of all studies on these topics, we have attempted to include and discuss at least the key references on which our assessment judgments have been based.

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[1] The ESCAP/WMO 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.

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CHAPTER 2. TROPICAL CYCLONE FREQUENCY, INTENSITY, AND PRECIPITATION CHANGES

In this chapter we focus on the question of whether there has been any detectable human influence on tropical cyclone (TC) frequency, intensity, precipitation or related aggregated storm activity metrics in the Western North Pacific (WNP) basin. In its 2010 global assessment report, the WMO Expert Team on Climate Change Impacts on Tropical Cyclones (Knutson et al. 2010) concluded: "It remains uncertain whether past changes in any tropical cyclone activity (frequency, intensity, rainfall, and so on) exceed the variability expected through natural causes, after accounting for changes over time in observing capabilities." This conclusion referred to global mean changes as well as changes in any of the world's basins. Therefore, it also applies to the WNP basin. Our conclusions for the WNP basin in the present report generally concur with the findings of the WMO team for this basin and with the Typhoon Committee team's First Report (Lee et al. 2010).

Despite the apparent lack of a robust detectable anthropogenic climate change signal in TC metrics in the Western North Pacific, we will go into some detail on the types of analyses that have been published, some of which document trend-like behavior over certain intervals of time.

2.1 Tropical Cyclone Frequency

A number of investigators have examined historical records of TC frequency for the WNP basin. Li et al. (2010) showed that there is a nominally positive trend in WNP TC frequency and duration in the JTWC data for 1945−2007, although they did not report on the statistical significance of the trends. Yuan et al. (2009) reported a significant increasing trend in the JTWC tropical storm frequency data (1945−2005). In contrast, Ma and Chen (2009) showed a decreasing tendency over time in the tropical cyclone frequency for the basin (1949−2007), based on data from a different center (the CMA). [See Table 2.1 for summary information on different sources of tropical cyclone data.]

The 1st Assessment Report of the WMO/ESCAP typhoon committee's expert team which was charged with assessing tropical cyclones and climate change in the WNP (Lee et al. 2010) analyzed the basin-wide time series of TC (tropical storm or above) and typhoon counts beginning from the 1940s. Trends from datasets available from several different centers were examined and compared (see Figs. 2.1and 2.2 of Lee et al. 2010). The results of these analyses are updated through 2010 for the current (2nd Assessment) report.

Table 2.1 Summaries of available tropical cyclone best track data for the WNP basin

Agency	Data period	Characteristics	Wind averaging time	Available from
CMA	1949–current	Maximum Sustained Wind (MSW) and Minimum Central Pressure (MCP) since 1949	2-min	http://www.typhoon.gov.cn/index.php?controller=spage&pid=170
HKO	1961–current	MSW and MCP since 1961	10-min	http://www.hko.gov.hk/publica/pubtc.htm
JTWC	1945–current	MSW since 1945, MCP since 2001	1-min	http://www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/
RSMC Tokyo	1951–current	MCP since 1951, MSW since 1977. Tropical storm category is assigned since 1951	10-min	http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/trackarchives.html

Time series of the frequency of TCs with tropical storm or above (i.e., all storms of at least tropical storm strength based on the categories assigned by various agencies) are shown in Fig. 2.1. In Fig. 2.2a the tropical storm determination is made based upon 10-minute sustained winds (where winds are reported), with conversions for different averaging times based on the wind conversion table in Harper et al. (2010). (The "off-land" and "off-sea" categories for use in this conversion are defined based on the areas separated by a boundary 20 km off of the coastline.) Similar results for *typhoon* counts (10-minute sustained winds of at least 33 ms^{-1}) are shown in Fig. 2.2b.

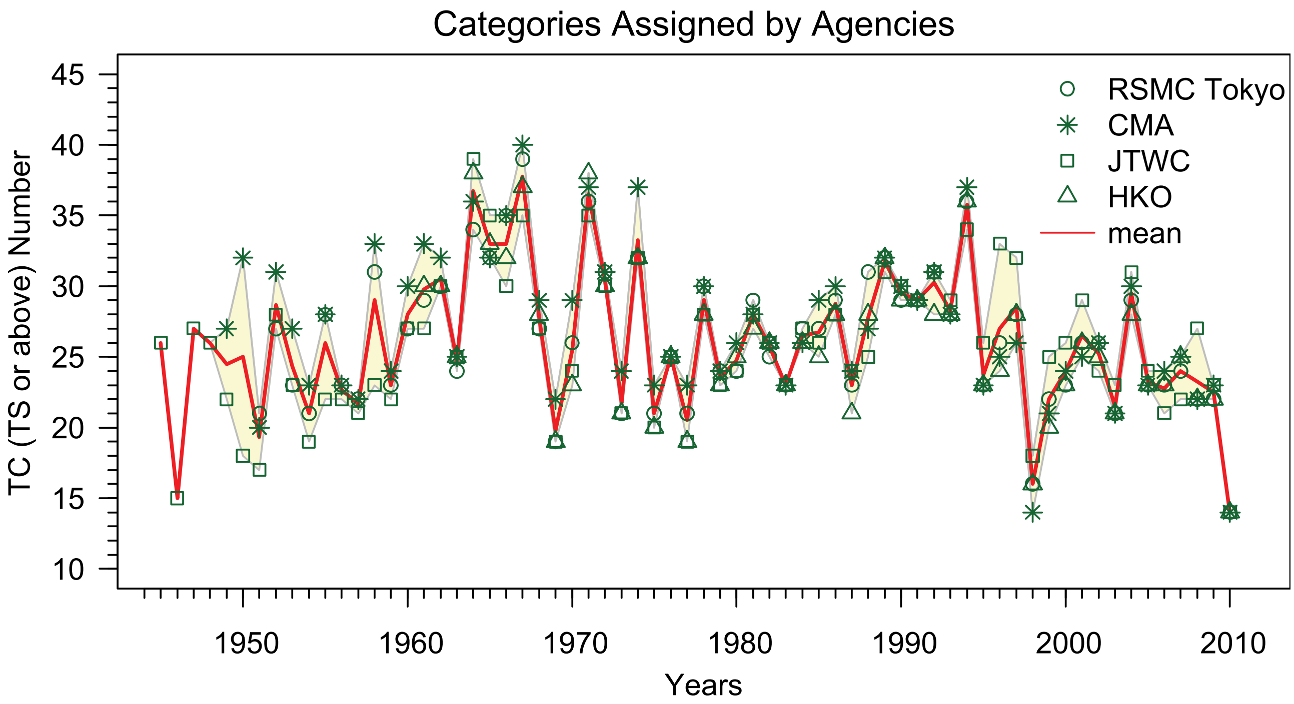

Fig. 2.1. Annual storm counts of TCs with at least tropical storm intensity based on the storm category assigned by agencies.

Note that the IBTrACS dataset was not used here since the current version of IBTrACS (v03r03) does not include a statistical summary of the data from the different agencies. A statistical summary (i.e., the median of the different estimates) was used in the First Report (Lee et al. 2010).

Results of statistical tests on linear trends are shown in Tables 2.2 and 2.3 for various data centers, averaging periods and for either tropical storm counts or typhoon counts. Results are compared for original categorization and using reported wind speeds adjusted to a 10-minute averaging time. Statistically significant decreases are found for annual counts of storms of at least tropical storm or at least typhoon intensity according to the CMA (1949–2010) and HKO (1961–2010) data sets, but no significant trends are found for the JTWC (1945–2010) or RSMC-Tokyo (1977–2010) data sets. Using a common period across the data sets (1977–2010) the CMA and HKO data sets (Table 2.3) show significant declines in tropical storm (and above) counts but not typhoon counts. In summary, similar to the 1st Assessment Report, some of the data sets indicate significant declines in overall counts of TCs (tropical storm or above) or typhoons in recent decades, but this finding is not robust across the various data sets.

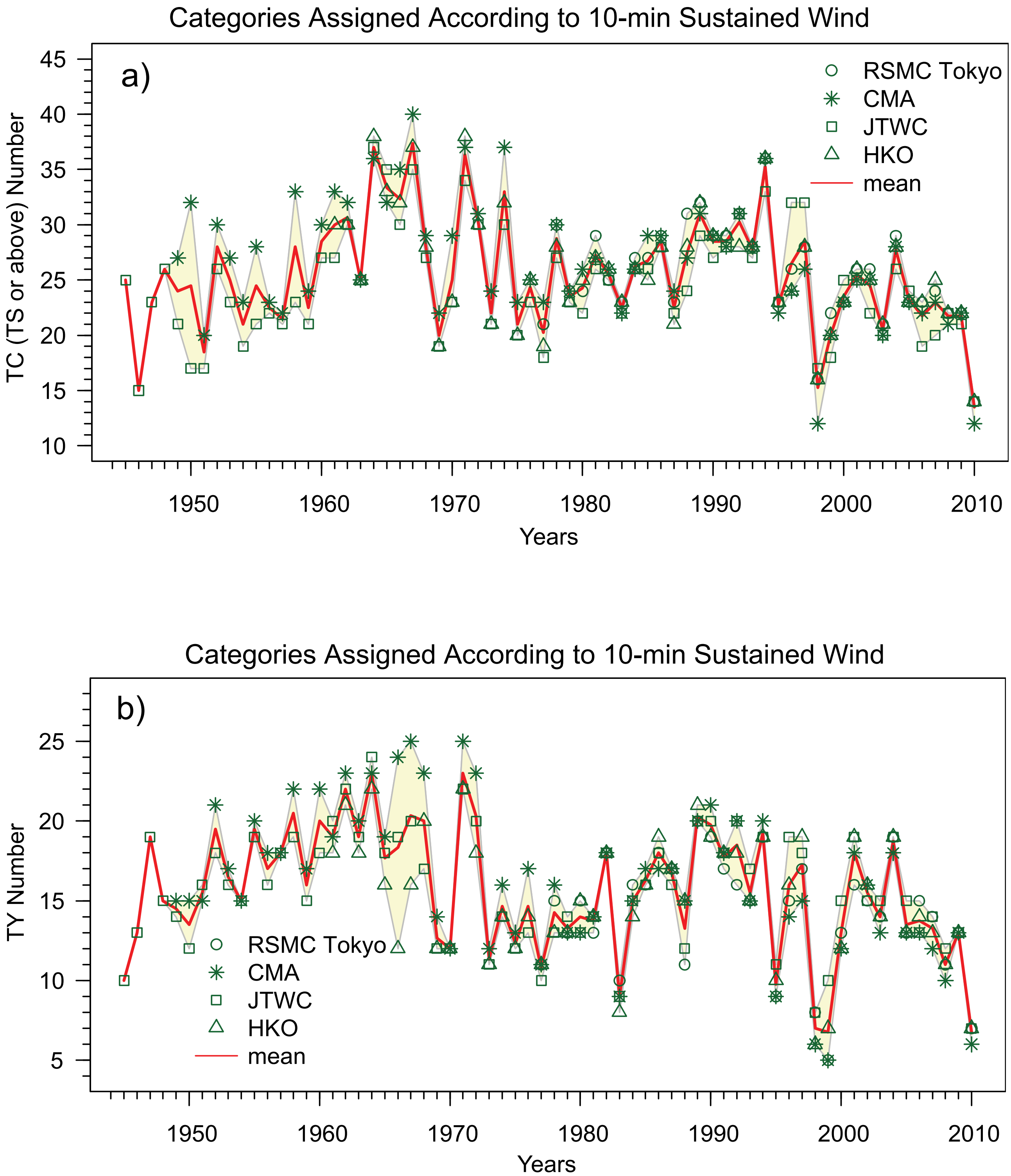

Fig. 2.2. Annual storm counts based on the categories assigned according to reported maximum sustained winds converted into 10-min mean. (a) storms of tropical storm intensity and above, and (b) storms of typhoon intensity.

Table 2.2 Trends of annual numbers of TCs in WNP based on different datasets for all available data up to 2010. The trends are estimated by linear least square regression. Data in bold indicate the trends are statistically significant at 5 % level. Residuals from the trend are assumed to be temporally independent, based on inspection of the lag-one autocorrelation coefficients.

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	1949-2010	**-0.96/decade**	**-1.00/decade**	**-1.20/decade**	**-1.25/decade**
JTWC	1945-2010	+0.30/decade	-0.19/decade	-0.02/decade	-0.38/decade
RSMC-Tokyo	1951-2010	-0.58/decade*	-0.77/decade**	-0.58/decade*	-0.77/decade**
HKO	1961-2010	**-1.59/decade**	**-0.78/decade**	**-1.59/decade**	**-0.78/decade**

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

** Period from 1977 to 2010 as MSW data in RSMC-Tokyo dataset only available since 1977.

Table 2.3 Trends of annual numbers of TCs in WNP based on different datasets from 1977 to 2010. The trends are estimated by linear least square regression. Data in bold indicate the trends are 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	**-1.73/decade**	-0.66/decade	**-2.15/decade**	-1.15/decade
JTWC	-0.72/decade	+0.26/decade	-1.28/decade	+0.29/decade
RSMC-Tokyo	**-1.63/decade**	-0.77/decade	**-1.63/decade**	-0.77/decade
HKO	-1.24/decade	-0.68/decade	-1.24/decade	-0.68/decade

All of the trend findings discussed above should be treated with caution as there is uncertainty in the degree to which natural climate variability can cause trend-like behavior on these time scales, and not all of the different data sets agree on the significance of the trends. Possible inhomogeneities in the data due to changes in observing capabilities over time (as has been assessed in detail for the Atlantic basin by Vecchi and Knutson (2011) or Landsea et al. (2010)) must also be considered in an overall assessment of these reported trends for the WNP. A promising new approach in this regard is the use of reanalysis fields to identify possible candidate missing storm cases (Truchelat and Hart 2011). While these techniques has been developed for the Atlantic basin, these or similar methodologies may be useful for the WNP in future studies.

Since tropical cyclones generally form over relatively warm tropical oceans, the question arises whether any increase in the area of cyclogenesis as the climate warms, particularly as there is some evidence for a detectable anthropogenic influence on tropical SSTs in the Western North Pacific basin (Gillett et al. 2008). Dare and McBride (2011) have assessed this issue using historical TC and SST data for all basins and conclude that while there has been a small increase in the average SST associated with TC genesis, there has as yet been no detectable shift of the so-called “threshold temperature” for TC formation toward higher values.

Related to the question of understanding and attributing past changes in tropical storm or typhoon frequency and other metrics, several recent studies have demonstrated the ability of models to reproduce to some degree the observed past variations in the WNP. This can be assessed, for example, by examining whether the correlation between a model’s simulated time series of interannual variations of tropical cyclone counts and the observed time series is statistically significant. Substantial correlations have been shown for some basins using either global models forced by observed SSTs (Zhao et al. 2009; Murakami et al. 2011) or a statistical-dynamical downscaling framework forced by large-scale environmental information from NCEP Reanalyses (Emanuel et al. 2008), although not all of these studies report on formal statistical significance tests of these correlations. Nonetheless, such modeling tools have been improving and will be useful for future assessments of causes of changes in TC activity in the WNP and other basins.

2.2 Tropical Cyclone Intensities

Analyses of maximum intensities of TCs depend on the ability to accurately monitor the intensity of storms during the intense stages of their lifetimes, and to have a consistent measurement of storm intensities across several decades for use in climate trend analyses.

A promising technique to deal with potential inhomogeneities in global TC intensity estimates using satellite data was pioneered by Kossin et al (2007) in developing the HURSAT data set. Advantages of their technique include its global coverage and its focus on maintaining a homogeneous degree of bias over time, which is important for climate trend studies. Limitations include the relatively short record length, as the data set extends back only to 1981−1983, and the relatively large absolute (though temporally more consistent) errors or biases. The HURSAT data set, which is designed to have a more homogeneous degree of bias over time, can also be useful for regional assessments such our assessment for the WNP. No statistically significant trends were claimed for PDI or the number or percent of 2-sigma hurricanes in the basin over time (that is, in storms with intensities higher than two standard deviations above the 23-year sample mean intensity of 65 ms^{-1} for the WNP basin).

Elsner et al. (2008) expanded on the Kossin et al study by developing and analyzing a revised version of the HURSAT data set and by using a quantile regression technique to isolate and evaluate intensity trends within different parts of the intensity distribution. The revisions to the HURSAT data set for Elsner et al. (2008) vs Kossin et al. (2007) were most pronounced in the Indian Ocean basins, where changes in satellite view angles over time necessitated a time-dependent adjustment to the intensities. The quantile regression analysis for the WNP basin showed little evidence for significant intensity trends except for a significant (p=0.012) increase in the 0.975 quantile. However, caution is required in interpreting this result as their data record length was relatively short (1981−2006) for assessing the potential role of natural variability on any observed trends. In addition, since they showed multiple trend test results for the WNP, the probability of obtaining a single significant trend result by chance was increased above that for a single test.

Among the many factors affecting TC intensities, Wu and Wang (2008) conclude that changes in storm formation locations and prevailing tracks may have contributed to the observed changes in the proportion of intense hurricanes reported for several basins over the past 30 years. Changes in these factors are examined in detail in Chapter 3 of this report.

Concerning analyses of storm intensities in the original TC intensity data sets, Ren et al. (2011) showed that the JTWC intensities were higher than the intensities from the other two data sets examined, and speculated that TC intensities were overestimated in the JTWC data set after 1988 and especially from 1993–2003.

Wu and Zhao (2012) used a tropical cyclone intensity model and storm track data from three centers in the basin (JTWC, RSMC-Tokyo, and STI/CMA) to simulate trends in TC intensities in the various data sets and their relation to change in SST, vertical shear, and storm track changes. They used the statistical-dynamical downscaling framework of Emanuel et al. (2008), but assumed a constant outflow temperature over time, rather than the strong decreasing outflow temperature trend from the NCEP reanalysis discussed by Emanuel (2008). According to their analysis of the dynamically derived TC intensities, the JTWC trends appeared more realistic than those derived from the other centers. Their study suggested that the increasing intensity trend in the JTWC data over 1975–2007 was nominally positive, though possibly overestimated, and they concluded that the TC intensity trends in the RSMC and STI intensity data sets were dynamically inconsistent with other environmental variables, at least according to their model simulations. Concerning the JTWC data in particular, the earlier analysis of Wu et al. (2008) had found significant positive trends in WNP intensities (1975–2004). However, the trends that Wu and Zhao (2012) derived using the model simulation approach and the JTWC input data were not significant (1975–2007). This finding was consistent with the satellite-based analysis of Kossin et al. (2007) who found evidence that the JTWC overestimated intensities during 1988−2004. A step toward resolving these differences in storm histories between the various centers in the WNP was undertaken at a Best Track Consolidation Meeting, held in Hong Kong, China (13–14 December 2010) and sponsored by the ESCAP/WMO Typhoon Committee.

2.3 Intense Typhoon Frequency

Analysis of very intense typhoon frequency represents a blend of information about frequency and intensity, since the storms much reach very high intensity, such as Saffir-Simpson category 4 and 5 (see Annex I for the comparison of the TC classifications internally used by different Members of the Typhoon Committee), at some point in their lifetime to be included in the count statistics for very intense typhoons. Very intense typhoons show particularly notable discrepancies between data sets from different centers for the WNP basin (e.g., Fig. 2.3), which affect recent trends in those metrics. For example, Wu et al. (2006) compared time series of annual numbers of category 4 and 5 storms for JTWC, RSMC-Tokyo, and HKO. Yu et al. (2007) compared data from JTWC, RSMC-Tokyo and CMA. Song et al. (2010) and Ren et al. (2011) compared time series from CMA, JTWC, and RSMC-Tokyo. After 1987, the RMSC-Tokyo data shows very few category 4 or 5 storms, while JTWC data set records roughly 6 per year over the same time period. The HKO and CMA category 4-5 time series are closer to that of RSMC-Tokyo than to JTWC.

There has been considerable discussion of these differences among the long-term WNP Cat 4-5 time series. The cessation of aircraft reconnaissance in 1987 has been pointed to as one of the possible causes for temporal inhomogeneities in the data sets. The relationship between satellite-based intensity estimates and inferred maximum surface winds differ between different agencies and operational procedures have changed over time in some cases (Knapp and Kruk, 2010). Chan (2009) also noted that the number of Cat 4-5 storms in the basin is not correlated with a basin-wide measure of potential intensity of hurricanes in the WNP basin, even though these metrics are significantly correlated in the Atlantic and to some extent the eastern North Pacific basins.

Despite the above differences in Cat 4-5 time series from different centers, from the analyses of Wu et al. (2006), Song et al. (2010), Ren et al. (2011) or Chan (2008), a consistent finding among the data sets is that none of the available WNP Cat 4-5 time series from any of the centers shows a pronounced positive trend over time, at least when data are examined including the relatively active period of the 1950s and 60s. (e.g., Fig. 2.3). Unfortunately, confidence in these earlier intensity estimates is tempered by the lack of satellite data to use for independent assessment of intensities, as in Kossin et al. (2007).

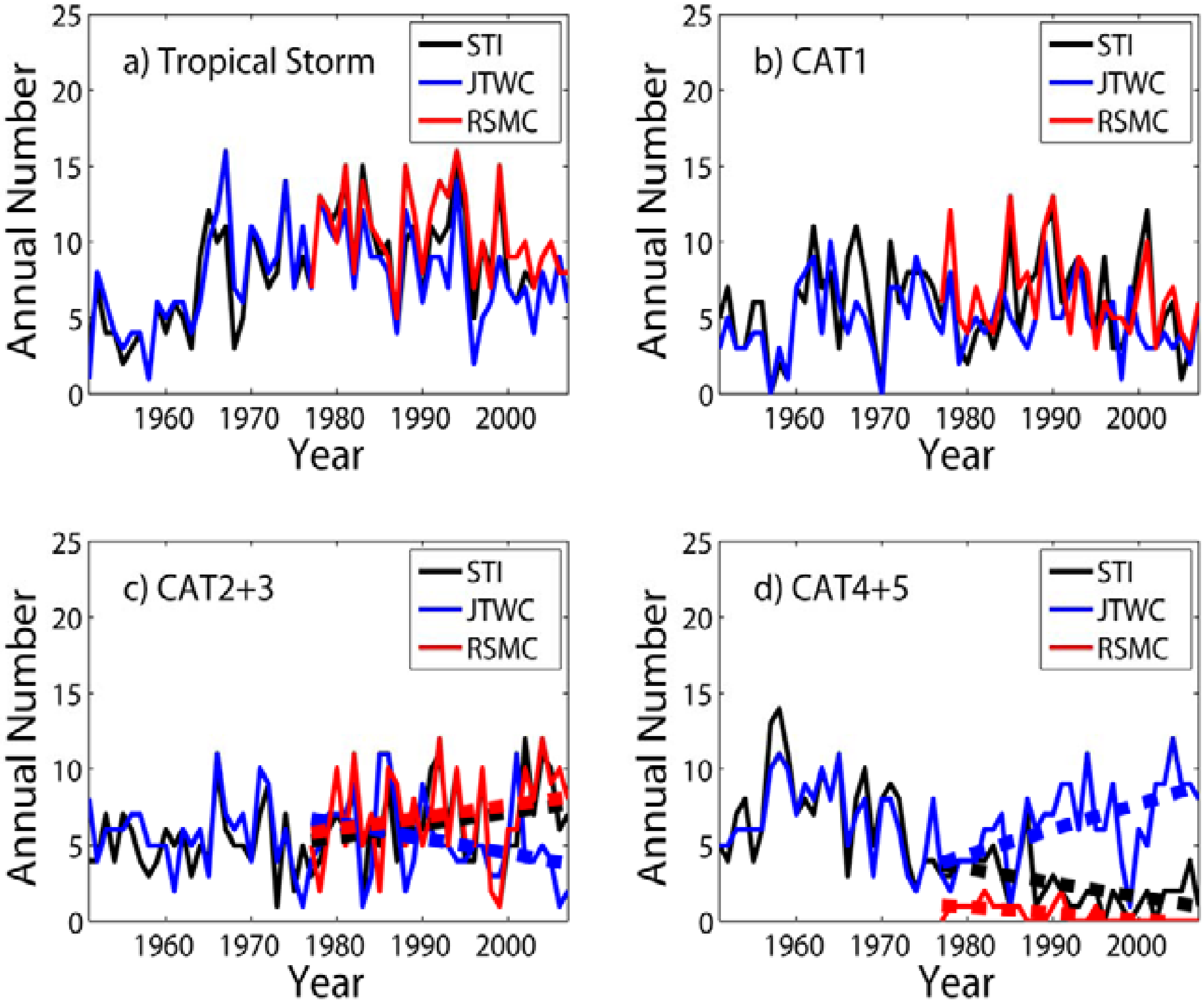

Fig. 2.3. Annual numbers and linear trends of: a) tropical storms; b) Category 1 storms; c) Category 2 and 3 storms; and d) Category 4 and 5 storms for the Western North Pacific basin according to data from the Shanghai Typhoon Institute (STI, black), the U.S. Joint Typhoon Warning Centers (JTWC, blue), and the Regional Specialized Meteorological Center – Tokyo (RSMC, red). (Extracted from Song et al. (2010)).

Wu and Wang (2008) reported increases in the proportion of intense typhoons (there defined as storms with wind speeds exceeding 32 ms^{-1}) in the WNP basin over 1975−2004, consistent with the analysis of Webster et al (2005). They further noted that changes in formation locations and prevailing tracks may have contributed to these increases. Note that their study used JTWC data, which Wu and Zhao (2012) later concluded possibly had a positive intensity bias after 1987.

2.4 Integrated Storm Activity Metrics (ACE and PDI)

A widely cited series of analyses of a TC power dissipation index (PDI) and a local basin sea surface temperature index (Emanuel 2005; 2007) have been updated for the WNP in Emanuel

(2008) and is shown in Fig. 2.4. The PDI is an integrated measure of tropical cyclone activity and is formed by summing the 3rd power of the maximum wind speed for each storm over its entire lifetime and then summing across all storms in a season to form the seasonal total PDI value. According to this integrated metric and analysis, the JTWC and JMA data sets have similar low-frequency PDI variations and are similar to the UW/NCDC satellite-based “HURSAT” reconstruction (Kossin et al. 2007) over the period since 1981, except for a period of substantial discrepancies during the mid-1990s. In addition, the HURSAT reconstructed counts are lower than the RSMC-Tokyo or JTWC estimates in the early 1990s. The agreement between JMA and JTWC is also fair in the years prior to 1987, which was a period in which aircraft reconnaissance was occurring over the basin. The PDI series for RSMC-Tokyo was constructed by converting the central pressures reported in the JMA archive to maximum wind speeds using a wind-pressure conversion (“Takahashi’s formula”) as discussed in Emanuel (2007). The PDI curves extending from the late 1940s show some evidence for a rise over time, although Emanuel presents no formal trend analyses of these data. In addition, the low-frequency PDI variations show some correlation to low frequency variations of the WNP SST index, although this relationship appears to degrade in the years following discontinuation of the aircraft reconnaissance.

In order to more reliably assess whether a detectable increase has occurred in basin-wide PDI, further analysis is needed both to assess the possible influence of data inhomogeneities, and to more reliably estimate the potential influence of natural variability on trends in the index (see also the recent global assessment of TC ACE by Maue (2011)). These are important future projects in the context of climate change detection and attribution for TC activity in the WNP.

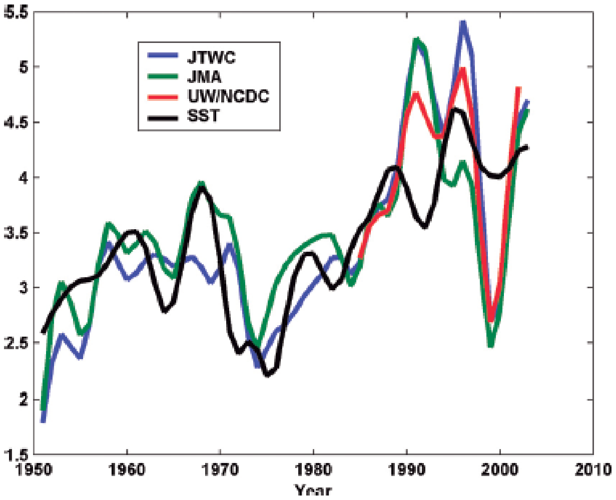

Fig. 2.4. Power dissipation (colored curves) in the western North Pacific according to (blue) data from the JTWC as adjusted by Emanuel (2005), (green) unadjusted data from the RSMC-Tokyo, and (red) reanalyzed satellite data from Kossin et al. (2007). The black curve represents a scaled Jul–Oct SST in the tropical western North Pacific region. All quantities have been smoothed using a 1-3-4-3-1 filter. (Extracted from Figure 1 of Emanuel (2008)).

2.5 Tropical Cyclone Duration and Size

Integrated storm metrics such as accumulated cyclone energy, power dissipation, or integrated kinetic energy, in their complete forms depend on accurately monitoring the intensity, duration, and size of tropical cyclones throughout their lifetimes. Therefore any temporal inhomogeneities in duration statistics could affect trends in the integrated storm measures, although weak stages of systems do not contribute very much, especially to PDI statistics, due to the use of wind speed squared or wind speed to the third power. (Storm duration is discussed in Chapter 3.)

Storm size has a particularly strong influence on storm damage (e.g., Powell and Reinhold, 2007), since a large storm is associated with a larger area of potentially damaging winds and large storm size can contribute toward creation of an enhanced storm surge. Both of these effects can potentially lead to larger storm damage.

One study considering past temporal variations in tropical cyclone size (Yuan et al. 2007) reported increases in the radii of 15.4 ms^{-1} winds (1972–2004) in the WNP, but not in the radius of 25.7 ms^{-1} winds for TCs there (based on RSMC-Tokyo data). However, the homogeneity characteristics and limited length of available records for TC size remain areas of concern for such studies.

2.6 Tropical Cyclone Precipitation

Tropical cyclones provide about 11% of total seasonal rainfall in the WNP basin, and in some subregions of the basin (e.g., near Taiwan) can account for up to 35−40% (Jiang and Zipser (2010) based on TCs of at least tropical storm intensity; see also Rogers et al. 2000; Kubota and Wang 2009; Chen et al. 2010). In addition, rainfall from tropical cyclones can cause freshwater flooding disasters. Therefore, it is of great interest to understand how climate change could be affecting the rainfall from TCs. There are several different types of tropical cyclone-related precipitation measures that could be considered (e.g., seasonal total, average total precipitation per storm, precipitation flux rate from a mature storm, averaged over various radii, etc.).

Few long-term trend analyses have been done of basin-wide (non-landfalling) TC precipitation in the WNP basin. Lau et al. (2008) analyzed GPCP and TRMM rainfall data over the period 1979 − 2005. They found mixed trend signals, with for example some evidence for an increase in the TC average rain intensity since 1979. However, as they noted, the trends from the longer-term record (GPCP data set since 1979) could be contaminated by temporal inhomogeneities. For precipitation characteristics of landfalling TCs, our survey on landfalling TC impacts and a number of recent studies indicate mixed results, with differing TC-related rainfall trends in various locations within the basin. This may be partly attributed to the spatial variations in the TC landfalling frequency which are likely related to the observed shift of TC tracks in the region in the last few decades. More discussion and detailed information on the TC impacts and landfallingTC rainfall characteristics are presented in Chapter 4.

One robust aspect of climate change is the increase in atmospheric moisture content in recent decades over many ocean regions (Trenberth et al. 2005). In addition, all climate models, to our knowledge, project that the column-integrated water vapor will increase in the tropics, on average, as the atmosphere warms. The expectation is that as the water-vapor content of the tropical atmosphere increases, the moisture convergence for a given amount of mass convergence will be enhanced. Based on physical reasoning, this should lead to higher rainfall rates in weather systems (such as tropical cyclones) where moisture convergence is an important component of the water vapor budget. Any increase in the convergence of winds toward the storm center (i.e., through more intense storm circulation) would further increase the moisture convergence. Despite this expectation and the observed changes in TC related rainfall in sub-basin scale as reported by some studies, further studies are still required to determine whether the anthropogenic forcing has substantial influence on the TC related rainfall in this basin. Key limitations include characteristics of the observational record together with the relatively small size of the expected anthropogenic signal to date compared with the observed background variability of TC activity in this basin.

2.7 Conclusions

Existing datasets show pronounced interdecadal variations in a number of TC metrics in the WNP basin, such as storm frequency, intensity, and power dissipation index (PDI). Trends in basin-wide TC (tropical storm or above) frequency are highly dependent on which Best Track data set is used, on the analysis period chosen, and other analysis details. Trends in intense typhoon frequencies, such as Category 4-5, are particularly divergent in recent decades, and remain uncertain. Satellite-based intensity trends since 1981 show only modest evidence for significant trends and their utility is limited by the relatively short record length together with uncertainty about natural variability levels. PDI series show some low-frequency correlation with SST and a rising tendency since 1950 but key uncertainties remain about both data homogeneity and the potential role of natural variability. In general, uncertainties in observed TC datasets, as reflected for example in the differences between records from different centers in the basin, as well as uncertainties about the potential role of natural variability on TC trends and other changes in the basin, limit our ability to make a confident attribution of any observed changes in these TC metrics to human influences. It remains uncertain whether there has been any detectable human influence on tropical cyclone frequency, intensity, precipitation or related aggregated storm activity metrics in the WNP basin.

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CHAPTER 3. TROPICAL CYCLONE GENESIS, TRACKS, AND DURATION

The term tropical cyclone (TC) used in this chapter refers to storms of tropical storm (TS) intensity or greater.

3.1 Brief Description of Climatology of TC Genesis, Tracks, and Duration

Figure 3.1 shows the distribution of TC formation frequency on 2.5° latitude x 2.5° longitude boxes during July−September calculated using the JTWC Best Track data from 1965 to 2000 (Wu and Wang, 2004). They chose the starting year of 1965 when satellite monitoring of weather events first became available in order to reduce the likelihood that TCs would be missed. Most TC genesis occurs in the Philippine Sea and South China Sea within a latitude band of 10°N to 25°N, while few TCs form in latitudes poleward of 25°N. The highest formation rates are found in a northern part of the South China Sea and in the Philippine Sea.

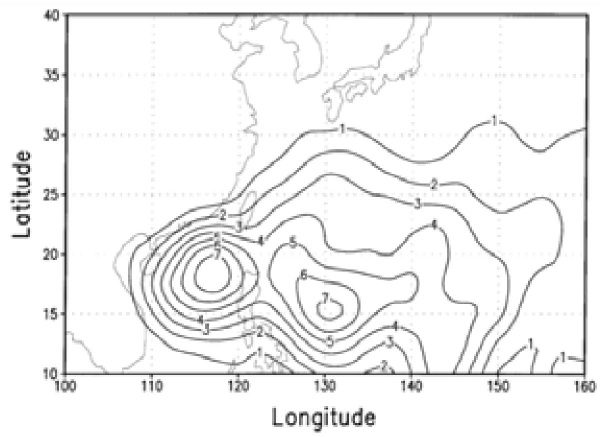

Fig. 3.1 Distribution of the mean TC formation frequency in the western North Pacific during the TC peak season (Jul−Sep) derived from JTWC best track data from 1965 to 2000 (Wu and Wang, 2004).

Figure 3.2 shows distribution of the frequency of TC occurrence, which indicates how frequently TCs enter a specific grid box of 2.5° latitude by 2.5° longitude, for the typhoon season (June−October) over 1965−2003 (Wu et al. 2005). There are two maximum centers of TC occurrence, which are located to the east of Taiwan Island and in the South China Sea, respectively. Although a maximum of the formation frequency (Fig. 3.1) coincides with the center in the South China Sea, the TC formation frequency has a different distribution within the WNP basin, primarily reflecting the TC motion after genesis.

Figure 3.2 also shows three prevailing tracks as interpreted by Wu et al (2005): a westward-moving (Track I), a recurving and going to Japan or Korean Peninsula (Track II), and a recurving northeastward east of 130°E (Track III).

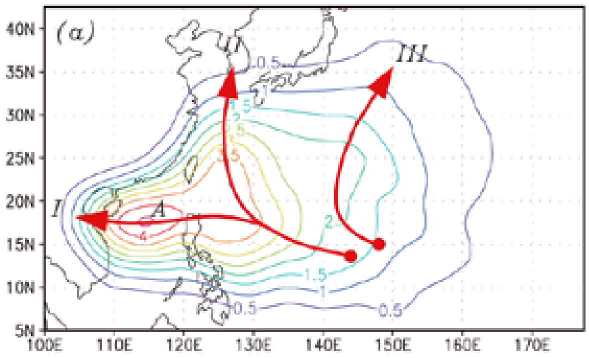

Fig. 3.2. Distribution of June−October mean frequency of TC occurrence (unit per year) derived from the JTWC Best Track data from 1963 to 2003 (Wu et al., 2005).

3.2 Trends of TC Genesis Positions and Potential

Changes in TC track are composed of changes in formation location and changes in large-scale steering flow translating the TCs. Tu et al. (2009) examined changes in the total number of typhoon formations over the entire WNP, and found no noticeable changes over time (1970−2006). However, on a regional scale, they found a reduction of the formation number over the South China Sea and the Philippine Sea, but little change over the vicinity of Taiwan.

Wu et al. (2005) evaluated the influence of the changes in the TC formation locations on the changes in the prevailing tracks, using the trajectory model developed by Wu and Wang (2004). They found that the changes in the formation locations play a minor role in terms of the magnitude under the same mean TC translation velocity.

Kim et al (2011) separated the ENSO variation into two modes, an east Pacific warming (EPW) and a central Pacific warming (CPW) and investigated their relationship with TC genesis positions. They found that the genesis and the track density of TCs tend to be enhanced over the southeastern part of the WNP and suppressed in the northwestern part during EPW years, while TC activity is shifted to the west and is extended through the northwestern part of the western North Pacific in CPW years (Fig. 3.3).

Zhan et al. (2011) also indicated that both ENSO and East Indian Ocean (EIO) sea surface temperature (SST) play important roles in modulating the TC frequency in the WNP, but their effects are significantly different. ENSO affects the east-west shift of the mean TC genesis location, but has little contribution to the basin-wide TC frequency. In El Niño years, TC genesis region shifted eastward compared to that in La Nina years. Also there are on average more frequent intense TCs formed in El Niño years. For EIO SST, the WNP TC genesis frequency is considerably higher in the years with cold EIO SST than that in warm EIO SST.

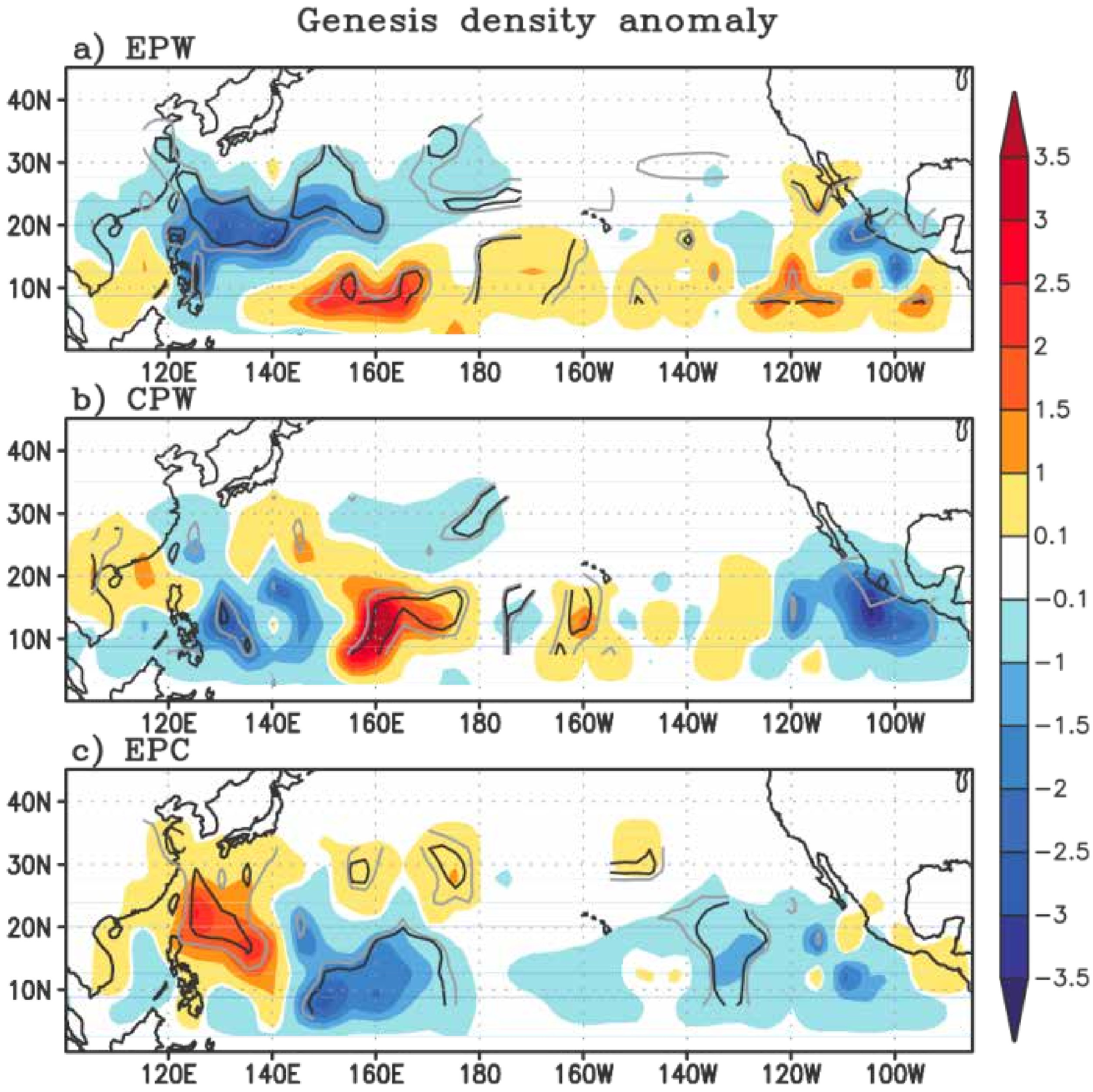

Fig. 3.3 Composites of genesis density anomalies (x10) in JASO for an East Pacific warming (EPW, upper), Central Pacific Warming (CPW, middle), and East Pacific Cooling (EPC, lower) years of ENSO variation. Light (dark) contour show statistical significance at the 90% (95%) level. (Extracted from Kim et al. (2011)).

3.3 Trends in Track Pattern, Moving Speed/ Direction, and Storm Duration

To detect the trends in the frequency of TC occurrence and the mean translation velocity, Wu et al. (2005) calculated the linear trend of TC occurrence indicated in Fig. 3.2 for the period of 1965−2003. Figure 3.4 shows linear trend of TC occurrence frequency corresponding to Fig. 3.2, during the 39 year period of 1965 to 2003. The negative trend values over the central South China Sea depict a decrease in the number of the TCs that follow track I, while the positive trends extending from the Philippine Sea to the eastern coast of China and the eastern part of the basin indicate a westward shift of prevailing tracks II and III, respectively. Their results suggest a decrease in westward-moving TCs and an increase in recurving TCs—including those taking tracks toward Japan or the Korean Peninsula.

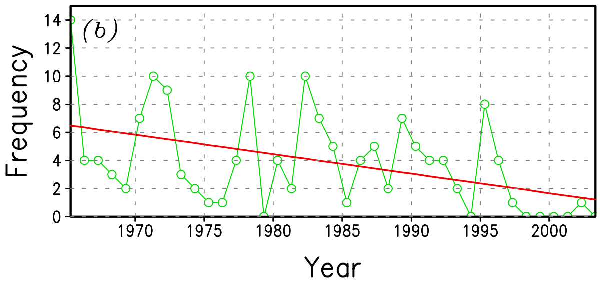

Fig. 3.4. Linear trends in the June−October mean frequency of TC occurrence and in the TC motion vectors. The areas with confidence level exceeding 95% for the TC occurrence changes are shaded. The contour interval is 0.3 year^{-1} and the unit of the vectors is ms^{-1}. The thick solid lines with arrows denote the prevailing typhoon tracks. (Extracted from Figure (2a) of Wu et al. (2005)).

Figure 3.5 shows the temporal evolution of the seasonal mean frequency of TC occurrence in the activity center (the grid box centered at 17.5°N, 115°E) indicated as "A" in Fig. 3.2 (Wu et al. 2005). In this grid box, a downward trend is significant, indicating that the TC activity over the central South China Sea has persistently decreased since 1965.

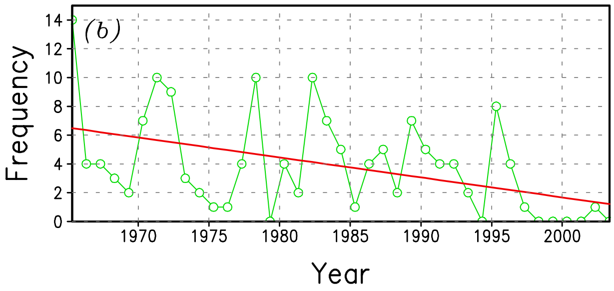

Fig. 3.5. The time series of the seasonal mean frequency of TC occurrence at the most active center A in Fig. 3.2 (grid box centered at 17.5°N, 115°E) with a linear fit indicated by the straight line. (Extracted from Wu et al. (2005)).

The prevailing track shift was found to be mainly due to the changes in the mean steering flows. Wu et al (2005) found that the changes in the mean steering flows are part of a large cyclonic circulation anomaly centered over eastern China. Their results indicate that a decreasing trend in TC influence in the South China Sea area and increasing trend in the east coast of China, Korea, and Japan, may be due to the anomalous anticyclone and anomalous westerly winds in the South China Sea and easterly winds along the east coast of China.

Tu et al. (2009) examined an abrupt increase in typhoon counts in the vicinity of Taiwan. Figure 3.6 shows the time series of seasonal (JJASO) typhoon numbers in an area of 21°–26°N, 119°–125°E from 1970 to 2006. An increase of the number of typhoons after 2000 is evident. The average typhoon rate is 3.3 yr^{-1} during the epoch (1979−1999), but increased to 5.6 yr^{-1} during the epoch (2000–2006). This abrupt change is consistent with a northward shift of the typhoon track over the western North Pacific-East Asian region and an increase of typhoon frequency over the Taiwan-East China Sea region. They noted that the northward shift of the typhoon track is associated with a weakening of the western North Pacific subtropical high, a strengthening of the Asian summer monsoon trough, and enhanced positive vorticity anomalies in the lower troposphere. They suggested that warm SST anomalies over the equatorial western and central Pacific appear to be a major factor contributing to a northward-shifted typhoon track, based on model simulations and analysis of observational relationship among TC tracks, SST anomaly distribution, and location of the subtropical high and a monsoon trough. By using SVD analysis and IPCC AR4 historical forcing runs, Wang et al. (2011) suggest that the observed shift of TC tracks and associated circulation changes may have a substantial contribution from radiative forcing. However, further study is needed to assess this conclusion.

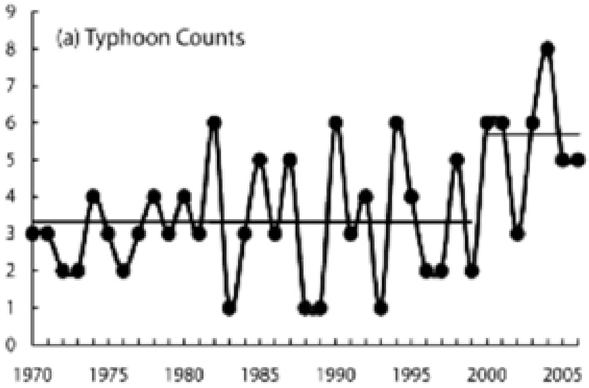

Fig. 3.6. Time series of seasonal (JJASO) typhoon numbers passing the vicinity of Taiwan from 1970 to 2006. The vicinity is defined as 21°–26°N, 119°–125°E (Extracted from Tu et al. (2009)).

Li et al. (2010) investigated long term variation in TC formation frequency, duration, and intensity over the WNP using the JTWC dataset from1945 to 2007. They found an increasing trend in TC frequency and duration over the WNP (Fig. 3.7). (See Chapter 2 for more discussion of TC frequency trends in various data sets.) However, there was also large decadal variability both in frequency and duration. In terms of the decadal variation, they identified three types of relationship between TC frequency and duration: low frequency and short duration during 1945–1955 (Period I), high frequency and short duration in the 1960s (Period II), and high frequency and long duration in the 1990s (Period III) as shown in the lower panel of Fig. 3.7. They suggested that relationship between TC frequency, duration, and active regions modulated strongly by large-scale atmospheric circulation.

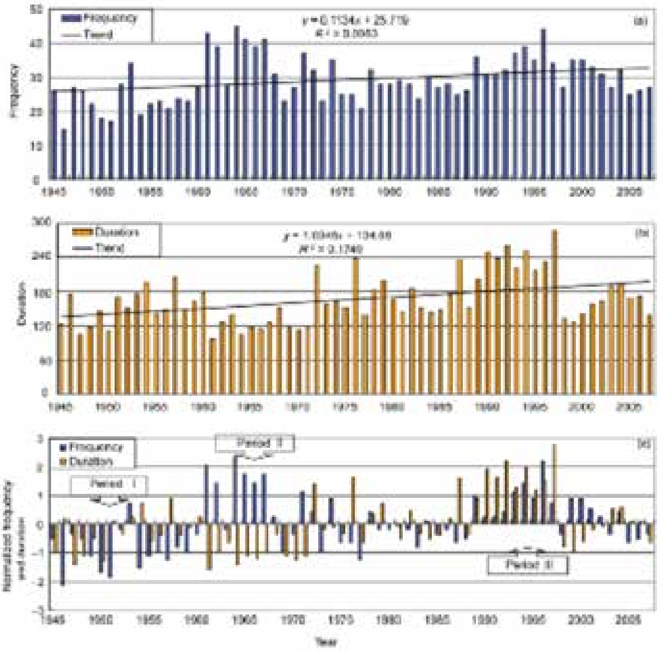

Fig. 3.7. Time series of annual tropical cyclone frequency (top), average duration (middle), and normalized annual frequency and duration anomalies (bottom) over the Western North Pacific. Tropical depressions were included in the analysis. (Li et al., 2010)

Focusing on the duration of intense TC stages, Rozynski et al. (2009) performed an extreme value analysis of the duration of periods where TCs exceed intensities of at least 120 knots (about 62 ms^{-1}). They examined a sub-region of the WNP (10°−22°N, 110°−140°E) comparing the periods 1960–1982 and 1982–2000 and using best track data from JTWC. Their analysis showed a substantial increase of duration during for the latter period; however, they did not address the question of possible inhomogeneities in the storm data.

As noted above, the TC occurrence frequency and tracks over the western North Pacific exhibit significant interdecadal variation. Liu and Chan (2008) performed an EOF analysis of the distribution of the TC occurrence frequency and studied the temporal changes in the principal modes 1, 2, and 3 from 1960 to 2005. Figure 3.8 shows spatial patterns of the principal modes 1, 2, and 3 and the time series of their amplitudes. The EOF1 is related to the variation of TC activity in the areas near Japan and its east. The EOF2 is characterized by a northeast-southwest dipole of TC occurrence anomalies along the southeast coast of China and an east-west dipole near Japan and its east. The EOF3 is similar to the second mode, except for the absence of the east-west dipole. Modes 1, 2, and 3 were dominant in the period 1977–1988, 1964–1976, and 1989–1997, respectively, while the period 1998–2005 is in negative phase of the second and third modes. Track A in Fig. 3.7 corresponds to the Track I in Fig. 3.2, the Tracks B and C Fig. 3.7 to Track II in Fig. 3.2, and the Track D in Fig. 3.7 to the Track III in Fig. 3.2. Wu et al., 2005 interpreted change in frequency of TC occurrence as a trend. However, one can interpret such change as an interdecadal variation following Liu and Chan (2008). Several studies confirm a decrease in TC frequency in

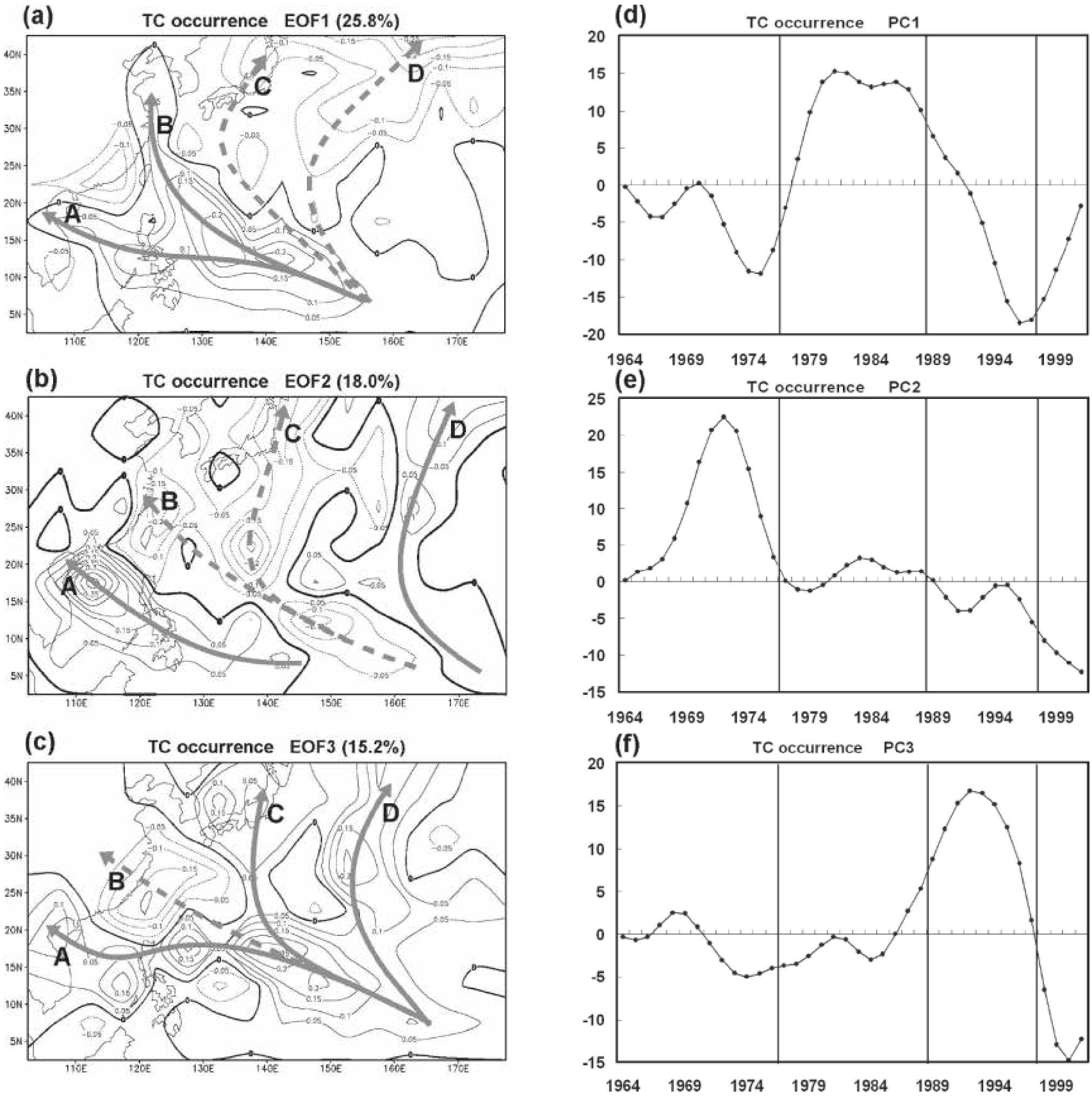

Fig. 3.8. Loading patterns of the annual TC occurrence pattern for (a) the first, (b) second, and (c) third EOFs. The prevailing tracks (A, B, C, and D) are depicted with solid arrows (increased frequency) and dashed arrows (decreased frequency). Time series of (d) PC1, (e) PC2, and (f) PC3 coefficients are shown in the right panels; the vertical lines divide the study period into four subperiods. (Liu and Chan, 2008)

the South China Sea and an increase in the East China Sea and the Philippine Sea. At this point, however, we cannot determine whether these changes in TC frequency are part of a long-term trend or an interdecadal variation, particularly because of the relatively short data periods.

3.4 Conclusion

Climatologically, most TCs in the WNP are generated in the Philippine Sea or the South China Sea, within a latitude band of 10°N to 25°N. There are three prevailing tracks of TCs: a westward moving track, a recurving track that continues toward Japan or the Korean Peninsula, and a recurving track to the northeast, mostly east of 140°E. There are indications that the most important factor for TC track change is a change in the large scale TC steering flow, while the change in genesis position is of secondary importance. Observations indicate a decreasing trend in TC occurrence in part of the South China Sea and an increasing trend along the east coast of China during the past 40 years. This change is related to local circulation change in the eastern Asia and WNP. One modeling study suggests that this change has a large contribution from radiative forcing, but further studies are needed to understand the relative contributions of natural variability and anthropogenic forcing to these observed changes in TC occurrence.

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CHAPTER 4. TROPICAL CYCLONE IMPACTS IN THE TYPHOON COMMITTEE REGION

The impacts of tropical cyclones (TCs) vary significantly in different parts of the Typhoon Committee region, depending on the frequency, intensity, track and structure of the TCs. In order to gather more regional information on the impacts of TCs on the Member nations of the Typhoon Committee, the Expert Team conducted a survey in mid-2011 on the past TC impacts affecting each nation or region. This chapter will briefly summarize the data collected from this survey. Moreover, findings of some recent publications on TC impacts are also incorporated in this chapter. The term tropical cyclone (TC) used in this chapter will include tropical depression, tropical storm, severe tropical storm, and typhoon. Study results which adopt different interpretations (e.g. only storms of tropical storm (TS) intensity or greater are considered) will be stated explicitly.

4.1 A Brief Climatology of Landfalling / Affecting TCs

Based on the survey results, the average number of TCs / typhoons affecting and making landfall in the different Members of the Typhoon Committee are tabulated in Table A1 of Appendix A. The definitions of landfalling and affecting TC adopted by these Members are also summarized in Table A2.

On average, both China and the Philippines experience about 9 landfalling TCs each year. There are about 2.7 TCs with TS or above strength landfalling in Japan each year. The average annual number of TCs landfalling in the Republic of Korea is about 0.9. There is about 1.2 TCs (TS or above) necessitating the issue of Tropical Cyclone Signal No. 8 in Macao each year and the average annual number of TCs landfalling within 300 km of Hong Kong is about 2.5. There are about 1 to 2 TCs per year landfalling in Viet Nam. Malaysia and Thailand are affected by about 3 to 4 TCs each year. Singapore is not directly affected by TCs, except for TS Vamei in 2001. There are about 18 to 20 TCs affecting the area of responsibility of Guam (Eq–25°N, 130°E–180°E) each year.

4.2 Regional Impacts of TCs

The survey results for the impacts of landfalling/affecting TCs, including frequency, intensity, landfalling location, high winds, precipitation and casualties/economic losses, are summarized in Table A3 of Appendix A. The survey results and the findings of some recent published work are concisely documented in Sections 4.2.1 to 4.2.4.

4.2.1 Frequency and Intensity of Landfalling/Affecting TCs

Chan and Xu (2009) studied TC (TS or above) landfalling trends in East Asia from a regional perspective using the JTWC dataset. Three sub-regions are defined in their study, namely South (south China, Viet Nam, and the Philippines), Middle (east China), and North (Korean Peninsula and Japan). They found that none of the time series of annual number of landfalling TCs shows a statistically significant linear trend during 1945–2004.

In China, Yang et al. (2009) found a decreasing trend in the number of TCs landfalling in China from 1949 to 2006, but the trend was not statistically significant at 5% (significant at 10 %). There is no trend for landfalling typhoons in China (Fig. 4.1). Moreover, the TC landfalling frequency in southern China is decreasing while the trend for East China was relatively small. Yang et al. (2009) also indicated that the locations of landfalling TCs in China are mostly situated in the middle of the east coast, around 23°–25°N, consistent with the finding of Cao et al. (2006). Xiao and Xiao (2010) also reported a slight decreasing trend in the number of landfalling TCs in China from 1983 to 2008.

By adopting the definition of "influencing TC" proposed by Feng et al. (1998), Ying et al. (2011a) conducted a study on the trends of TCs influencing China using the TC dataset of CMA from 1955 to 2006 and the quantile regression approach. They reported that, although the total frequency of TCs affecting China has remained steady, the trend estimated by quantile regression indicates a significant decreasing trend in the third quantile (75%) of the frequency over the past 50 years. This suggested that years with more TCs affecting China have become less frequent over the past 50 years. There is no significant trend in the number of TCs influencing the four sub-regions (namely South China, East China, Northeast China and China's inland area) as analyzed by the quantile regression approach.

Li and Duan (2010) studied the spatio-temporal features of TC strikes from 1949 to 2008 at 49 coastal cities along the southern and eastern coasts of China and Taiwan using the TC data of CMA (TS or above). Their results suggested that the cities of Hainan, Guangdong, and the island of Taiwan are frequently struck by the TCs (TS or above), with the most severe and most frequent strikes found in Taiwan. There is no significant trend for the overall number of strike events during the analysis period. Xiao and Xiao (2010) also indicated that the locations in their study with the greatest number of TCs making landfall are Guangdong, followed by Hainan, Taiwan, Zhejiang and Fujian.

Tu et al. (2009) examined the possible changes in TC activity (TS or above) in the vicinity of Taiwan and the shift in TC track over the western North Pacific-East Asian (WNP-EA) region from 1970–2006 using a Bayesian change point analysis technique. They reported a high likelihood of a change point on the TC (TS or above) rate near Taiwan in 2000. On average, 3.3 TCs (TS or above) per year have been noted before 2000 (1970–99), with the rate increasing to 5.7 TCs (TS or above) per year since 2000 (2000–06). This change is consistent with the northward shift of the typhoon track over the WNP region. Wang et al (2011) sought to establish whether the observed TC track changes in the WNP over the past several decades were associated with the ongoing global warming through a singular value decomposition (SVD) analysis. They reported that the observed TC track changes are linked to the leading SVD mode of global sea surface temperature (SST) warming and the associated changes in large-scale steering flows.

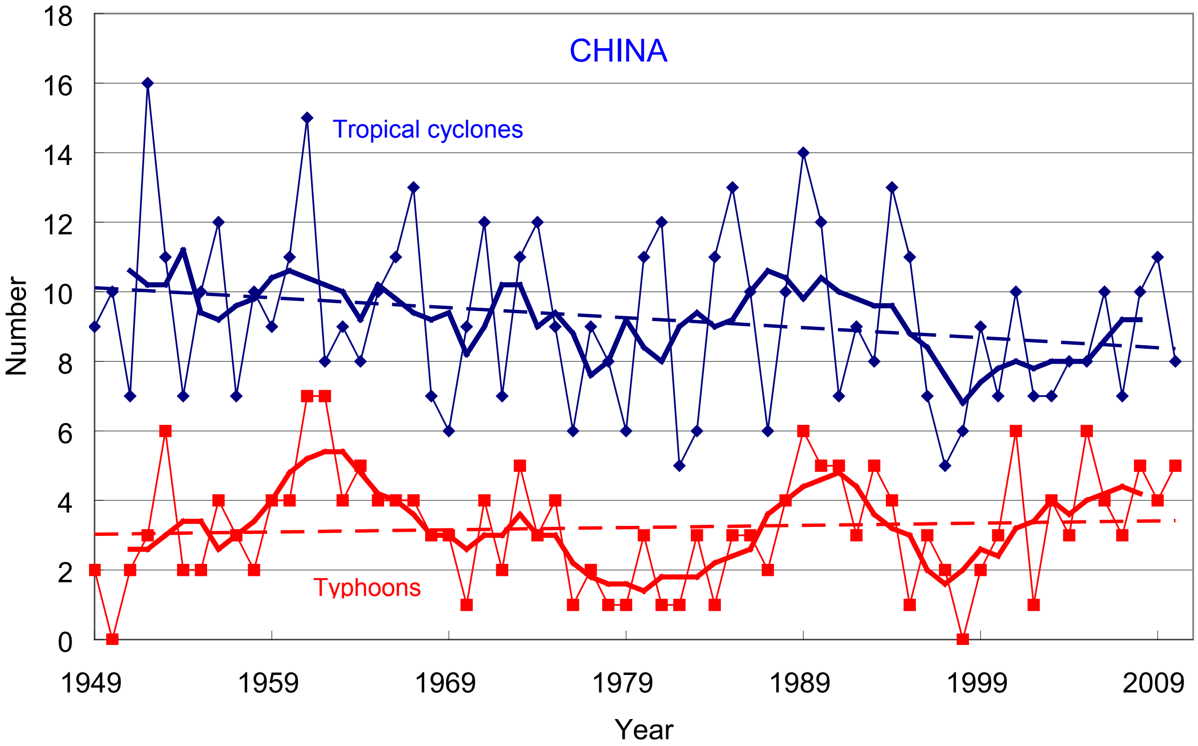


Fig. 4.1 Number of TCs (blue) and typhoons (red) landfalling in China (1949–2010). The solid, thick and dashed lines represent the annual number, 5-year running mean and linear trend respectively. Trends are estimated in the period of 1949–2010. (Courtesy of CMA)

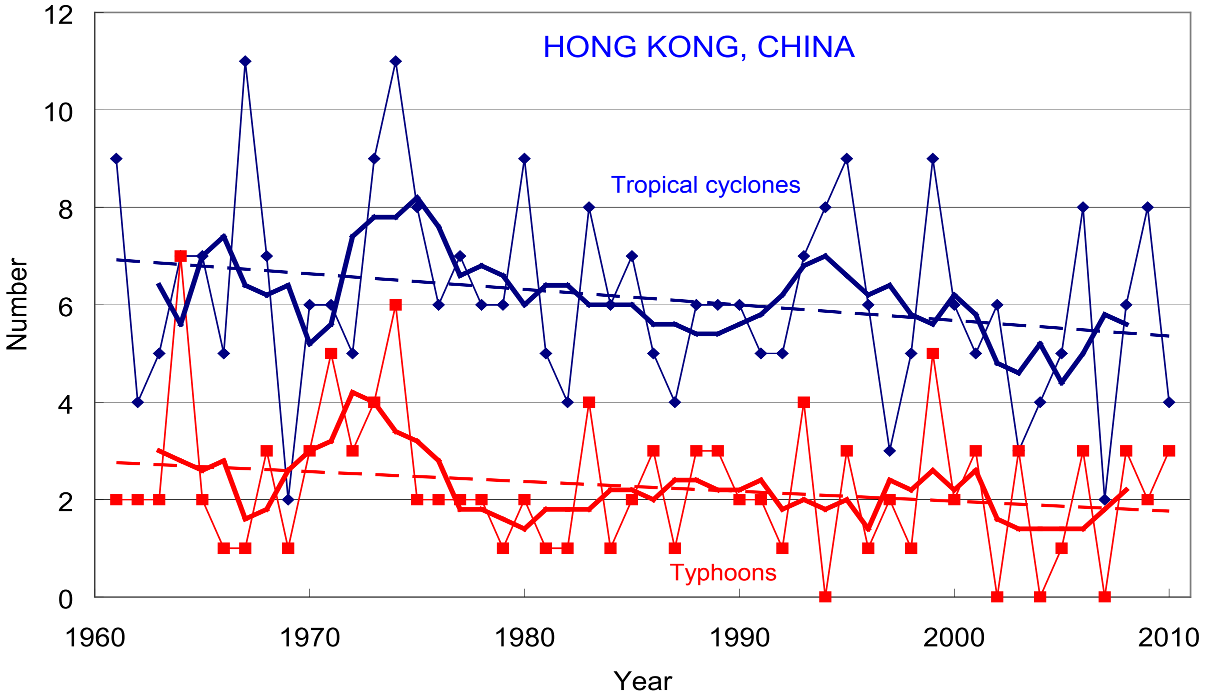


Fig. 4.2 Annual number of TCs (blue) and typhoons (red) come within 500 km range of Hong Kong, China. The solid, thick and dashed lines represent the annual number, 5-year running mean and linear trend respectively. (Courtesy of HKO)

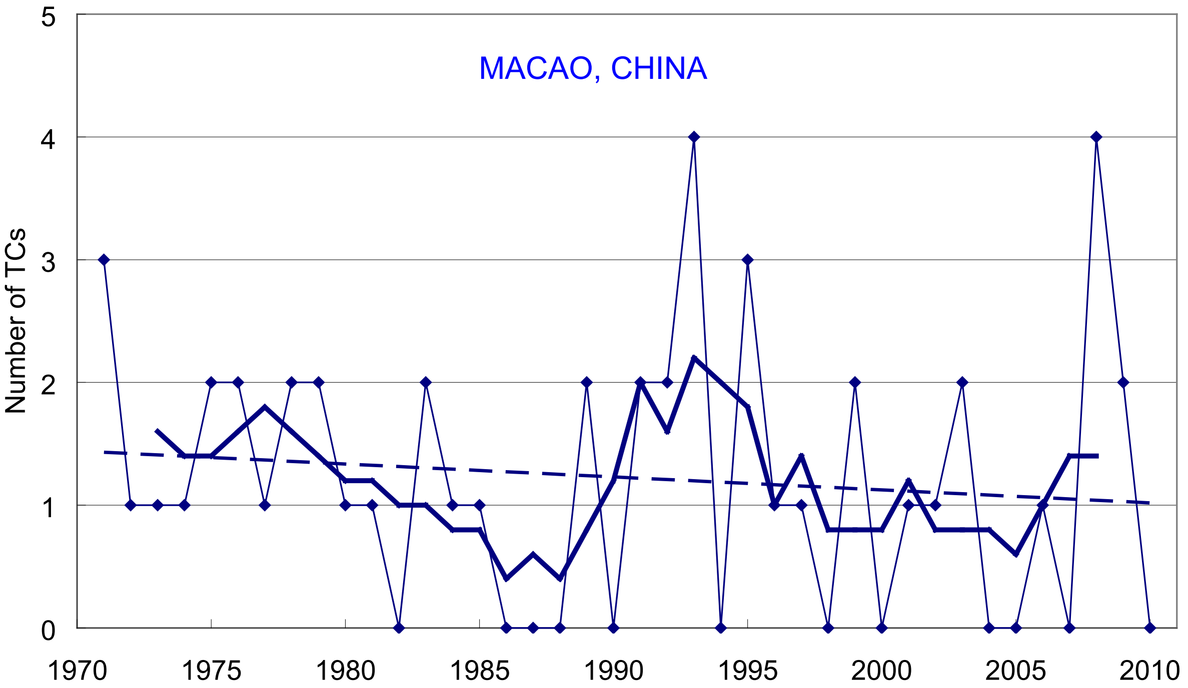


Fig. 4.3 Annual number of tropical cyclones (TS or above) necessitating the issuance of Tropical Cyclone No. 8 in Macao, China. The solid, thick and dashed lines represent the annual number, 5-year running mean and linear trend respectively. (Courtesy of SMG)

For Hong Kong, analysis of HKO TC data from 1961 to 2010 found that there is no significant trend in the number of TCs landfalling within 300 km of Hong Kong. The number of TCs and typhoons entering 500 km range of Hong Kong is decreasing during this period, but there are significant inter-decadal variations and the trend is not significant at 5 % level (Fig. 4.2). (Wong and Mok, 2009; Ginn et al., 2010). The data of Macao also revealed that there is no significant change in the number of TCs (TS or above) necessitating the issuance of Tropical Cyclone No. 8 in Macao from 1971–2010 (Fig. 4.3).

In Japan, JMA's analysis revealed that although the numbers of TCs (TS or above) approaching and hitting Japan from 1951 to 2009 shows variations with different time scales, there is no significant trend in the time series (Fig. 4.4). For landfalling TCs (TS or above), 2004 appears to be a single exceptional year, with 10 TCs landfalling in Japan, as compared with the average annual number of 2.6 in 1971–2000 (JMA, 2010). Moreover, there is no observed trend in the number of strong TCs with maximum winds of 33 ms^{-1} or higher reaching high north latitudes in the western North Pacific region during 1977–2004 (JMA, 2005).

Over the Korean peninsula, although the long term increasing trend of the number of landfalling TCs is not statistically significant, Choi and Kim (2007) found that the frequency of the landfalling TCs has a nominal increase since late 1980s, especially for TCs with TS intensity or above. They also reported that the preferred location of landfall changed from the middle or northern region of the west coast to the south coast of the Korean Peninsula in recent years. Choi et al. (2010) investigated the inter-decadal variations of TCs making landfall over the Korean Peninsula from 1951 to 2004 using the RSMC Tokyo dataset (including extratropical cyclones that transitioned from a TC). They found that there are substantial inter-decadal variations in the frequency of TCs making landfall over the Korean Peninsula. By using a change-point analysis method, they classified the variations into three main periods,

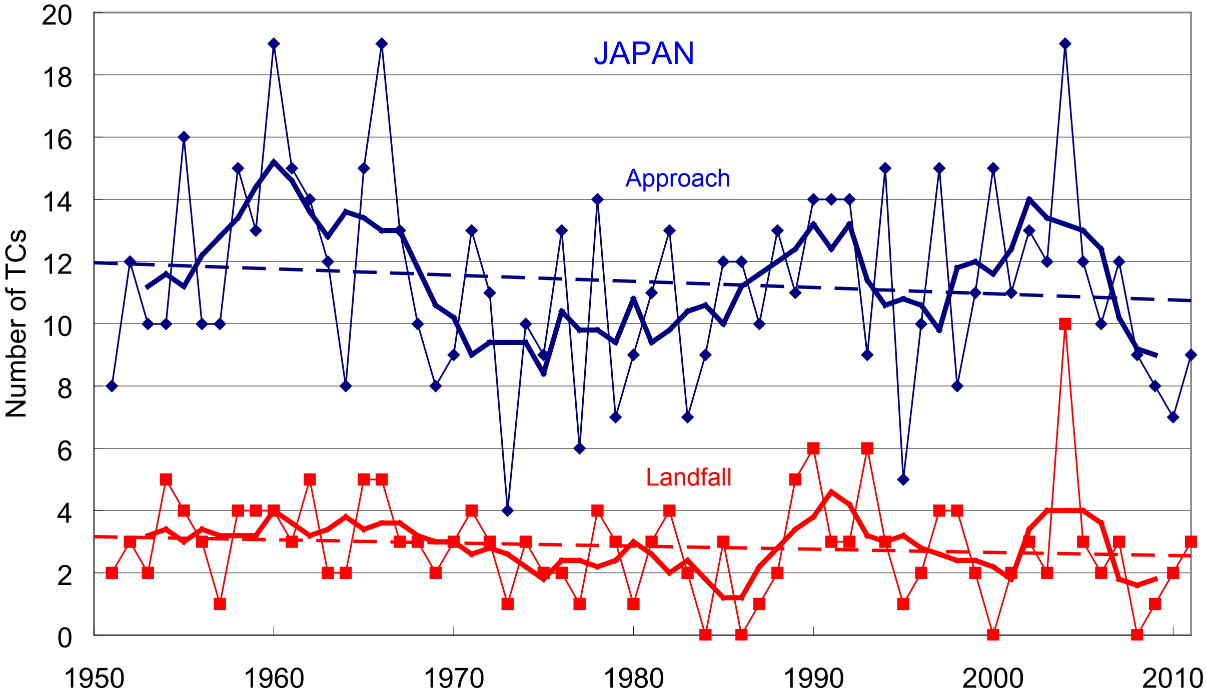


Fig. 4.4 The number of TCs with maximum winds of 17.2 ms^{-1} or above approached Japan (blue) and those making landfall in Japan (red). The solid, thick and dashed lines represent the annual number, 5-year running mean and linear trend respectively. (Courtesy of JMA)

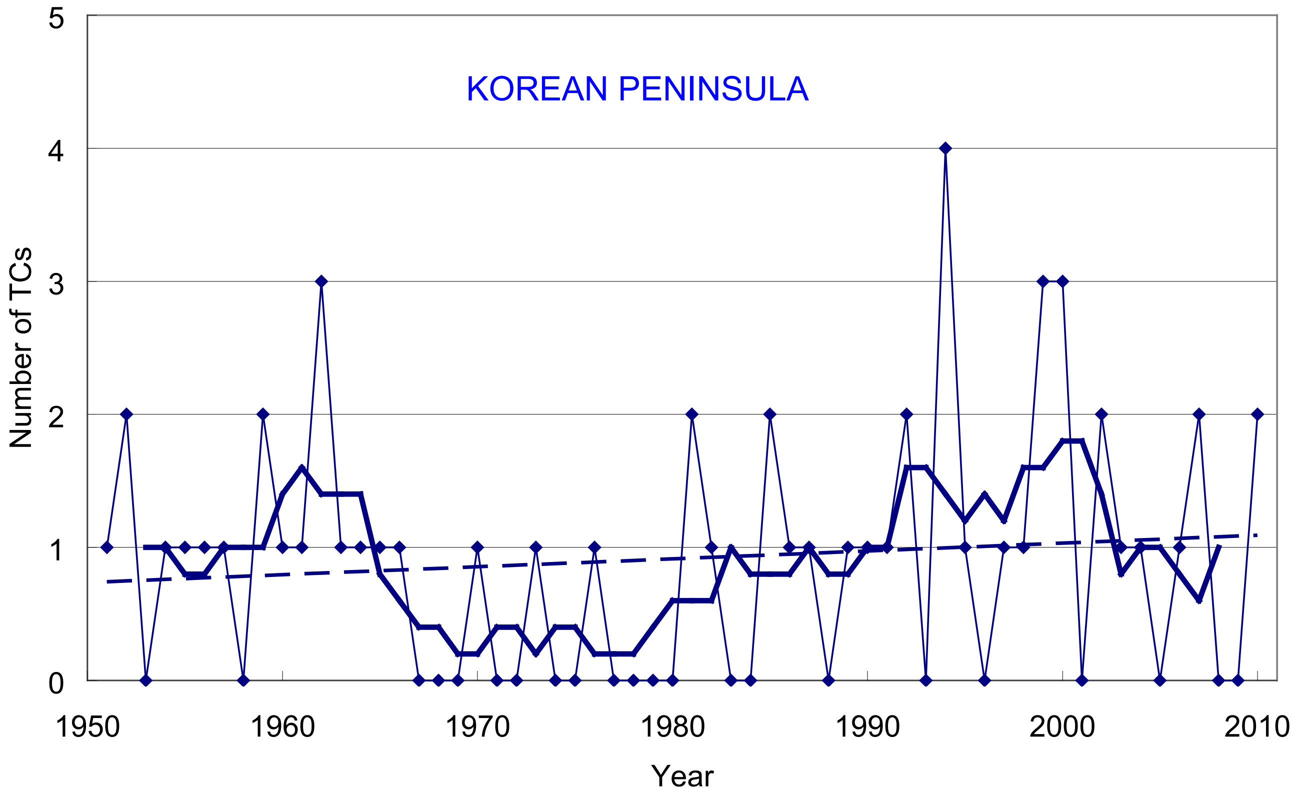


Fig. 4.5 The variability and trend of annual landfalling TCs for the Korean peninsula. The solid, thick and dashed lines represent the annual number, 5-year running mean and linear trend respectively. (Courtesy of KMA)

namely, the first high frequency period (1951–1965), a low-frequency period (1966–1985) and a second high-frequency period (1986–2004). They identified changes in decadal scale tropospheric climatological steering flows as the likely cause of these changes.

Park et al. (2011) examined the changes in the number of TCs (TS or above) that made landfall in Korea and Japan during June–October for the period 1977–2008. Changes in the PDI, TC-induced rainfall, number of landfalling TCs and TC duration between the two decades, 1977–1988 and 1997–2008, are assessed in their study. They found that, with the increase in the number of TCs (TS or above) and the longer duration of TCs over the two countries, the PDI and TC-induced rainfall for TCs landfalling in Korea and Japan increased significantly in the later decade. They suggested that the increase in the number of landfall TCs is associated with the enhanced northward steering flows over the East China Sea. They interpreted the longer TC duration over the two countries as mainly due to the higher intensity of the approaching TCs prior to landfall. This in turn could be attributed to the observed changes in the large-scale environments in the vicinity of the two countries in the later decade, including warmer sea surface temperature, highly humid midtroposphere, and weaker vertical wind shear over the region.

There is no trend in the time series of the number of TCs landfalling/crossing the Philippines during the period from 1948 to 2010. However, the number of typhoons landfalling / crossing the Philippines has a statistically significant decreasing trend, mainly due to the reduced numbers since mid-1990s (Fig. 4.6).

For Thailand, the reported frequency of TCs (mostly tropical depressions) entering Thailand also has a significant decreasing trend with the decrease occurring after mid-1960s (Fig. 4.7). In contrast, the annual number of storms of at least tropical storm intensity has a slight increasing

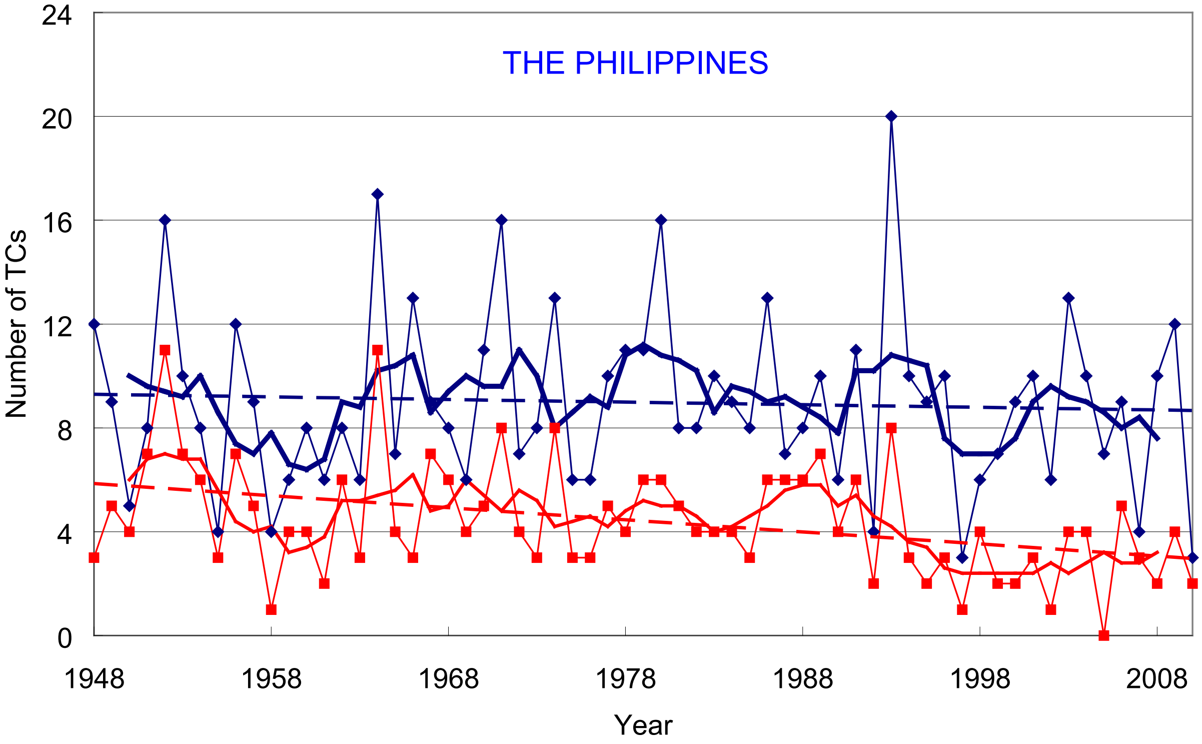


Fig. 4.6 Annual number of TCs (blue) and typhoons (red) landfalling/crossing the Philippines (1948–2010). The solid, thick and dashed lines represent annual, 5-year running mean and linear trend respectively. (Courtesy of PAGASA)

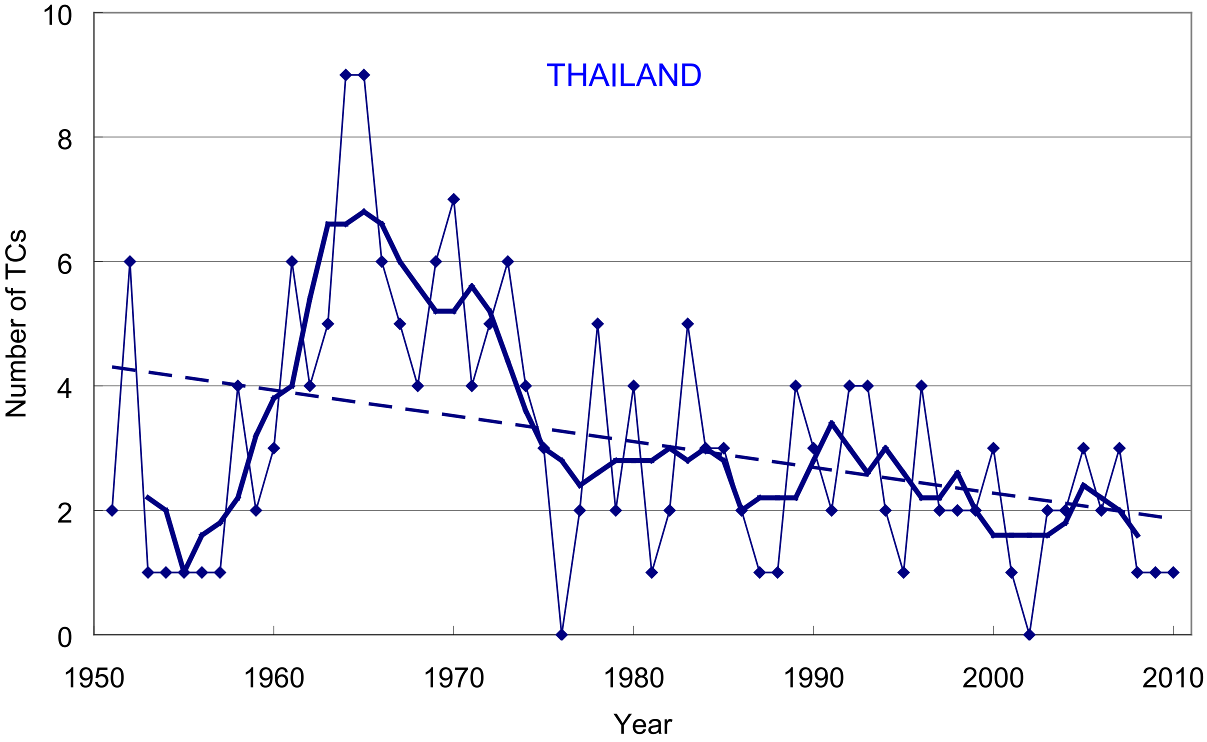


Fig. 4.7 Annual number of TCs (including TDs, blue) and tropical storms or above (red) entering Thailand (1951–2010). The solid, thick and dashed lines represent annual, 5-year running mean and linear trend respectively. (Courtesy of TMD)

tendency, with six occurring in the first 25 year of the 1951–2010 record and eight occurring in the last 25 years of the record.

4.2.2 High Winds

Ying et al. (2011a; 2011b) analyzed the variations of TC-induced winds and precipitation impacting China based on the data of CMA from 1955 to 2006 and using the quantile regression approach. For winds, they found that the maximum sustained winds of TCs affecting the whole China and sub-regions have a decreasing trend with the decreasing trend being especially pronounced at the coastline of southeast China is more prominent (Fig. 4.8 a). They speculated that the decrease in the TC induced wind intensity along the coast may be partly attributed to the increase in surface roughness related to the rapid urbanization in the past few decades. For the trends of the maximum wind gust data, there is a mix of significant increases and significant decreases along the coastal areas, with a greater number of the latter, and few inland stations with significant changes (Fig. 4.8 b).

In Hong Kong, there is no significant trend in the annual maximum 10-minute mean wind and maximum 1-sec gust as recorded at Waglan Island, an offshore island about 20 km southeast of Hong Kong Observatory Headquarters (Fig. 4.9 b). However, the maximum 10-minute wind at Kai Tak (an urban station) has a significant decreasing trend from 1961 to 2009 (Wong and Mok, 2009; Fig. 4.9 a). Data from Macao show periodic changes but no significant trends in the maximum wind speed (Fig. 4.10).

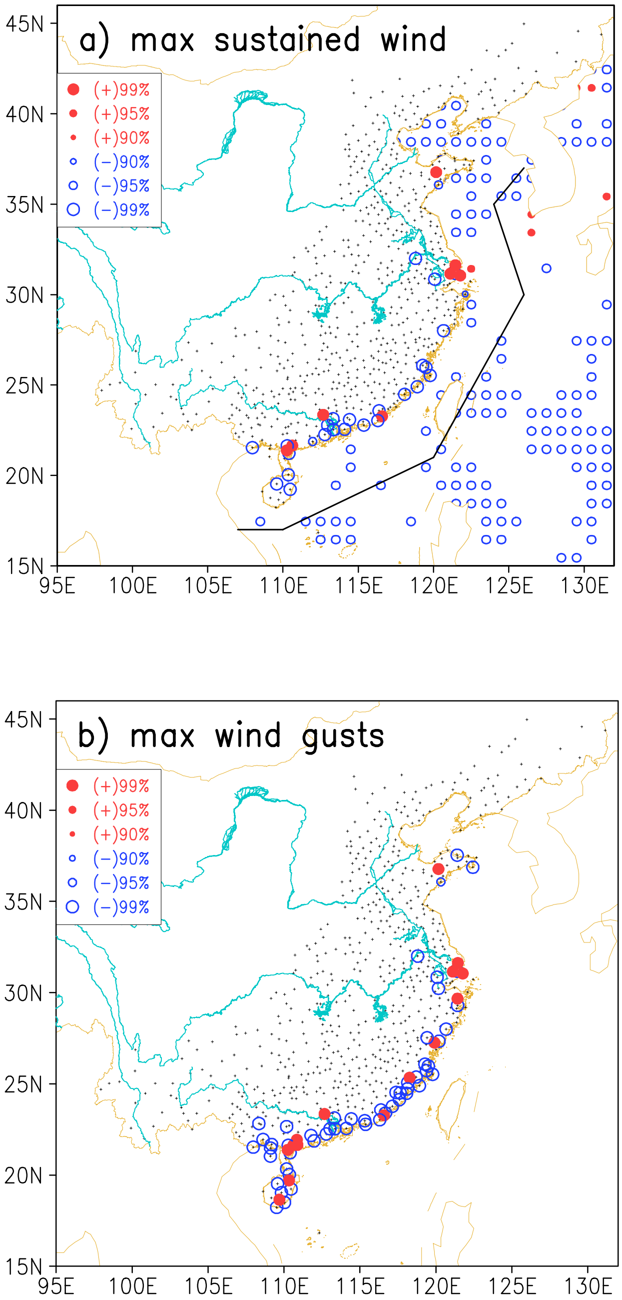
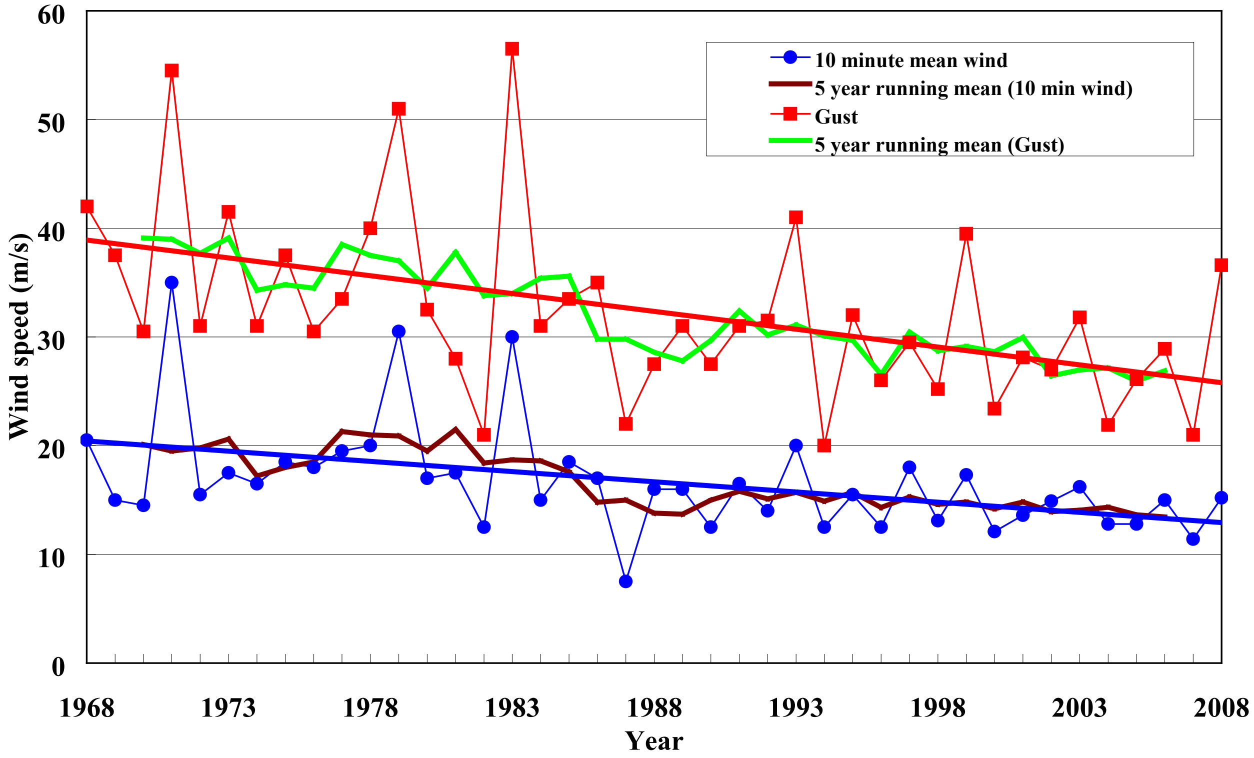
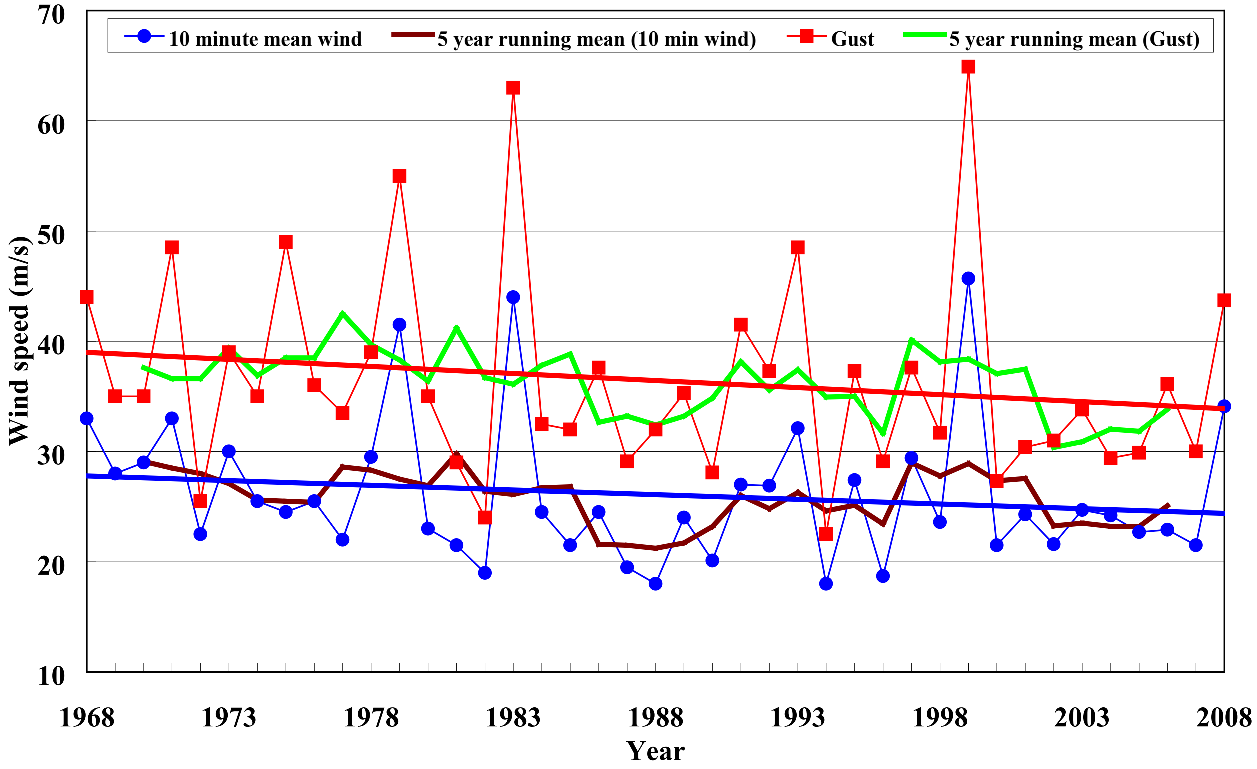


Fig. 4.8 Significant climatic trends (red and blue dots) for the median of (a) maximum 2-min sustained winds and (b) maximum wind gusts in China. Black symbols indicate station locations; the solid (red) and open (blue) dots denote significant increasing and decreasing trends, respectively; small, median and large dots represent 90%, 95% and 99% significant levels, respectively. In Fig. 4.8(a), the circles over the ocean are 95% significant trend estimated from the best track data gridded in 1° x 1°, and the solid line is about 300 km away from the continent (Extracted from Fig. 2 of Ying et al. (2011b)).



(a)



(b)

Fig. 4.9 Annual maximum 10 minute mean wind speed and gust at (a) Kai Tak and (b) Waglan Island brought by TCs entering 500km range of HK from 1961 to 2010. Thin lines represent the year by year statistics, bold lines represent its five year running mean, and the straight lines represent its linear fit.

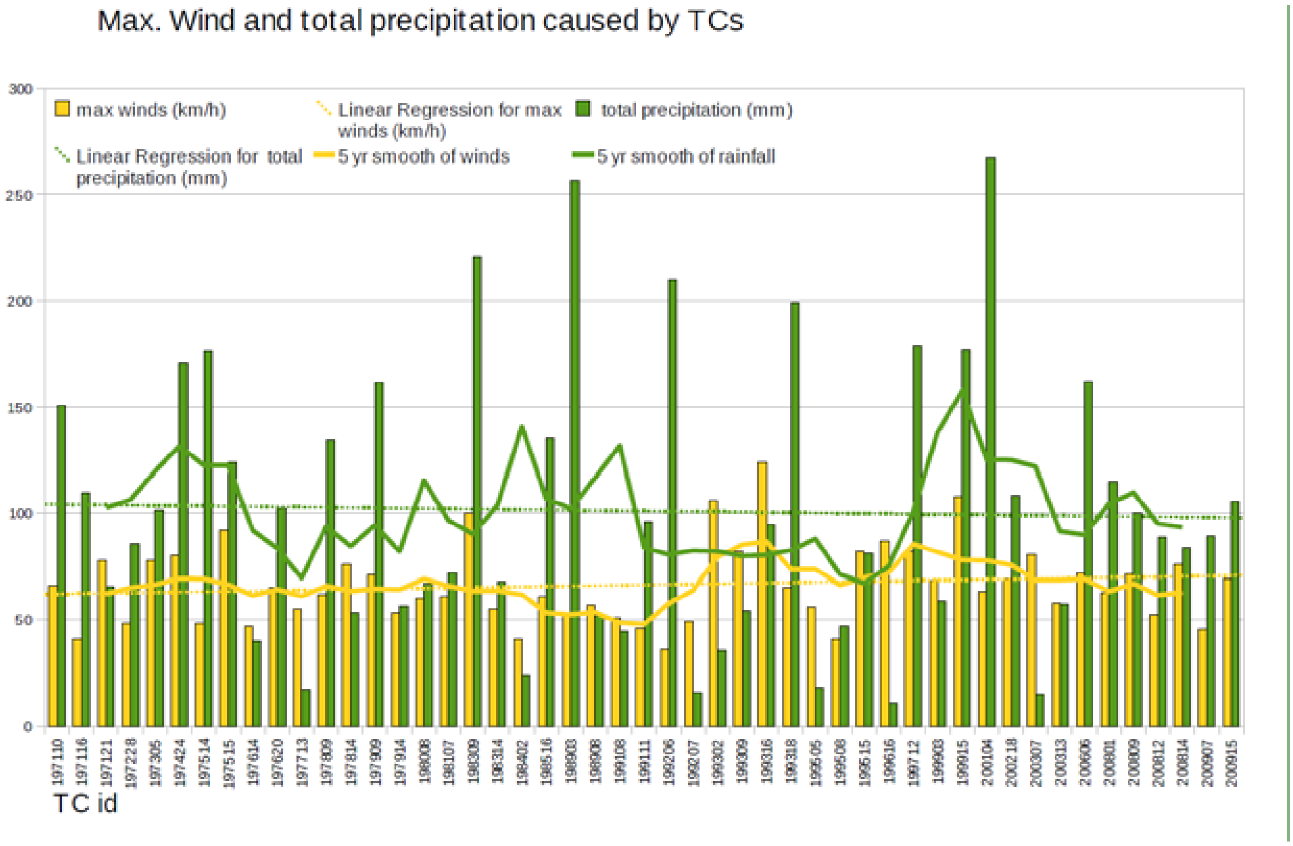


Fig. 4.10 Maximum wind speed and total precipitation caused by TCs in Macao from 1971 to 2010, China (Courtesy of SMG)

4.2.3 Precipitation

Regarding TC related precipitation, Wang et al. (2008) examined rainfall data from the CMA National Meteorological Information Center and showed that there is a statistically significant decreasing trend in parts of Taiwan, Hainan, coastal Southeast China and the southern part of Northeast China from 1957 to 2004. By using an objective synoptic analysis technique on the same dataset, Ren et al. (2006) also found that there is a statistically significant decreasing trend in the tropical cyclone precipitation (TCP) volume and the annual frequency of the torrential TC precipitation (daily rainfall^{3} 50mm) from 1957–2004. However, the analysis by Ying et al. (2011a) using the quantile regression method on the CMA-STI rainfall data suggested that the trends in national and subregional scales are not significant. For precipitation intensity, Ying et al. (2011b) found that the changes in TC induced precipitation per TC (Fig. 4.11 a) and maximum 1-hour precipitation (Fig. 4.11 b) have substantial spatial variations in China with significant increasing trends at a number of stations, mainly over coastal and near-coastal areas of southeastern China. However, the majority of stations over central and northeastern China in their analysis did not have statistically significant trends (Fig. 4.11 b).

In Hong Kong, although there is a slight decrease in the annual rainfall brought by TCs entering 500km range of Hong Kong from 1961 to 2010, the trend is not statistically significant at 5% level. The variations of the annual rainfall per TC and annual maximum hourly rainfall related to TCs also have no significant trend during the study period (Lee et al., 2012; Fig. 4.12). In Macao, there is also no significant trend in total precipitation due to tropical cyclones (Fig. 4.10).

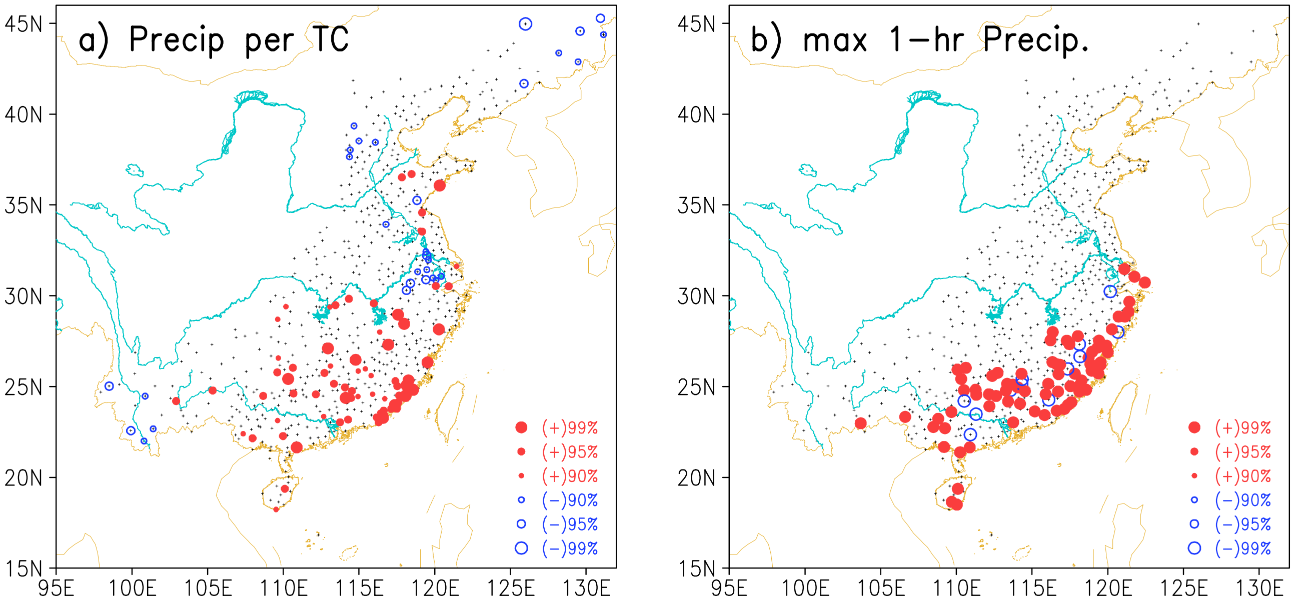


Fig. 4.11 Same as Fig. 4.9, but for TC precipitation (a) Precipitation per TC and (b) the maximum 1-hr precipitation (Extracted from Fig. 3 of Ying et al. (2011b))

Chen and Chen (2011) investigated the interdecadal variability of summer (June to August) rainfall in Taiwan from 1950 to 2008 by partitioning of rainfall due to TCs (TS or above) and seasonal monsoon. They found that there is a significant long term increasing trend in the TC related rainfall which is likely related to the increase in the number of TCs affecting Taiwan in the last few decades.

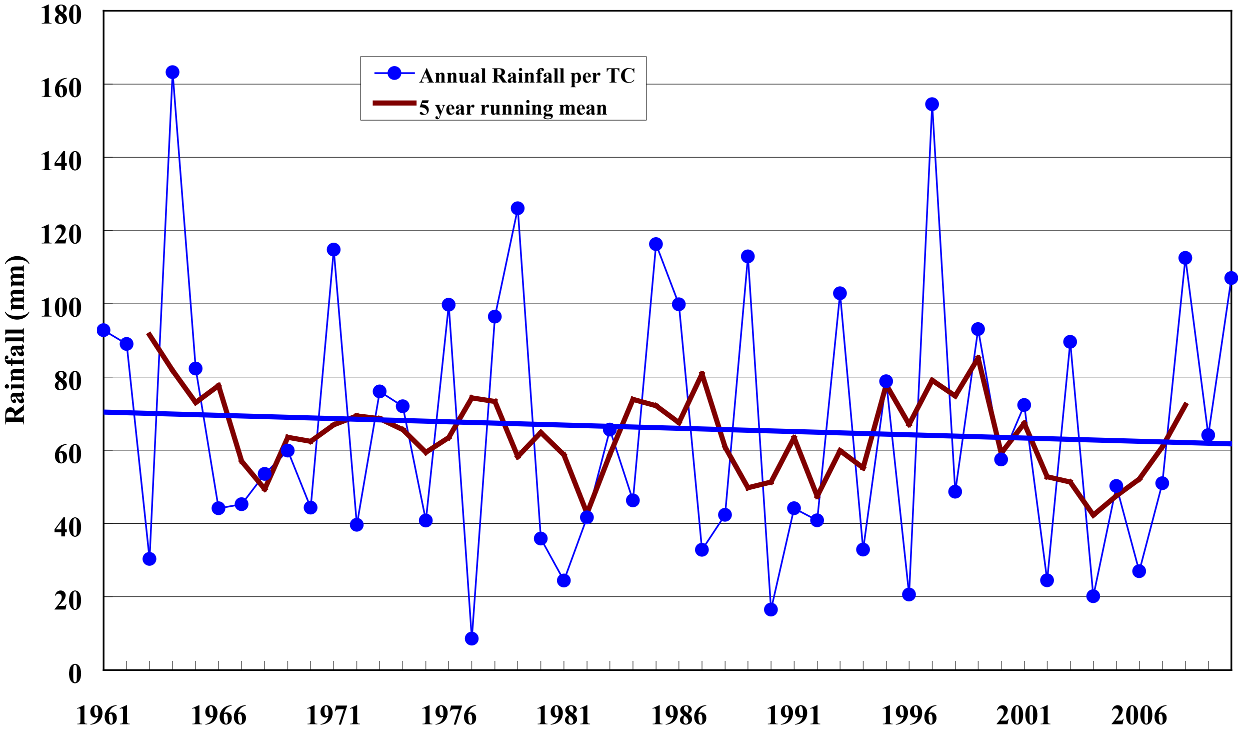


Fig. 4.12 Annual rainfall per TC brought by TCs entering 500km range of Hong Kong from 1961 to 2010. Thin line represents the year by year statistics, bold line represents its five year running mean, and the straight line represents its linear fit. The trend is not significant at 5% level.

Ikema et al. (2010) examined the daily rainfall variation of Okinawa for 1982–2005. Their analysis, using a probability distribution function for each year, revealed that the frequency of light (0–3 mm d^{-1}) and heavy (26–50 mm d^{-1}) rainfall events have a statistically significant decreasing trend, while extreme (>75 mm d^{-1}) rainfall events have been increasing. They found that such increases could be attributed to the increase in the rainfall amounts per typhoon, especially in September. They interpreted this as partially due to a slowing of the mean translation speed of typhoons in the latter half of the record. However, they also indicated that, owing to the limited length of the record, they are not able to determine at this time whether the observed trends are unusual compared with natural multidecadal variability.

Kim et al. (2006) examined the heavy rain associated with TCs (TS or above) landfalling in the Korean Peninsula during August and September from 1954 to 2005. They found that the average accumulated heavy rainfall at 12 stations across the Korean Peninsula in these two months increased significantly from the period 1954–1977 to the period 1978–2005. The study by Park et al. (2011) also found that the PDI and TC-induced rainfall for TCs (TS or above) landfalling in Korea and Japan during June−October increased significantly from the decade 1977–1988 to the decade 1997−2008.

Takahashi and Yasunari (2008) investigated a long-term decreasing trend in rainfall over Thailand in September, using daily rainfall from Thailand, JMA and JTWC TC tracks, and the ERA-40 Reanalysis dataset from 1950–2000. They noted that September rainfall over Thailand is strongly influenced by TCs (including residual lows) propagating westward from the South China Sea and western North Pacific to the Indochina Peninsula and suggested that the weakening of TC activity over the Indochina Peninsula was probably a main factor in the statistically significant long-term decrease in September rainfall over Thailand.

4.2.4 Casualties and Economic Losses

In China, Zhang et al. (2009) studied the direct economic losses and casualties (number of fatalities) caused by landfalling TCs (TS or above) during 1983– 2006 using a dataset released by the Department of Civil Affairs of China and the TC database of CMA. They found that on average landfalling TCs cause about 28.7 billion yuans (4.5 billion U.S. dollars) in direct economic losses and 472 casualties per year. Most of the casualties occurred in Zhejiang, Fujian, and Guangdong Provinces. They noted that there is no significant trend in TC casualties over the study period. The direct economic losses have a rising trend, likely in relation to the economic development in China. Xiao and Xiao (2010) examined the trend of economic losses and casualties caused by landfalling TCs in China during 1983 – 2008 utilizing the data recorded by the National Climate Center of the China Meteorological Administration. They found that the annual number of casualties caused by TCs showed a slight decreasing trend while the direct economic losses caused by TCs showed a significant increasing trend since 1983. They also pointed out that the increase in the economic losses can be attributed to the rapid economic development in China--particularly in TC-prone areas. By quantifying the number of casualties, damage/collapsed houses, inundated farmland areas and direct economic losses, Lei et al. (2009) developed an “Advanced Typhoon Disaster Index (ATDI)” to assess the severity of TC damages in China. Their analysis showed that there is a slight increase in the ATDI from 1980 to 2004.

In Hong Kong, the implementation of various disaster prevention and mitigation measures has led to a steady decrease in the number of deaths/missing associated with TCs in the past 50 years (Lam et al., 2012; Fig. 4.13). The damage in monetary terms varied from year to year depending on the incidence and severity of TCs making close call to Hong Kong.

Kurashima (2005) noted that the significant reduction in number of casualties by typhoons in Japan after Typhoon Vera in 1959 (Fig.

4.14) could be attributed to changes in social structure such as the establishment of Disaster Measures Basic Law in 1961, and the diffusion of TV around that time. He also proposed that typhoon disasters could be categorized into two types, namely “developing country-type typhoon disaster” characterized by a large number of dead and missing, and “developed county-type typhoon

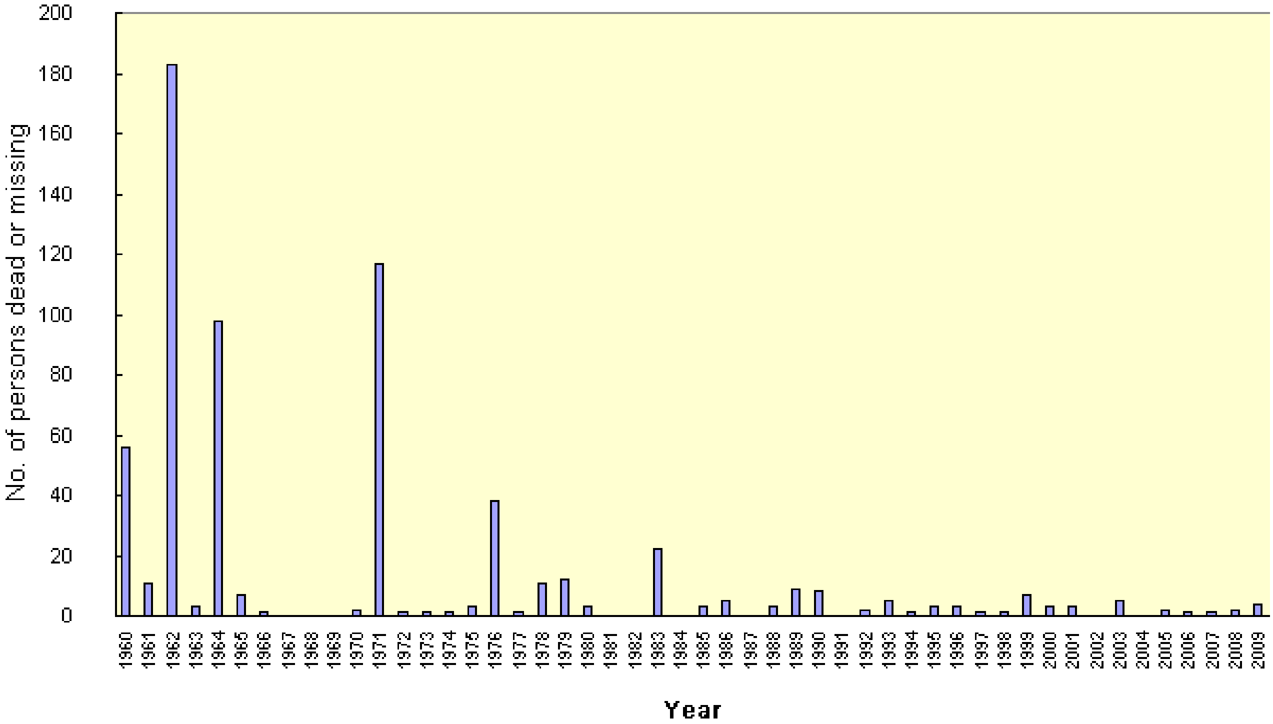


Fig. 4.13 Lives claimed (death or missing) by tropical cyclones in Hong Kong from 1960 to 2009 (Courtesy of HKO)

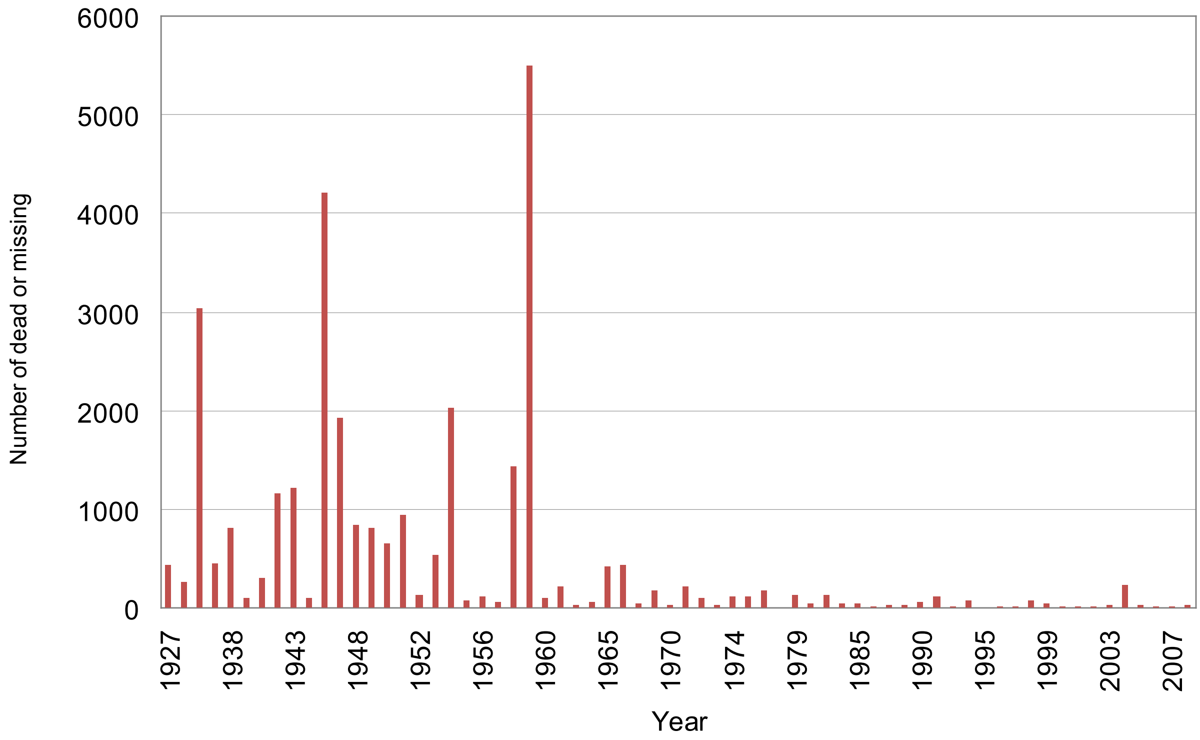


Fig. 4.14 Number of dead or missing due to tropical cyclones in Japan from 1927 to 2009 (Data source : “White Paper on Disaster Management” published by the Cabinet Office of the Japanese Government)

disaster" characterized by smaller number of dead and missing and larger amount of economic losses. Japan appears to have transformed from having developing type to having developed type typhoon disasters beginning around 1960. Esteban and Longarte-Galnares (2010) employed a Monte Carlo method to simulate the possible economic risks that a future increase in TC intensity would have on Japanese economy. Two main climate change scenarios were formulated, for different relationships between maximum wind speed and tropical cyclone size, which would result in the Gross Domestic Product of Japan being between 6% and 13% lower by 2085 compared to a scenario with no increase in TC intensity. However, they cautioned that there is still large uncertainty in this simulation.

In the Republic of Korea, there is no significant trend in the casualties but economic losses due to TCs have an increasing trend after 1990s (KMA, 2011).

In the Philippines, between 1970 and 2010, 9 of the 10 most destructive tropical cyclones (in terms of cost) occurred in the past 2 decades (1991−2010). Also, 9 of the 18 deadliest typhoons in the Philippines occurring in the 59-year period 1952−2010 occurred during the last twenty years (1991−2010). Total damages brought about by these natural calamities have increased by 379% for the period 2006 to 2010, compared with the period 2001 to 2005.

4.3 Conclusions

4.3.1 Landfalling Frequency

Analysis of time series of landfalling TCs indicates no significant trend in the number of landfalling TCs for China, Japan (TS or above), the Philippines, the Korean peninsula and in the vicinity of Hong Kong and Macao. Although not statistically significant, the trends are negative for China and in the vicinity of Hong Kong and positive for the Korean peninsula.

The number of typhoons landfalling in /crossing the Philippines has a significant decreasing trend. The frequency of TCs (mostly tropical depressions) entering Thailand also has a significant decreasing trend, although there is a slight increasing trend in the number of TCs of tropical storm strength reaching Thailand. According to a change point analysis, the number of TCs affecting the vicinity of Taiwan increased significantly in the last decade.

The variations of the landfalling TCs in this region are likely related to the shift of TC tracks as observed in the last few decades as a result of the changes in the large scale steering flow. However, with significant inter-decadal variations in the TC activity being evident in this region, the data period may be too short to confidently determine whether any of these changes are outside the range of natural variability. More research will also be required to further our understanding of the natural variability in this basin and the relative contributions of natural variations and anthropogenic forcing to the observed changes.

4.3.2 High Winds and Precipitation

The maximum sustained winds of TCs affecting the near-coastal China and off-shore sub-regions have a decreasing trend, with a prominent decreasing trend at the coastline of southeast China including the urban areas of Hong Kong. There is no significant trend in maximum wind speed due to tropical cyclones in Macao.

For precipitation, while the annual TC induced precipitation in China has a statistically significant decreasing trend for some of the stations along the coast, the changes in TC induced precipitation *per TC* and maximum 1-hour precipitation have significant spatial variations in China with increasing trend at a number of stations, especially over coastal areas of southeastern China.

A significant increase has been reported in the TC-induced rainfall for TCs landfalling in the Korean peninsula and Japan and the summer rainfall related to TCs (TS or above) affecting Taiwan. There is no significant trend in the TC-induced rainfall in Hong Kong and Macao.

It remains to be demonstrated that whether any of these reported sub-basin-scale changes have a substantial contribution from anthropogenic forcing.

4.3.3 Casualties and Economic Losses

In terms of casualties, there is no significant trend in China and the Republic of Korea. The number of casualties in Hong Kong and Japan is decreasing.

However, the economic losses due to TCs have an increasing trend in China, the Republic of Korea and the Philippines. Analysis available for China suggests that the increase in economic losses there is likely due mostly to the economic development.

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CHAPTER 5. FUTURE PROJECTIONS

Dynamical models and some associated diagnostic approaches have been developed for assessing the potential impacts of global warming on the future of tropical cyclone (TC) activity. In this chapter, late 21st century projections of western North Pacific (WNP) TC activity are summarized. These projections are based on a number of published studies using either high resolution dynamical models directly or coarse resolution models together with diagnostic tools or statistical-dynamical methods.

Uncertainties associated with TC projections are discussed in Chapter 6. The projections will depend on details of the future tropical environment (SST patterns, lapse rates, etc.) such that any uncertainties in the projection of these environmental factors must propagate onto and lead to uncertainty in the TC projections. In addition, there is uncertainty in modeling the TC response to projected large-scale environmental changes even if those environmental changes were perfectly known. Thus the reliablility and uncertainty associated with these projections is difficult to assess quantitatively at present. Among the information which is useful for this assessment are inferences made from examination of past trends in TC activity and evaluations of the ability of models to simulate past variability and change in TC activity and related environmental factors.

The discussion and text in this chapter emphasizes recent studies not contained in the first ESCAP/WMO assessment report (Lee et al., 2010), but the conclusions are based on consideration of all available studies. Tables 5.1 – 5.4 in the supplemental material present summary projections for all studies that we surveyed which we considered useful and relevant for projections of the given TC metric.

Global coupled models and high resolution models have been improved in terms of their ability to represent the climatology, variability, and typical structure of TCs (e.g. Bengtsson et al., 2007; Oouchi, et al., 2006; Sugi et al., 2009; Murakami and Wang, 2010; Murakami et al., 2011a, b; Murakami et al., 2012). Higher resolution global models potentially have higher capability to simulate extremely intense TCs (e.g., Kobayashi and Sugi, 2004; Murakami et al., 2012), which can enable simulations and projections of intensity changes for such intense TCs. In addition, regional climate models have also been applied in downscaling simulation (Knutson et al, 1998, 2007; Knutson and Tuleya, 2004; Sugi et al., 2002). A combined statistical-dynamical downscaling approach has also been proposed (Emanuel, 2006; Emanuel et al., 2008). Statistical methods have been introduced to adjust for the biases in model simulations of the present-day probability distribution of TC intensity; these methods may also be useful for future TC projections (Zhao and Held, 2010).

Other TC-related diagnostics, such as potential intensity (Bister and Emanuel, 2002; Zeng et al., 2007, 2008), genesis parameters (Emanuel and Nolan, 2004; Kim et al., 2011) and trajectory models based on large-scale steering flows (Wu and Wang, 2004), have been proposed as methods to assess potential changes in TC activity caused by changes in the large-scale environmental conditions projected for the late 21st century. Both simulation models and diagnostic approaches provide useful tools for assessing current TC activity metrics such as frequency, intensity, rainfall, track patterns and so on. The utility of various approaches for future projections remains difficult to assess quantitatively, since TC activity depends on a number of factors.

5.1 Frequency

The first ESCAP/WMO assessment report (Lee et al., 2010) had summarized the dynamical model projections on future changes of TC frequency and intensity in the 21st century from a number of studies. In general, the majority of those model studies projected a reduction in TC numbers and increase in intensities over the WNP in various greenhouse gas scenarios. An updated summary based on an expanded set of studies using relatively high resolution models or TC diagnostic tools is presented in Table 5.1.

As shown in Table 5.1, some studies or models project increases in TC frequency while others project decreases. (In the following sections, “TC” will be used to refer to storms of tropical storm (TS) intensity and above). However, considering just the studies using the relatively higher resolution dynamical models, most of these studies project a decrease in WNP TC frequency in the 21st century.

The highlights of additional studies included since the first assessment report (Lee et al. 2010) are now briefly summarized. Zhao et al. (2009) simulated the response of TC frequency to different SST change scenarios, all based on the IPCC A1B forcing scenarios. They used four different SST trend projections together with two different SST climatologies. Their projections included decreasing WNP typhoon frequency in response to SST changes generated from CMIP3 ensemble mean and ECHAM5 model, while no significant changes were projected using SST change projections from the GFDL CM2.1 or HadCM3 models.

Murakami and Sugi (2010) examined four different GCMs with grid spacing ranging from about 180 km down to 20 km. All of these models project a decrease in TC genesis frequency over the WNP over the 21st century, although the decrease in one of the four models was not statistically significant.

Murakami et al. (2011b) and Murakami et al. (2012) also suggested significant reductions in both TC genesis number and frequency of occurrence over the WNP, although not all of the individual model results were statistically significant. However, their projection on storm days is only significant over the coastal region of Southeast Asia. Murakami et al (2011a) analyzed the modified GPI (Murakami and Wang, 2010) and suggested that the reduction in storm days in the WNP region in one of their high resolution simulations is mainly due to an eastward shift in the location of TC genesis, though in part is attributable to the changes in large-scale steering flows.

In contrast to the decreasing WNP TC frequency projections from the above studies, Emanuel et al.'s (2008) statistical–dynamical downscaling approach suggests increasing TC frequency trends in the WNP basin. This framework was applied to seven IPCC AR4 models simulations (A1B scenario), and the ensemble mean simulations for the years 2181−2200 project this increase (see Table 5.1).

Other studies have used genesis parameters (GPs), as opposed to explicit TC simulations, to assess the potential changes of TC genesis (Caron et al., 2008; Kim et al., 2011; Zhang et al., 2010). Caron et al. (2008) used the yearly GP and convective-YGP to evaluate the potential changes in TC genesis using the CMIP3 projections (nine models, each having coarser resolution than T106 or ~120 km grid spacing). Their results suggested that TC frequency would increase in WNP during the 21st century. Kim et al. (2011) also applied a genesis parameter--the convective seasonal genesis parameter (ConvGP, Royer et al., 1998)—to assess relatively low resolution HadCM3 and HadSM3 simulations and found that the TC frequency decreased over the WNP in response to a doubling of CO_2. Using the TC genesis potential index of Emanuel and Nolan (2004), Zhang et al. (2010) found that the GPI derived from two models selected from among the CMIP3 models--the CGCM3.1-T47 and IPSL-CM4--show increasing trends over the WNP. However, their process for selecting the two models to emphasize for projections seemed not well-justified, as it was based on model correlation performance for interannual variability. This is not well-posed, since the 20th century forcing runs that they analyzed a priori are not expected to have interannual variability that correlates well with observed interannual variability. Rather, any internal (unforced) variability generated in the models, such as ENSO, should have a random phasing in time as compared with the observed internal variability.

Only a few model studies focus on intense TC frequency in the WNP basin (see Table 5.1). Among these, Zhao and Held (2012) explored typhoon counts; their 50 km grid model projected a decrease in typhoon counts for most of the CMIP3 models that they downscaled, including an 18-model ensemble climate change. Murakami et al. (2012) used a 20 km-grid global model that simulated storms up to category 5 intensity, although their model lacks ocean coupling, which meant that they did not simulate the negative influence on storm intensity of a storm-generated "cold wake" in SST. For the 18-model average CMIP3 climate change scenario, they project no significant change (4% decrease) in the frequency of category 4 and 5 storms, but a significant increase (+45%) in the frequency of category 5 storms in the WNP.

5.2 Intensity

The first assessment report (Lee et al., 2010) found that most of the models projected increasing trends in TC intensity over the WNP in response to projected 21st century warming. These increasing trends in the 21st century are further supported by more recent studies using various relatively high resolution models or using potential intensity theory (Table 5.2). These studies are now briefly reviewed.

Murakami et al. (2012) used two different versions of the MRI/JMA high resolution model (20 km mesh) and both projected that the TC intensity in the WNP would increase over the 21st century with a range of +6 to +18%, while Murakami et al. (2011a) focused on intensity changes in coastal regions of the WNP. They found significant increases in some regions and no significant change in others. In particular, the reported that the projected changes for Japan, South China, Southeast Asia, and Philippines are significant (Table 5.2). It is unclear how reliable such projections would be for such subregional scales. For example, Knutson et al. (2008) note that model TC projections appear to be more robust across different model studies at the global and hemispheric scales. The seven statistical-dynamical downscaled IPCC AR4 model projections of Emanuel et al. (2008) consistently indicate increasing tendencies in both TC intensity and power dissipation in the WNP basin as a whole. These increasing tendencies in Emanuel et al. (2008) were more consistent across different models in the WNP than for other basins in their study.

Other TC intensity metrics have been considered in existing studies. Three studies suggesting increasing trends in aggregate TC activity in a warmer climate include Stowasser et al., 2007; Vecchi and Soden, 2007; and Yu et al., 2009. Stowasser et al. (2007) simulated about 50% increasing in PDI for an idealized (6□CO_2) scenario, using a dynamical-downscaling approach with the NCAR CCSM2 model. Vecchi and Soden (2007) examined potential intensity 21st century projections based on the theory of Bister and Emanuel (2002) and found a 3% increase in the WNP, averaged across 18 models, with a range of -3 to +13%. Yu et al. (2010) also used Bister and Emanuel's potential intensity (PI) as well as a dynamically-adjusted potential intensity (DPI, Zeng et al., 2007, Zeng et al., 2008) of TCs that included some dynamical effects such as translation speed and wind shear from CMIP3 model experiments. Their projections for both PI and DPI suggested increases over the WNP by about 2% in a period of 70 years with projected climate warming.

5.3 Tropical Cyclone Precipitation Rates

As summarized in Table 5.3, six studies that examined either global, Northern Hemisphere, or western North Pacific (WNP) TC-related storm precipitation all suggested that there would be increased TC-related rainfall rates in association with projected 21st century warming. Of those studies, two reported results specifically for TC-related precipitation over at least part of the WNP, and both of these studies indicated an increase (Chiang and Chang, 2011; Hasegawa and Emori, 2005). The projected rates of increase are difficult to compare quantitatively between the various studies, since they examined different TC/precipitation metrics. However, the reported changes ranged from about +5% to +30%.

5.4 Shifts in Activity / Track Pattern and Landfalling

According to several studies, in the WNP basin, the general circulation rather than the underlying sea surface temperature (SST) appears to have the primary influence on the TC activity with the indirect effects of remote SST variations on TC activity apparently being more influential than local SST effects (Wang and Chan, 2002; Chan and Liu, 2004; Zhan et al., 2011). The most significant climate variation that affects interannual variability in TC activity over the WNP is the El Niño-Southern

Oscillation (ENSO). The tropical atmospheric circulation anomalies associated with ENSO, including the Pacific Walker Circulation, has large influence on interannual TC variations in the WNP, especially through shifts in the preferred tropical cyclogenesis regions and in the TC track patterns (Wang and Chan, 2002). In addition, the SST in the eastern Indian Ocean may also influence the TC genesis frequency over the WNP according to Zhan et al. (2011). Consequently, projections of changes in the tropical circulation and ENSO will likely be very important for projections of changes of TC activity due to greenhouse warming.

To explore whether different studies of projected shifts in TC activity/track patterns in the WNP show common features for their climate change projections, several such studies are compared in Table 5.4. Among the seven studies examined, Yokoi and Takayabu (2009) projected a shift of TC activity from the western part of the WNP toward the eastern part, with a maximum decrease in frequency over the South China Sea. Similarly, based on the high resolution ECHAM5 T319 (about 40 km mesh) projection (A1B scenario), Li et al. (2010) suggested that the preferred location of TC activity would shift from the western to central Pacific, which they associated with the change in variance of tropical synoptic-scale perturbations, which in turn was associated with changes in vertical wind shear and boundary layer divergence. Based on coupled climate models, Kim et al. (2011) suggested that as CO_2 doubled, a TC genesis parameter, ConvGP (Royer et al., 1998), may increase preferentially to the north and east of the current genesis region. They noted that, in their projections, significant uncertainties would to be attributable to details of ocean physical processes incorporated in the models.

Murakami et al. (2011a) projected an eastward shift in the positions of two prevailing northward recurving TC tracks during the peak season (July–October), and significant reduction in TC frequency approaching coastal regions of the Southeast Asia. They also suggested that in the future, the mean number of landfalling TCs would be stable for the season from July to October. The MRI–AGCM model also suggested a northward shift in the most intense TCs over the WNP (Murakami et al., 2012).

Wu and Wang (2004) had proposed a trajectory model to assess the possible impacts of the global climate change on tropical cyclone (TC) tracks by examining the changes of large scale environmental steering flows and TC genesis locations. They evaluated the potential changes of TC tracks over the WNP by applying the trajectory model to global warming projections (scenarios A2 and B2) from a Geophysical Fluid Dynamics Laboratory (GFDL) climate model. In their projections, the prevailing TC tracks shifted slightly southwestward during the period of 2000–29 but northeastward during the period of 2030–59.

Wang et al., (2011) investigated the relationship between track patterns and SST warming, and suggested that the trends in track pattern as demonstrated by Wu et al. (2005) could continue through 2040, that is, increasing influences of TCs on the subtropical East Asia and decreasing influences of TCs on the South China Sea.

In summary, while there is some tendency for a number of models to project eastward shifts of TC activity in the WNP over the 21st century, the details vary between different studies. The projection of such shifts and changes remains uncertain and needs further investigation using observed data and models.

5.5 Sea Level Rise and Storm Surge

Storm surge flooding associate with tropical cyclones can cause enormous damage and loss of life. For example, the death toll from Tropical Cyclone Nargis (2008) was estimated at over 138,000. Furthermore, a robust projection of IPCC AR4 for the 21st century is that global averaged sea level will continue to rise. According to the IPCC AR4, the average rate of global sea level rise over the 21st century will very likely exceed that observed during the 1961–2003 for a range of future emission scenarios. Given this projected sea level rise, along with coastal development, the vulnerability of most coastal regions to storm surge flooding is expected to increase over the 21st century, although this vulnerability will also depend on future storm characteristics.

There are large uncertainties in the 21st century projections of the storm characteristics for the WNP basin, as well as uncertainties in the magnitude of regional sea level rise affecting the Typhoon Committee members. A small number of studies have begun to combine future tropical cyclone projections, sea level rise projections, and storm surge models to begin to explore this issue quantitatively. Several available studies focus on surge changes for U.S. landfalling regions (Hoffman et al. 2010; Mousavi et al. 2010; Lin et al. 2012), and so may have limited applicability in the WNP. One study (Brecht et al. 2012) uses highly idealized climate change/storm surge change scenarios, but takes a more global perspective in terms of affected locations, and suggests that disproportionately large future increases in surge impacts will affect some cities within the WNP basin, including Manila. Nonetheless, given the uncertainties in future storm climate discussed elsewhere in this report as well as uncertainties in sea level rise, this topic remains an area needing further research.

5.6 Casualties and Economic Losses

Globally, Mendelsohn et al. (2012) indicated that future increases in income are likely to double tropical cyclone damage even without climate change. They also suggested that the predicted increase in the frequency of high-intensity storms in selected ocean basins (including the East Asia) in the future could increase the economic damages, depending on the climate model and parameters of the damage function. However, three of four climate models that they used for downscaling TC changes showed reduced tropical storm power in the WNP basin by the late 21st century.

In another global study using a new methodology based on physically observed events and related contextual parameters, Peduzzi et al. (2012) pointed out that, projected increases in demographic pressure over the next 20 years can be expected to greatly increase the number of people exposed to TC threat per year and exacerbate disaster risk, despite potential progression in development and governance. Their simulations (their Fig. 5) show that projected global increasing trends in mean TC intensity and decreases in TC frequency over the next 20 year (using rescaled late 21st century projections of Knutson et al. 2010), would have opposing effects on total the TC hazard, although the influence of demographic pressure leads to increased population exposure to TC hazards under all the climate change scenarios they analyzed. They did not explore TC projections at the individual basin scale (e.g., WNP basin).

5.7 Conclusions

According to the WNP projections from dynamical models having a grid spacing finer than about T106 or 120 km (twelve available studies), more models suggest a decreasing trend in tropical storm frequency over the 21st century than an increasing trend. The projected changes for the late 21st century range from about -70% to +60%. Other studies using statistical/dynamical methods (one) or empirical genesis parameters (three) tend to have more mixed projections, with three of four suggesting an increase in frequency.

For TC intensity, we reviewed nine available studies that used either dynamical models with 50 km or finer grid spacing or evaluations by potential intensity theory. Most of the studies projected an increase in TC intensity over the WNP, although several studies projected a mix of positive and negative intensity changes depending on the model downscaled. Studies with quantitative results suggested changes ranging from -3% to +18% for maximum wind speeds.

Six available studies reported TC precipitation rate projections either for all basins, northern hemisphere basins, or the WNP. All of these projected increases with the quantitative projections ranging from roughly +5% to +30%.

A common general feature noted in several late 21st century projection studies is the tendency for track/occurrence of TCs to shift eastward or northward in the WNP. However, this finding requires further studies to assess the robustness of the projection.

The vulnerability of coastal regions to storm surge flooding is expected to increase with future sea-level rise and coastal development, although this vulnerability will also depend on future storm characteristics. Globally, a recent study concludes that projected increases in future income and demographic pressure over the next 20 years may increase the number of people exposed to TC threat per year and exacerbate disaster risk, despite potential progress in development and governance. Projected global increases in TC intensity and decreases in TC frequency are projected to have opposing effects on TC exposure, though these effects are generally smaller than the projected influence of societal changes.

Table 5.1 Summary of projections of changes in Western North Pacific TC frequency for approximately the late 21st century. Projections for TCs of higher than TS intensity are presented in the latter part of the table. See Knutson et al. 2010 for further details.

Study reference	Model details	GHG	WNP (changes: %, significance in bold)	Notes
Tropical Storm and above				
Sugi et al. (2002)[#]	JMA , T106 L21 (~120 km)	10 years 1xCO_2, 2xCO_2	**-66**	
McDonald et al. (2005)[*#]	HadAM3, N144 L30 (~100 km)	15 years IS95a 1979-1994; 2082-2097	**-30**	
Hasegawa and Emori (2005)[#]	CCSR/NIES/FRC GC T106 L56 (~120 km)	5x20 years at 1xCO_2 7x20 years at 2xCO_2	-4	
Oouchi et al. (2006)[#]	MRI/JMA, T106 L21 (~120 km)	10 year A1B 1982-1993, 2080-2099	-38	
Stowasser et al. (2007)[#]	NCAR CCSM2 IPRC regional model (downscaling)	1991-2000, present climate; 10 years, 6xCO_2	+19	IPRC Regional Downscaled NCAR CCSM2 simulations
Bengtsson et al. (2007)[#]	ECHAM5 T213 (~60 km) T319 (~40 km)	2071-2100 A1B	-20 (T213) -28 (T319)	
Emanuel et al. (2008)	(CCSM3, CNRM-Mk3.0, CSIRO-Mk3.0, ECHAM5, GFDL-CM2.0, MIROC3.2, MRI-CGCM2.3.2a)	2180-2200 (22nd century) A1B	+6 (7-model mean)	Statistical-dynamical downscaled IPCC AR4 future simulations
Gualdi et al. (2008)[#]	SINTEX-G coupled model T106 (~120 km)	30 years 1xCO_2, 2xCO_2, 4xCO_2	-20	
Caron and Jones (2008)[#]	Nine CMIP3 models (only MIROC3.2 is T106, others are coarse than it)	20 years 20c3m (1981-2000) A1B, A2, B1 (2081-2100)	**+22** (A2) **+16** (A1B) +10 (B1) +7 (20c3m, changes over 1901-1920 to 1981-2000).	Yearly genesis parameter (YGP) based on Gray's SGP (Gray, 1979), and Convective-YGP that was first used in Royer (1998)
Zhao et al. (2009)	GFDL AM2.1 (~ 50 km)	18 years, A1B (SST forcing: GFDL CM2.1, HadCM3, ECHAM5, and CMIP3)	-29 (CMIP3 Ensemble) -5 (CM2.1) **-12** (HADCM3) **-52** (ECHAM5)	High resolution model projections

Sugi et al. (2009)#	JMA/MRI AGCM (~20km, ~60 km)	A1B	**-36** (MRI CGCM2.3, 20km) **-29** (MRI CGCM2.3, 20km) **+28** (MIROC-H,20km) **-26** (CMIP3, 18 ens. mean, 20km) **-36** (MRI CGCM2.3, 60km) **+64** (MIROC-H, 60km) -14 (CMIP3, 18 ens. mean, 60km) +13 (CSIRO, 60km)	Downscaled
Murakami and Sugi (2010)	MRI/JMA-AGCM TL95 (180 km) TL159 (120 km) TL319 (60 km) TL959 (20 km)	A1B	-18.5 (TL95) -26.0 (TL159) -11.7 (TL319) -26.8 (TL959)	High resolution model projections
Zhang et al. (2010)	CGCM3.1-T47, IPSL-CM4	A2 (2040-2060, 2081-2100) 20C3M (1970-1999)	+13 (2041-2060, CGCM3.1-T47), +20 (2081-2100, CGCM3.1-T47); +7 (2041-2060, IPSL-CM4), +9 (2081-2100, IPSL-CM4)	GPI (Emanuel and Nolan, 2004). Fractional changes were based on 1970-1999 climatology, no test on confidence.
Kim et al. (2011)	HadCM3 (ocean model with full dynamics), HadSM3 (mixed layer ocean model) 2.5° x 3.75° (~300 km)	2xCO_2	Decrease	ConvGP (Royer et al., 1998)
Murakami et al. (2011b)	MRI–AGCM (60 km)	A1B 1979-2003 2075-2099	+8, -1, -5, -22, -22, **-25, -28, -30, -35, -35, -40, -45**	High resolution model projections (90% confidence)
Murakami et al. (2012)	MRI–AGCM v3.2 and v3.1 (20 and 60 km)	25 years A1B 1979-2003 2075-2099	**-27** (v3.1 20km) **-23** (v3.2 20km) -20 (v3.1 60km) **-28** (v3.2 60km)	High resolution model projections (90% confidence)
Typhoon				
Zhao and Held (2012)	18-model ensemble 8 models	A1B 1982-2005, 2081-2100.	**-30** (18-model ensemble) **-19** (GFDL-CM2.0) +9 (GFDL-CM2.1) -11 (UK-HADCM3) **-29** (UK-HADGEM1) **-49** (ECHAM5) **-37** (CCCMA) **-33** (MRI-CGCM) **-17** (MIROC-HI)	CMIP3 results. (90% confidence)
Very Intense Typhoon (i.e., Saffir-Simpson categories 4 and 5 hurricane)				
H. Murakami pers.comm. (2011)	MRI-AGCM (20 km)	A1B 1979-2003 2075-2099	-4 (Cat.4-5) **+45** (Cat. 5)	High resolution model projections (99% confidence)

Cited in the first assessment report (Lee et al., 2010).

Table 5.2 Summary of projections of changes in Western North Pacific TC intensity for approximately the late 21st century. See Knutson et al. 2010 for further details.

Study reference	Model details	GHG	WNP (changes: %, significance in bold)	Notes
Knutson and Tuleya (2004)[#]	Regional model downscale (~9km grid) of TCs in idealized (e.g., no shear) environments	80-year trend +1%/yr CO_2	+7.0 (-1.0, +19.6) in MCP** +8.5 (+2.8,+25.2) in MCP +17.3 (+9.4, +30.6) in MCP +5.4 (+3.3, +6.7) in MSW +13.6 (+8.0, +16.5) in MCP	PI (Bister and Emanuel, 2002) PI (Bister and Emanuel, 2002), Pseudoadiabatic, PI (Holland, 1997) GFDL Hurricane model, 9km inner nest GFDL Hurricane model, 9km inner nest
Hasegawa and Emori (2005)[#]	JMA, T106 L21 (~120 km)	5x20 years at $1xCO_2$ 7x20 years at $2xCO_2$	Decrease (all intensity)	
Oochi et al. (2006)[#]	MRI/JMA TL959 L60 (~20km)	10years A1B 1982-1993, 2080-2099	+4.2 (average lifetime MSW) -2.0 (average annual max MSW)	
Stowasser et al. (2007)[#]	NCAR CCSM2 IPRC Regional Model downscale (~50km)	1991-2000, present climate; 10 years, $6xCO_2$	+50 PDI) and increased intensity, July to October season	IPRC Regional Model downscaled NCAR CCSM2 simulations, PDI (Emanuel, 2005)
Vecchi and Soden (2007)	CMIP3 18 models	100-year trend A1B	+2.9 (-3.1, +12.6)	PI (Bister and Emanuel, 2002), Reversible w/ dissipative heating
Emanuel et al. (2008)	(CCSM3, CNRM-Mk3.0, CSIRO-Mk3.0, ECHAM5, GFDL-CM2.0, MIROC3.2, MRI-CGCM2.3.2a)	A1B, 2181-2200 minus 1981-2000,	+4.1 (MSW, PDI)	Statistical-dynamical downscaled IPCC AR4 projections
Yu et al. (2010)	CMIP3	A1B 70-years trend	PI: +1.3 (-0.1, +2.4) ms^{-1}, i.e., +2.0 (-0.2, +3.9) %. DPI: +2.3% (13 out of 15 models show an increase).	PI (Bister and Emanuel, 2002), DPI includes dynamical contribution (Zeng et al., 2008)

Murakami et al. (2011a)	MRI/JMA-AGCM (20 km mesh)	A1B 1979-2003 2075-2099	**+7.4** (East Japan, 95% confidence) **+7.2** (West Japan, 95% confidence) +1.8 (Korea) +4.4 (North China) +1.1 (Central China) **+7.4** (South China, 99% confidence) +1.0 (Taiwan) **+5.8** (Southeast Asia, 90% confidence) **+8.7** (Philippines, 95% confidence)	Instantaneous maximum wind velocity. Only changes in intensity over the coastal regions are reported.
Murakami et al. (2012)	MRI-AGCM v3.2 and v3.1 (20 km)	A1B, 1979-2003 2075-2099	**+18.1** (v3.1, mean MSW, 99% confidence) **+7.1** (v3.2, mean MSW, 99% confidence) **+15.5** (v3.1, lifetime max MSW, 99% confidence) **+6.2** (v3.2 lifetime max MSW, 95% confidence)	High resolution model projections.

Cited in the first assessment report (Lee et al., 2010).

** MSW: mean sustained wind speed; MCP: minimum central pressure.

Table 5.3 Summary of projections of changes in Western North Pacific TC-related rainfall for approximately the late 21st century. Some results are shown for multiple-basin estimates that include the WNP basin. See Knutson et al. 2010 for further details.

Study reference	Model details	GHG	Global or NH (changes: %, significance in bold)	WNP (changes: %, significance in bold)
Hasegawa and Emori (2005)	CCSR/NIES/ FRCGC AGCM, T106 (~120km)	5´20 years at 1xCO_2 7´20 years at 2xCO_2	-	+8.4 (with radius of 1000km)
Yoshimura et al. (2006)	JMA GSM9603 AGCM, T106	10 years 1xCO_2, 2xCO_2	+10 (Global, Arakawa-Schubert, with radius of 300 km) +15 (Global, Kuo, with radius of 300 km)	-

Bengtsson et al (2007)	ECHAM5/MPI-OM, ECHAM5; T213 (60 km), T319 (40 km)	A1B	+21 (all TCs in NH)* +30 (TYs in NH)	-
Knutson and Tuleya (2008)	GFDL Hurricane model (idealized)	CMIP2+	+22 (Atlantic, ENP, and WNP combined, with radius ~100km)*	+ 20 (with radius of ~100 km)
Gualdi et al. (2008)	SINTEX-G (SXG) AOGCM, T106 (~120 km)	30 years 1xCO$_2$, 2xCO$_2$	+11 (global, with radius of 100 km, time of max winds) +4.9 (with radius of 400 km, time of max winds)	-
Chiang and Chang (2011)	21 GCMs, Statistical downscaling (Lin et al. 2010)	A2 1960-2008 2010-2099	-	annual maximum TC rainfall in Taiwan island: from 322mm (1960-2008) to 371mm (2010-2099)

* NH: Northern Hemisphere; ENP: eastern North Pacific.

Table 5.4 Summary of projections of changes in Western North Pacific TC activity regions and track patterns for approximately the late 21st century.

Study reference	Model details	GHG	WNP	Notes
Wu and Wang (2004)	GFDL	A2 and B2	The prevailing tracks would shift slightly southwestward during 2000-29, but shift northeastward during 2030-59	trajectory model (Wu and Wang, 2004)
Yokoi and Takayabu (2009)	Five CMIP3 models CCCMA CGCM3.1 (T63, ~200 km) CSIRO-Mk3.0 (T63) CSIRO-Mk3.5 (T63) INGV-SXG (T106, ~120 km) ECHAM5/MPI-OM (T63)	40 years A1B, A2, B1, 20C3M	Frequency increase in the central North Pacific (5°–20°N, 150°E–180°), while decreasing in the western part, with a maximum decrease over the South China Sea (10°–25°N, 110°–120°E).	Detect TC-like vortex as Yokoi et al. (2009) GP (Emanuel and Nolan, 2004) was used to analyze the environmental conditions

Kim et al. (2011)	HadCM3 (full dynamics ocean model), HadSM3 (mixed layer ocean model). 1.25°x1.25°, L20	1xCO_2, 1981-2000, 2xCO_2, 20 years	Increase in east of the Philippines in DJFMAM (HadSM3) Increase in the north and east of the genesis center in JJASON (HadSM3)	Seventeen-member ensemble, genesis potential index ConvGP (Royer et al., 1998) is used in assessment.
Li et al. (2010)	ECHAM5 T319 (about 40km mesh)	A1B	TC activity would shift from the western to central Pacific	High resolution model projections
Murakami et al. (2011a)	MRI/JMA-AGCM (20 km mesh)	A1B	eastward shift of two prevailing northward recurving TC tracks during July-October, **-44** (TC frequency approaching coastal regions of the Southeast Asia, significantly)	High resolution model projections
Murakami et al. (2012)	MRI-AGCM v3.2 and v3.1 (20 and 60 km mesh)	A1B	Northward shift of the most intense TC (category 5)	High resolution model projections
Wang, et al. (2011)	CCCma CGCM3.1 GFDL CM2.0 MIROC3.2(medres) HadGEM1 HadCM3	IPCC AR4 1965-1998 (1965-2009) 2001-2040	The increasing TC influence over the subtropical East Asian and decreasing TC activity over the South China Sea will continue through 2040.	Five-point smoothed TC frequency, large scale steering flow and SST, analyzed by the SVD method.

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CHAPTER 6. UNCERTAINTIES

In this chapter, the uncertainties in both TC observed datasets and TC model projections are summarized. Uncertainties may be introduced by the imitations of data, numerical models, methodologies, and understanding of the underlying physics of the climate change and tropical cyclone activity (Emanuel et al., 2008; Grossmann and Morgan, 2011; Knutson et al., 2010; Lee et al., 2010; Song et al., 2010; Wang et al., 2008; Wu et al., 2006; Zhao et al., 2009). While uncertainties in future emission scenarios and anthropogenic and natural climate forcing agents contribute to uncertainties future TC projections, large uncertainties remain even if the 21st century climate forcing scenario (e.g., IPCC A1B) is assumed to be known.

6.1 Uncertainties in Datasets Used for TC Trend Analyses

For climate change detection, an essential issue is the homogeneity of data over time, since spurious trends may be induced by non-climatic influences, such as instrumental changes, etc. The current TC best track datasets over the WNP all suffer from inhomogeneity induced by various reasons. For instance, improvements or changes in measurement techniques (e.g., aircraft to satellite-based) and development of the observation systems (Landsea, 2000; Chu et al., 2002) may be important sources of temporal inhomogeneity in WNP TC climate records. There may be some TCs which were simply missed due to relatively sparse observations over the open ocean before the satellite era, as has been argued for the Atlantic basin (Vecchi and Knutson 2011). The under-sampling in early years of a TC record may lead to difficulties in detection and attribution of the long term trends in TC activity since undersampling can result in spurious positive biases in trends in TC numbers or other metrics. The cessation of aircraft reconnaissance in the WNP in 1987 and the utilization of the Dvorak technique (Dvorak, 1975) are also significant events affecting the homogeneity of TC intensity in this basin. Other technical developments may have introduced spurious changes to the TC intensity data, such as increases in the resolution of satellite imagery, changes over time in both the radiosonde and land observation networks, and improvements over time in quasi-real time TC analysis techniques at various centers.

Furthermore, discrepancies between different TC Best Track datasets persist (e.g. chapter 2; Lee et al., 2010; etc.) indicating substantial data problems for climate change studies (Knapp and Kruk, 2010). Analysis practices may also introduce uncertainties and in turn cause discrepancies in trends computed using different data sets (e.g., Hoarau et al., 2006). Considering the existing discrepancies between different best track datasets for the WNP basin, further reanalysis of these data has been recommended (Hoarau et al., 2006; Knaff and Sampson, 2006) and has been attempted already for some cases and parts of the record (Hoarau et al., 2006; Knaff and Sampson, 2006; Kossin et al., 2007). Effects of several kinds of inhomogeneities, such as the possible influence of unrecorded TCs on trends in annual TC time series, need to be carefully evaluated. With reference to recent work for the Atlantic basin, short duration (<2 days) tropical storms, which had a large contribution to the observed trends of storm numbers in the original HURDAT dataset, which Landsea et al. (2010) argue may be largely attributable to changes in observing capabilities. Careful studies of atmospheric reanalyses may be a useful way to quantify or estimate the under-sampling of TCs in the pre-satellite era (Truchelut and Hart, 2011) although their methods must be carefully evaluated before confident application in new basins such as the WNP.

The ESCAP/WMO Typhoon Committee sponsored a Best Track Consolidation Meeting (13-14th December, 2010, Hong Kong, China) to discuss the reasons for discrepancies between the TC best track data from the various centers, especially regarding the intensity of very intense WNP TCs. Comparison of the analysis practices among the agencies, that is, RSMC Tokyo, JTWC, CMA and HKO, indicated that in addition to the different available data used for the best track analysis, details of the analysis procedures are also different, i.e., the averaging time of the sustained wind, details of the utilization of the Dvorak technique (Dvorak, 1975) and wind-pressure relationship (WPR). The WMO Tropical Cyclone Programme (TCP), WMO World Weather

Research Programme (WWRP), and the World Data Center (WDC) for Meteorology also jointly organized the first WMO International Workshop on the Satellite Analysis of Tropical Cyclones (Hawaii, U.S.A., 13-16 April 2011) to share experiences and discuss ways to increase the accuracy and reliability of satellite analyses of TCs.

In early days, the Dvorak technique was applied relatively subjectively and a different Current Intensity (CI) number may have been deduced for the same TC case by different analysts. Even when the CI numbers from different agencies were very close to one another, the different CI/intensity conversion tables could be another source of discrepancies. Moreover, both the CI number and CI/intensity conversion tables are defined empirically (Dvorak, 1975), so without extensive *in situ* measurements it is difficult to determine how well they can estimate the intensities of extremely intense TCs. This problem may be particularly serious over the WNP as there has been essentially no routine aircraft reconnaissance since 1987 that can be used in calibration of the satellite based intensity estimates over the open ocean.

The wind-pressure relationship may also introduce differences into the results of some studies since there are not indicators in the original best track data identifying which elements of the intensity, (i.e., the maximum sustained wind (MSW) or the minimum near central sea level pressure (MCP), is estimated first for the different stages, such as over the land or over the far ocean, and during the pre-satellite vs. satellite eras. Moreover, Knaff and Zehr (2007) concluded that a widely used wind-pressure relationship for WNP (Atkinson and Holliday, 1977) is not suitable for very intense TCs. Other uncertainties may also exist in the current wind-pressure relationship due to the influence of the storm size, storm motion, latitude, and environmental pressure (Knaff and Zehr, 2008; Courtney and Knaff, 2009).

6.2 Uncertainties in Models and Future Projections of TC Activity

For assessing either the causes of past changes in TC activity or future projections, the uncertainties in climate models and projections include both technical and physical issues. The technical issues may include the model resolution, TC detection scheme, and so on. Examples of physical issues include: uncertainties in projections of large-scale environmental conditions affecting TCs, uncertainties in how various physical processes affect TCs, and uncertainties in the estimating the potential role of natural climate variability which can also affect TC activity.

Regarding climate model resolution, recent global atmosphere-only and coupled model simulations demonstrated that atmospheric models with resolution in the range of 20-100 km may be sufficient to study TC genesis and geographic distributions (Zhao et al., 2009). However, these models may still fail to reproduce a realistic probability distribution of storm intensity (Zhao et al., 2009). Zhao and Held (2010) attempted to address this problem using a statistical refinement approach, taking the North Atlantic as an example. Their results indicated that an adjustment based on the probability distributions of the modeled and observed MSW improved the model's ability to simulate the occurrence and variability of intense TCs in the Atlantic, though their statistical refinement method did not work as well in other basins. The number of TCs detected in model simulations can increase with the resolution (Kobayashi and Sugi, 2004; Bengtsson et al., 2007; Murakami and Sugi, 2010). Bengtsson et al. (2007) also showed that the typical size of TCs is reduced and the upper range of TC intensities is increased as the model resolution increases. Bengtsson et al. (2007) and Murakami and Sugi (2010) showed that in some cases, high resolution models (e.g., T213 in Bengtsson et al. (2007) and TL319 and finer in Murakami and Sugi (2010)), would project significant future increase in the frequency of intense TCs in global scale, but coarser versions of those same models would not project a such trend. This suggests that higher model resolution may be important for modeling the occurrence of intense TCs and the probability distribution of TC intensity.

A related issue to the model resolution is the use of semi-empirical TC detection schemes. The criteria in TC detection schemes are often tuned with model produced storms and real TC climatologies as references (Bengtsson et al., 1995; Walsh, 1997; Camargo and Zebiak, 2002; Zhao et al., 2009). Walsh (1997) demonstrated that small changes in the criteria would cause relative large changes in probability of detection and false-alarm ratio. The criteria in TC detection schemes are also often adjusted to work with different model physics, resolution, and even different basins (Camargo and Zebiak, 2002). Storm detection methods suitable for assessing the extratropical transition and extension of the TC activity area into the middle latitudes (Hart 2003) can also be tested and applied. Another common problem is the detection in models of more TCs over the South Atlantic than occur in observations (e.g., Gualdi et al., 2008; Zhao et al., 2009).

In summary, a suitable model resolution and storm detection scheme should be chosen, and models carefully evaluated in comparison to past TC activity to help assess confidence in model projections of changes of TC activity. While it is possible to evaluate both model physics and detection schemes by comparing simulations of TC interannual variability with observations (Knutson et al., 2010; Zhao et al., 2009), reasonable performance in simulating internannual variablities is a necessarily but not sufficient condition for higher confidence in TC projections. Moreover, the physical mechanisms of the natural and anthropogenic influences on the TC activity in WNP may be very different from those in other TC basins (e.g., Chan and Liu, 2004; Wang and Chan, 2002; Zhan et al., 2011; Zhao and Held, 2012). More research will be required to further understand these influences and their relative contributions to the observed / projected changes in TC activity in the WNP.

Uncertainties in projections may also be introduced by uncertainties or biases in projections of large scale oceanic and atmospheric general circulation features, which are important for TC genesis. Several studies (Knutson et al. 2008; Sugi et al. 2009; Zhao et al. 2009) have suggested that regional TC frequency changes are very sensitive to the projected patterns of SST change. Zhao et al. (2009) showed that TC projections can even be sensitive to which SST climatology is used for the control (present day) simulations. Murakami et al. (2011b) suggested that the large-scale dynamical parameters (related to SST anomalies) are the primary sources of uncertainties in TC occurrence and TC genesis number in the WNP while the thermodynamic parameters (potential intensity, relative humidity) are of secondary importance. Using a statistical analysis of model results for the Atlantic basin, Villarini et al. (2011) showed that the differences in the relative warming of the tropical Atlantic compared to the tropical mean was the main source of discrepancies in a substantial number of model TC projections for that basin. These results strongly suggest that details of the pattern of SST change are very important for future TC projections. These SST patterns in turn depend on how well the coupled ocean-atmosphere model simulates the coupled response to the future climate forcing (e.g., Kim et al. 2011) and uncertainties in future forcings. Model responses, in turn, will also depend on several key climate modeling uncertainties, including indirect aerosol effects, cloud feedback, and so forth, which are discussed in more detail in IPCC AR4 (Solomon et al., 2007). Finally, TC simulations are sensitive to the vertical profiles of temperature and moisture change (e.g., Shen et al. 2000) so that uncertainties in these profiles will also lead to uncertainties in TC projections.

In summary, a variety of observational and modeling issues contribute to the overall uncertainty in TC climate change studies including for detection/attribution and future projections. Reducing these uncertainties will depend on efforts made across a range of disciplines related to the TC/climate change problem.

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CHAPTER 7. RECOMMENDATIONS FOR FUTURE WORK

7.1 TC Best Track Analysis

To further improve the quality and homogeneity of the TC best track datasets, the Typhoon Committee should encourage, and could consider coordinating, efforts by Members and the research community in the following areas:

- Provide better documentation / information on how the TC position and intensity are analyzed in the best track dataset. Researchers doing TC best track reanalysis (along the lines of HURDAT for the Atlantic basin) ideally should have access to available original "raw" historical observations concerning TCs (ship, aircraft, and satellite data, etc.) along with derived quantities such as the estimated TC intensity.
- In collaboration with the IBTrACS Team, continue work to refine existing data sets on tropical cyclone activity in the region (reanalysis/reconciliation of existing data sets).
- Assess impact of changes in observing capabilities over time (e.g., satellite vs. pre-satellite; ship tracks; aircraft recon vs. no aircraft recon) that may have introduced inhomogeneities (e.g., false trends, spurious jumps) in the TC data records.
- Explore innovative methods to search for possible 'missing storms' (e.g., ship tracks; inferring storms from coarse 'fixed-input' reanalysis data).
- Attempt to narrow differences in TC trends between data sets from different centers through use of independent assessment data (e.g., HURSAT homogenized satellite-based data; model simulation).
- Assess the costs and benefits of resuming aircraft reconnaissance in the basin. This could be done as part of a larger research effort to determine the best mix of TC observations (methods, techniques, platforms) in support of climate studies, forecasting, and other needs.

7.2 Model Projections

Members and the research community are encouraged to conduct further research to :

- Evaluate the sensitivity of TC projections to the details of TC detection schemes and model resolutions.
- Enhance the use of statistical significance testing, evaluation of present-day simulations (including interannual variations), and multi-model ensemble experiments to better quantify uncertainty in future projections.
- Evaluate present-day simulations and future projections for the full life cycle of the TCs and their related impacts, including winds, precipitation, and storm surge.
- Reduce uncertainties to the extent possible in the 21st century projections of regional SST patterns and the vertical structure of the atmosphere (temperature, winds, moisture) as these differences can lead to large differences in regional TC projections. This will be a complex task, primarily for the world's major climate modeling centres / groups. The importance of reducing, or at least better quantifying, uncertainties in large-scale climate drivers must be emphasized, and efforts of the larger modeling community to meet this challenge should be encouraged and supported.

7.3 Detection and Attribution of Past Changes

Members and research community are encouraged to conduct further research to :

- Enhance the use of detection and attribution techniques in studies of past TC variations to improve confidence in future projections (see section 7.2 above).
- Develop better estimates of expected levels of internal decadal to centennial scale variability of TC activity for use in climate change detection and attribution studies.
- Continue research to better understand the basic physical mechanisms that cause the observed changes in TC activity (including TC track / genesis position changes) in the basin using statistical and/or modeling approaches.

7.4 Impact Assessments

The Typhoon Committee may consider coordinating efforts by Members to :

- Conduct further research on the observed trends in TC-induced high winds, heavy rain and storm surge.
- Recommend definitions in TC landfall / affecting in the region.
- Set up a more comprehensive database on casualties and economic loss for monitoring any long term trends of TC impacts in the region.

APPENDIX I. SURVEY RESULTS SUMMARY

Table A1 : Climatological mean of landfalling / affecting tropical cyclones

Note : Definitions of landfalling TCs and affecting TCs adopted by Members are summarized in Table A2

Member	Tropical Cyclones		Typhoons		Data Period
	Landfalling	Affecting	Landfalling	Affecting	
China	9 (7*)	14	3	NA	1949-2010
Hong Kong, China	2.5#	6.1	0.8#	2.3	1961-2010
Japan	2.7*	11.4*	1.3**	7.1	1981-2010
Macao, China	NA	1.2	NA	0.9	1971-2010
Malaysia	3-4		1-2		NA
the Philippines	9	NA	4.3	NA	1948-2010
Republic of Korea	0.9	5.5	NA		1951-2010
Singapore	Not directly affected by tropical cyclones, except TS Vamei in 2001				
Thailand	3		<1		1951-2010
United States of America	18-20^		9-10^		1972-2010
Viet Nam	1-2	3-4	NA		NA

* TS or above

** data period from 1986–2010

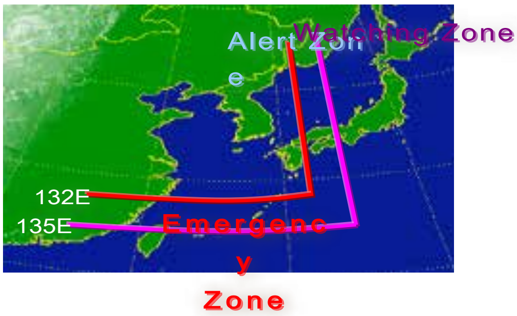
Landfalling within 300 km of Hong Kong (the number of landfalling tropical cyclones and typhoons with the center passing over Hong Kong are 0.3 and 0.2 respectively).

^ Affecting the area of responsibility bounded by 0°–25°N, 130°E–180°.

NA means Information not available from the survey results.

Table A2 : Definitions of landfalling and affecting tropical cyclones

Member	Definitions	
	Landfalling	Affecting
China	Tropical cyclone centre passing both China's mainland and islands. *Note : The number of TS or TY landfalling in China may be influenced by the development of observation network since their intensities at the moment of landfall are determined according to the station observations.*	A tropical cyclone which induces wind or precipitation in China, with at least one station has been observed that (1) either sustained wind at least 13.9 ms^{-1} (Beaufort Scale 7) or wind gusts at least 17.2 ms^{-1} (Beaufort Scale 8), or (2) storm precipitation greater than 50mm, or (3) the storm precipitation greater than 30mm while either the sustained wind at least 10.8 ms^{-1} (Beaufort Scale 6) or wind gusts at least 13.9 ms^{-1} (Beaufort Scale 7). *Note : The annual number of tropical cyclone affecting China may be influenced by development of observation network since the definition of tropical cyclone affecting China is based on station observations.*
Hong Kong, China	(i) The centre of a tropical cyclone passing over any part of the territory of Hong Kong (ii) Since the number of tropical cyclones passing over Hong Kong is small, the number of tropical cyclones making landfall within 300 km of Hong Kong (a tropical cyclone that crosses the coast within 300 km of Hong Kong, including those coming within 300 km of Hong Kong over land after crossing the coast at more than 300 km) is also adopted in some studies to reflect the impact of landfalling tropical cyclones on Hong Kong.	Tropical cyclones entering 500 km range of Hong Kong
Japan	Tropical cyclone centre reaches the coastline of the four main islands; Hokkaido, Honshu, Shikoku or Kyushu.	Tropical cyclone centre comes within 300 km from Japan.

Macao, China	A tropical cyclone that causes Tropical Cyclone Signal No. 8 or above to be hoisted (before 1973, signals 8 NW, 8SW, 8NE and 8 SE was known as signals 5, 6, 7 and 8 respectively). Definition of Tropical Cyclone Signal No. 8: The center of a tropical cyclone is nearing and winds recorded in Macao SAR of the People's Republic of China, from the quarter indicated, may possibly range from 63 to 117 km/h with gusts reaching about 180 km/h.	
Malaysia	A tropical cyclone moves across or make landfall over Malaysia	A tropical cyclone location causes bad weather such as strong wind and high seas over Malaysia water, continuous and widespread heavy rain as well as low humidity and dry weather over Malaysia.
The Philippines	A tropical cyclone touches or step down to any landmass of the country	
Republic of Korea	The centre of tropical cyclones passing over coastal line of Korean Peninsula	The centre of tropical cyclones passing over the area of northward of 28°N and westward of 132°E (see figure below). 
Singapore	Singapore is not directly affected by tropical cyclones.	

Thailand		Tropical cyclones affecting Thailand is the event of a tropical cyclone (such as Depression, tropical storm, typhoon) directly coming onto Thailand or moving pass neighborhood country to Thailand which can then cause damage in Thailand from strong winds / heavy flooding rains / storm surge.
United States of America		Tropical cyclones developing in our area of responsibility (AOR) which is bounded by Eq–25°N, 130°E – 180°. Since the AOR does not contain any large (continental) land masses, any TCs affecting the AOR are those passing close or over one of the numerous islands in the AOR.
Viet Nam	Tropical cyclones' center across the Vietnam boundary	Tropical cyclones with observation wind greater or equal to 12 ms^{-1} (Force 6 in Beaufort scale)

Table A3-1: Changes in tropical cyclone landfalling/affecting frequency, intensity and locations

Member	Frequency and intensity of landfalling/ affecting tropical cyclones	Landfalling locations
China	(i) A slight decreasing trend in the number of landfalling tropical cyclones, but not significant at 5% level. No trend for the number of landfalling typhoons (1949–2006). (Yang et al., 2009) (ii) No significant trend in the numbers and days of tropical cyclones affecting China, but the probability distributions have changed (1955–2006). (Ying et al., 2011a)	Tropical cyclones tend to landfall in south part of East China (1949–2006). (Cao et al., 2006; Yang et al., 2009)
Hong Kong, China	(i) No significant trend for tropical cyclones with centre passing over Hong Kong and landfalling within 300 km of Hong Kong. (ii) The number of TCs entering 500 km range of Hong Kong is decreasing, but the trend is not significant (1961–2010). (Wong and Mok, 2009; Ginn et al., 2010)	NA

Japan	(i) No significant trend for tropical cyclone (TS or above) approaching and hitting Japan (1951–2009). (JMA, 2010) (ii) No observed trend of number of strong tropical cyclones reaching high north latitudes in the northwest Pacific region (1977–2004). (JMA, 2005)	NA
Macao, China	No significant change is observed (1971–2010).	NA
Malaysia	NA	NA
The Philippines	No significant trend for landfalling tropical cyclones (1948–2010). Decreasing trend for the annual number of landfalling/crossing typhoons (1948–2010).	NA
Republic of Korea	(i) The long term landfall trend in Korean peninsula is increasing from 1951-2010, but statistically insignificant. (ii) The frequency of affecting TCs (TS or above) shows an increasing trend after 1980's. The landfall of above TS category is increased whereas the landfall of TD is decreased (1951–2004). (Park et al., 2006; Choi and Kim, 2007) (iii) The frequency of landfall can be categorized in three phase: high phase 1951–1965, low phase 1966–1985, high-phase 1986–2004. (Choi et al., 2010)	The landfall location is showing some trend shifting recently from western coast to southern coast of Korean peninsula (1951–2004). (Choi and Kim, 2007; Choi et al., 2010)
Singapore	Singapore is not directly affected by tropical cyclones.	
Thailand	The frequency of TCs entering Thailand displays a general decreasing trend since mid-1960s	NA
United States of America	NA	NA

Table A3-2: Changes in intensity of high winds and heavy precipitation, and casualties and economic loss

Member	Intensity of high winds and heavy precipitation	Casualties and economic loss
China	(i) High winds: decreasing trends are found on national and subregional scales since dominant decreasing trends are found at the coastline of southeast China (1955–2006). (Ying et al., 2011a; Ying et al., 2011b) (ii) Heavy precipitation events: decreasing trend (1957–2004). (Ren et al., 2006) Precipitation intensity: no significant trends on national and subregional scales, but dominant increasing trends are found in the southeast China (1955–2006). (Ying et al., 2011b)	Casualties: no significant trend. Economic loss: increasing trend with significant contribution from social and economic development. (Lei et al., 2009; Zhang et al., 2009; Xiao and Xiao, 2010)
Hong Kong, China	Annual maximum 10-min mean wind and maximum 1-sec gust (1961–2008): (i) Offshore island (Waglan Island) : no significant trend (ii) Urban station (Kai Tak) : decreasing trend, significant at 5 % level (Wong and Mok, 2009)	Casualties : decreasing trend Damage in monetary terms : large inter-annual variation, no significant trend (1961–2010). (Lam et al., 2011)
Japan	NA	Significant reduction in damages by typhoon in Japan after Typhoon Vera in 1959. (Atsushi Kurashima, 2005)
Macao, China	Periodic change in the maximum wind speed may exist. No significant change in total precipitation is observed (1971–2010).	NA
Malaysia	NA	NA
The Philippines	NA	Total damages brought about by tropical cyclones during the period 2001 to 2005 have increased by 379% for the period 2006 to 2010.
Republic of Korea	There are increasing trend of heavy rainfall due to typhoon landing after later half 1970's (1954-2005). (Kim et al., 2006)	Casualties: no significant trend. Economic loss: increasing trend after 1990's (KMA, 2011)
Singapore	Singapore is not directly affected by tropical cyclones.	
Thailand	NA	NA
United States of America	NA	NA

APPENDIX II. ACRONYMS

ACE	Accumulated Cyclone Energy
AGCM	Atmospheric Global Circulation Model
AOR	area of responsibility
CMA	China Meteorological Administration
CMIP	Coupled Model Intercomparison Project
ENSO	El Niño and Southern Oscillation
ERA	European Centre for Medium-Range Weather Forecasts Re-Analysis
ESCAP	United Nations Economic and Social Commission for Asia and the Pacific
GCM	General Circulation Model
GFDL	Geophysical Fluid Dynamics Laboratory
GHG	greenhouse gas
GPCP	Global Precipitation Climatology Project
HKO	Hong Kong Observatory
HURSAT	Hurricane Satellite Data
IBTrACS	International Best Track Archive for Climate Stewardship
IPCC	Intergovernmental Panel on Climate Change
IPCC AR4	the 4th Assessment Report of IPCC
JMA	Japan Meteorological Agency
JTWC	Joint Typhoon Warning Center
KMA	Korea Meteorological Administration
MCP	Minimum Central Pressure
MRI	Meteorological Research Institute
MSW	Maximum Sustained Wind
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEP	National Center for Environmental Prediction
PAGASA	Philippine Atmospheric, Geophysical, and Astronomical Service Administration
PDI	Power Dissipation Index

RSMC	Regional Specialized Meteorological Center
SMG	Macao Meteorological and Geophysical Bureau
SST	Sea Surface Temperature
STI	Shanghai Typhoon Institute
TCAR1	the first Assessment Report of ESCAP/WMO Typhoon Committee
TCAR2	the second Assessment Report of ESCAP/WMO Typhoon Committee
TCP	Tropical Cyclone Programme
TMD	Thai Meteorological Department
TRMM	Tropical Rainfall Measuring Mission
UW	University of Wisconsin-Madison
WMO	World Meteorological Organization
WNP	western North Pacific
WPR	wind-pressure relationship
WWRP	World Weather Research Programme

ANNEX I COMPARISON OF THE TROPICAL CYCLONE CLASSIFICATIONS INTERNALLY USED BY SOME OF THE TYPHOON COMMITTEE MEMBERS

Maximum Sustained Wind Speed at the centre of the tropical cyclones			Hong Kong, China (10-minute average)	China (2-minute average)	Japan (10-minute average)	US Pacific (1-minute average)	US Atlantic (1-minute average)
kts	km/h	ms^{-1}					
< 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 Very Strong Typhoon 85 – 104 kts Violent Typhoon ≥105 kts	Typhoon 64-129kts Super Typhoon:≥ 130 kts	Hurricane categories 1: 64 – 82 kts 2: 83 – 95 kts 3: 96 – 113 kts 4: 114 – 135 kts 5: >135 kts
81 – 99	150 – 184	41.5-50.9	Severe Typhoon (ST)	Severe Typhoon			
≥100	≥185	≥51	Super Typhoon (SuperT)	Super Typhoon			

Note :
The conversion between kts to km/h and kts to ms^{-1} may vary slightly subject to rounding practices and conversion factor decimal places.

Reference

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