Climate Change and Tropical Cyclone Activity in Western North Pacific

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Background

Against the background of climate change and the economic damage and disruption resulted from tropical cyclones (TC) in the western North Pacific (WNP) basin, it is of great interest and societal importance to understand whether and how climate warming may have already affected TC activity in the basin.

ESCAP/WMO Typhoon Committee formed an expert team to assess the past and future changes of TC activity in the region. The first and second assessments completed in 2010 and 2012 respectively.

The content of this lecture mainly based on the literatures reviewed in the 2nd assessment of Typhoon Committee in 2012 and other relevant research findings published thereafter in last couple of years. However, it is not an exhaustive review of all the studies on this topic.

A quick recap of tropical cyclone facts
1. North Atlantic
2. Eastern North Pacific
3. Central North Pacific
4. Western North Pacific and South China Sea
5. Bay of Bengal and the Arabian Sea (Northern Indian Ocean)
6. Southwestern Indian Ocean
7. Southeastern Indian Ocean
8. Southwestern Pacific
9. Tasman Sea
10. Arafura Sea and the Gulf of Carpenteria
11. Coral Sea
12. Solomon Sea and Gulf of Papua
13. 90° – 125°E and 10°S – Equator

(Source: WMO, TCP)
Some common tracks of Tropical Cyclones in western North Pacific and South China Sea

- Typical track of tropical cyclone causing gales or even hurricane force winds in Hong Kong
- Typical track of tropical cyclone causing strong winds in Hong Kong
- Typical track of tropical cyclones in November or December
- Typical track of recurving tropical cyclone. Tropical cyclones may recurve at any time of the year but those occurring before June or after September generally recurve at lower latitudes.
Tropical cyclone frequency in western North Pacific
The most active basin with about 30 tropical cyclones* each year

(*1971-2000 average, based on HKO data, including tropical depressions)
Major Tropical Cyclone Warning Centers in the western North Pacific

• China Meteorological Administration, Beijing (CMA)
• Hong Kong Observatory, Hong Kong (HKO)
• Joint Typhoon Warning Center, Hawaii (JTWC)
• Tokyo Typhoon Centre of the Japanese Meteorological Agency (WMO Regional Specialized Meteorological Center) (RSMC-Tokyo)

All four agencies have their own best track dataset (post analysis of tropical cyclone position and intensity)
## Classification of Tropical Cyclones of Different Warning Centers in Western North Pacific

<table>
<thead>
<tr>
<th>Maximum Sustained Wind Speed near the centre of the tropical cyclone</th>
<th>Hong Kong, China (10-minute average)</th>
<th>China (2-minute average)</th>
<th>Japan (10-minute average)</th>
<th>United States (1-minute average)</th>
<th>United States (1-minute average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>kt</td>
<td>km/h</td>
<td>m/s</td>
<td>HKO</td>
<td>CMA</td>
<td>RSMC, Tokyo</td>
</tr>
<tr>
<td>&lt; 34</td>
<td>&lt; 63</td>
<td>&lt; 17.1</td>
<td>Tropical Depression (TD)</td>
<td></td>
<td></td>
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<tr>
<td>34 – 47</td>
<td>63 – 87</td>
<td>17.2 – 24.4</td>
<td>Tropical Storm (TS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>48 – 63</td>
<td>88 – 117</td>
<td>24.5 – 32.6</td>
<td>Severe Tropical Storm (STS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>64 – 80</td>
<td>118 – 149</td>
<td>32.7 – 41.4</td>
<td>Typhoon (T)</td>
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<tr>
<td>81 – 99</td>
<td>150 – 184</td>
<td>41.5 – 50.9</td>
<td>Severe Typhoon (ST)</td>
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<td></td>
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<tr>
<td>≥ 100</td>
<td>≥ 185</td>
<td>≥ 51.0</td>
<td>Super Typhoon (SuperT)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Tropical Storm
- Typhoon 64 – 84 kts
- Very Strong Typhoon 85 – 104 kts
- Violent Typhoon ≥ 105 kts
- Super Typhoon ≥ 130 kts

### Hurricane categories
- 1: 64 – 82 kts
- 2: 83 – 95 kts
- 3: 96 – 112 kts
- 4: 113 – 136 kts
- 5: ≥ 137 kts

### Notes
- The conversion between kt to km/h and km/h to m/s may very slightly subject to rounding practices and conversion factor decimal places.
- Acronym: HKO: Hong Kong Observatory; CMA: China Meteorological Administration; RSMC: Regional Specialized Meteorological Centre, Tokyo; JTWC: Joint Typhoon Warning Center; CPHC: Central Pacific Hurricane Center, Hawaii; NHC: National Hurricane Center, Miami.

### References
- WMO Tropical Cyclone Program Operational Plan / Manual (http://www.wmo.int/pages/prog/www/wcp/) operational-plan.html
- Typhoon Committee Operational Manual - Meteorological Component, Appendix 1-A
- Regional Association IV (North America, Central America and the Caribbean) Hurricane Operational Plan
- WMO Severe Weather Information Centre (http://severe.worldweather.org/)
- Hong Kong Observatory, Classification of Tropical Cyclones (http://www.hko.gov.hk/infoweb/class.htm)
Discrepancies among best track datasets

Some sources of the heterogeneity and discrepancy in best track dataset prepared by different agencies in WNP:

- Sources of observational data,
- Operational practices and methods of analysis
- Non-uniform improvements in technologies (remote sensing, observations, etc.)
- Termination of the aircraft reconnaissance in WNP since 1987
- Inherent limitations and the possibilities of misapplication when applying the Dvorak technique
- Different Dvorak look-up table by JMA since 1990 (Koba conversion table)

In particular, the intensity of TCs in JTWC’s best track was generally higher than those from CMA, HKO and RSMC-Tokyo, while the intensity given by CMA and HKO was slightly higher than that of RSMC-Tokyo.
Table 1. CI-number (≥ 2) and corresponding central pressure and maximum wind speed (kt) of tropical cyclone over the western North Pacific. Note that the maximum wind speeds are averaged over 1 minute in Dvorak and 10 minutes in Koba.

<table>
<thead>
<tr>
<th>CI</th>
<th>Central Pressure (hPa)</th>
<th>Max. Wind (kt)</th>
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<tbody>
<tr>
<td>2.0</td>
<td>1003</td>
<td>1000</td>
</tr>
<tr>
<td>2.5</td>
<td>999</td>
<td>997</td>
</tr>
<tr>
<td>3.0</td>
<td>994</td>
<td>991</td>
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<tr>
<td>3.5</td>
<td>988</td>
<td>984</td>
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<td>4.0</td>
<td>981</td>
<td>976</td>
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<td>4.5</td>
<td>973</td>
<td>966</td>
</tr>
<tr>
<td>5.0</td>
<td>964</td>
<td>954</td>
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<td>5.5</td>
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<td>6.0</td>
<td>942</td>
<td>921</td>
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<td>6.5</td>
<td>929</td>
<td>914</td>
</tr>
<tr>
<td>7.0</td>
<td>915</td>
<td>898</td>
</tr>
<tr>
<td>7.5</td>
<td>900</td>
<td>879</td>
</tr>
<tr>
<td>8.0</td>
<td>884</td>
<td>858</td>
</tr>
</tbody>
</table>

Advanced Dvorak Technique–Hurricane Satellite dataset (ADT-HURSAT)

With a view to reducing the TC data inconsistencies, Kossin et al. (2013) re-analyzed satellite imagery and constructed the Advanced Dvorak Technique–Hurricane Satellite dataset (ADT-HURSAT) to obtain a relatively more homogeneous satellite-based estimation of TC intensity in all ocean basins (1978-2009).

The Maximum Sustained Wind in the ADT-HURSAT are available in 3-hourly steps and presented in finer values than those in the common CI conversion tables.

Key activity metrics and impacts of tropical cyclones

**Key activity metrics**
- Occurrence frequency
- Intensity
- Rainfall rate
- Prevailing tracks

**Major Impacts**
- High winds and squalls
- Heavy rain
- Storm surge
- Swells and rough sea

(Photo source: NOAA/NASA CIMSS/SSEC)
Natural variations of tropical cyclone activity

Apart from “climate change”, there are many factors which may modulate the inter-annual and inter-decadal TC activities in the WNP and the South China Sea.

For examples:

• ENSO
• Pacific Decadal Oscillation (PDO)
• Quasi-Biennial Oscillation (QBO)
• East Indian Ocean SST

In gist, these “oscillations” affect the SST and/or atmospheric circulation over the WNP, subsequently affect the steering flow, TC genesis frequency, TC formation locations, chance of intensification, etc.

Andy Zung-Ching Goh and Johnny C. L. Chan, 2010 : Interannual and interdecadal variations of tropical cyclone activity in the South China Sea, 30 (6), 827–843
Spectral analysis of TC activity over WNP

2.4 year peak – Quasi-Biennial Oscillation (QBO)
3-4 year peak – ENSO
18 year peak – Pacific Decadal Oscillation (PDO)

MTM spectrum of the annual number of tropical cyclones in the western North Pacific.

Taking the ENSO as an example:

Genesis position shift to the east

Sub-tropical ridge split into two

Genesis position shift to the west

Sub-tropical ridge continuous

Composite circulation in the late season at 850 and 500 hPa for (top) El Niño, (middle) neutral, and (bottom) La Niña years.
**ENSO and Super Typhoon Activities**

Super typhoon (STY) activity could be related to the ENSO events. Generally speaking, there were more STYs in El Niño years than in La Niña years. Possible causes:

In El Niño (La Nina) years, affected by SST pattern, atmospheric circulation anomaly displaces the breeding ground of TCs in the WNP further east (west). Moving typically west to northwestwards after genesis, TCs forming further east (west) will stay over the oceans longer (shorter) during their lifespan, thereby increasing (decreasing) the chance for them to develop into super typhoons. As a result, there were more STYs in El Niño years, and less in La Niña years.

Weak vertical wind shear, positive low-level vortex and longer developing time are all advantageous to TC intensity in El Niño years.

(Source: Huang and Xu, 2010: Super Typhoon Activity over the Western North Pacific and Its Relationship with ENSO, J. Ocean Univ. China (Oceanic and Coastal Sea Research) 9 (2): 123-128.)
Frequencies and positions of TC formation during the typhoon season for (a) El Nino and (b) La Nina years. The numbers in the top-right corner indicate the TS to TY and STY genesis frequencies in the west and east WNP.

In 2015 (El Niño event), there were altogether 13 super typhoons according to the definition of HKO, eight more than the long-term (1961-2010) yearly average of about five and making it the most active super typhoon year since comprehensive record began in 1961.

Tropical cyclone genesis position in 2015. The shaded area in the background corresponds to the long term average (1961-2010) of tropical cyclone genesis distribution.
Long term variations of tropical cyclone activity in western North Pacific (WNP)
Frequency changes
Annual storm counts in western North Pacific based on the categories assigned according to reported maximum sustained winds converted into 10-min mean

(a) storms of tropical storm intensity and above

(b) storms of typhoon intensity

Trends of annual numbers of tropical cyclones in WNP based on different datasets for all available data up to 2015

<table>
<thead>
<tr>
<th>Datasets</th>
<th>Data Period</th>
<th>Original intensity</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>All TC (tropical storm or above)</td>
<td>Typhoons</td>
</tr>
<tr>
<td>CMA</td>
<td>1949-2015</td>
<td>-0.86/decade</td>
<td>-0.96/decade</td>
</tr>
<tr>
<td>JTWC</td>
<td>1945-2014</td>
<td>+0.13/decade</td>
<td>-0.32/decade</td>
</tr>
<tr>
<td>RSMC-Tokyo</td>
<td>1951-2015</td>
<td>-0.51/decade*</td>
<td>-0.72/decade**</td>
</tr>
<tr>
<td>HKO</td>
<td>1961-2015</td>
<td>-1.43/decade</td>
<td>-0.72/decade</td>
</tr>
</tbody>
</table>

* 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 2015 as MSW data in RSMC-Tokyo dataset only available since 1977.

- Blue = decrease
- Red = increase
- Bold = significant

- Two of the four best track data sets (CMA and HKO) show a significant decreasing trend in the TC (tropical storm or above) frequency over the last five decades or so, while JTWC and RSMC-Tokyo datasets show no significant trend.

- In general, multi-decadal trends in WNP basin-wide TC (tropical storm or above) frequency are highly dependent on which best track dataset is used, on the analysis period chosen, and other analysis details.
Changes in intensity and related metrics
Tropical cyclone intensity

- Significant inter-decadal variations
- Notable discrepancies between datasets from different centers for the WNP basin, in particular for intense typhoons
- After 1987, the RMSC data has less Cat. 4-5 storms, while JTWC data set has more over the same time period.

Integrated Storm Activity Metrics (Power dissipation index (PDI))

- Significant inter-decadal variations
- 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 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.

“PDI in WNP according to data from JTWC (blue) as adjusted by Emanuel (2005), unadjusted data from the RSMC-Tokyo (green), and reanalyzed satellite data from Kossin et al. (2007) (red).

The black curve represents a scaled Jul–Oct SST in the tropical WNP region.
All quantities have been smoothed using a 1-3-4-3-1 filter.”

Trend analysis using the upper 45% of the strongest TCs
(by Kang and Elsner, 2012)

To overcome the wind speed conversion / assessment issues in WNP, the quantile method is adopted to analysis the trend of intense TCs (upper 45%) of JTWC and JMA

The most reliable consensus is considered to be between 1984 and 2010 which shows a significant decreasing trend in the frequency and increasing trend in intensity, implying fewer but stronger TCs in the WNP during the study period.

A contour plot of the correlation values over the domains spanned by threshold Lifetime maximum wind (LMW) speeds from each agency using data over the period 1977–2010 (34 yr). The area of significant correlations at the 5% level is white. Along line A, the average quantile at the 0.55 quantile level in JTWC is 43 m/s, which corresponds to 37 m/s using the JMA data.

Trends of ranked probability per 10 yr for upper 45% storms after the mapping

(Ref: Kang and Elsner, 2012 : Consensus on Climate Trends in Western North Pacific Tropical Cyclones, J of Climate, 25, 7564-7573)
Spatial variations of intensity changes

On spatial variations, Park et al. (2013) investigated the spatial distribution of trends in TC intensity using 5 TC datasets (RSMC-Tokyo, HKO, CMA, JTWC and the ADT-HURSAT) in 1977-2010 and the overlapping latitude-longitude gridding method (Kim et al. 2010). All TC datasets depicted a spatial inhomogenous trends with weakening over the sea areas east of the Philippine (TP) and strengthening in the southern Japan and its southeastern ocean (SJ) region.

Linear trends (ms\(^{-1}\) per decade) of TC intensity during the period 1977-2010. Contours indicate the average of five TC datasets; red and blue colors indicate the number of TC data for which changes are significant with positive and negative signs at the 90% confidence level; dots indicate regions where all five TC datasets show the same sign.

ACCI and trends in intense TCs (1)

Holland and Bruyère (2014) developed an index “Anthropogenic Climate Change Index (ACCI)” – difference between global surface temperatures from ensemble means of model simulations with and without anthropogenic gases included.

Ensemble simulations of annual-mean global surface temperature with (red) and without (blue) anthropogenic gas forcing, together with the observed global surface temperatures (black) based on CMIP3 and CCSM4.

ACCI calculated from the differences between the ensemble annual means.

(Ref : Holland, G. and C. Bruyere, 2014 : Recent intense hurricane response to global climate, Climate Dynamic, 42, 617-627.)
ACCI and trends in intense TCs (2)

Find substantial relationships between ACCI and the observed proportion of very intense TCs (Saffir-Simpson categories 4 and 5) in the IBTrACS data from 1975 to 2010, and similar although smaller trends in the Kossin dataset.

While no change in global cyclone frequency or average intensity was found, but they concluded there has been a substantial increase in the proportion of intense hurricanes/typhoons, both globally and individually in all basins except for the eastern North Pacific.

Relationship of anthropogenic change defined from CMIP3 and CCSM4 with annual proportions of Cat 1–2 and Cat 4–5 hurricanes.
Changes in prevailing track and its influence
Changes in tropical cyclone prevailing tracks

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)

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 changes are shaded.

• Negative trend values over the central South China Sea depict a decrease in the number of the TCs that follow track I
• 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.
• A decrease in westward-moving TCs and an increase in recurving TCs — including those taking tracks toward Japan or the Korean Peninsula.

The prevailing track shift was mainly due to the changes in the mean steering flows. The changes in the mean steering flows are part of a large cyclonic circulation anomaly centered over eastern China. Decreasing trend in tropical cyclone activity 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.

Anomaly in TC track density for 2001-2010. Superimposed is the 500 hPa steering flow anomaly averaged over May-November (unit of ms-1). Anomalies are with reference to the 1961-90 mean. The TC track density is calculated based on the HKO TC dataset and the 500 hPa anomalous flow is drawn from the United States National Centers for Environment Prediction – National Center for Atmospheric Research (NCEP-NCAR) re-analysis data. (Prepared by Lee et al. 2012)

Poleward migration of tropical cyclones

Kossin et al. (2016) studied the TC exposure in the WNP using the four TC datasets of HKO, RSMC-Tokyo, CMA and JTWC from 1980 to 2013. The study showed that there is a poleward shift in the average latitude where TCs reach their lifetime maximum intensity (LMI) in the WNP.

Time series (°lat decade⁻¹) of annually averaged (φ_{LMI}) using best-track data from the four WNP sources - JTWC, JMA, CMA, and HKO—and an ensemble of the four sources. Shading shows 95% confidence bounds.

Kossin et al. (2016) also suggested that the poleward migration in the basin has coincided with decreased TC exposure in the region of the Philippines and South China Sea, including the Marianas, Philippines, Viet Nam and southern China, and increased TC exposure in the region of East China Sea, including Japan and Ryujyu Islands, Republic of Korea, and parts of Eastern China.

Observed WNP TC track density (ensemble-average number of days of exposure per year per 2°X 2° latitude–longitude grid box) in the (a) early and (b) later halves of the observed period 1980–2013, and (c) the difference between them, for the four-source ensemble. (d) Regions where the differences between periods are significant at the 90% confidence level, based on a two-sided Student’s t test, are colored red (blue) where exposure has significantly increased (decreased). Track density values in (a)–(c) are slightly smoothed with linear interpolation for better display clarity.

“Weak” TCs dominating the poleward migration

Further study by Zhan et al. (2017) revealed that the observed poleward migration is largely contributed by “weak” TCs (with maximum sustained surface wind speed less than 33 m s\(^{-1}\)) over the WNP.

- Linked to a significant decreasing trend of TC genesis in the southern WNP (south of 20\(^{\circ}\)N) and a significant increasing trend in the northwestern WNP over the past 30 years.

- Greater sea surface temperature (SST) warming at higher latitudes associated with global warming and its associated changes in the large-scale circulation favor more TCs to form in the northern WNP and fewer but stronger TCs to form in the southern WNP.

Trends in track density (decade-1 in each 5\(^{\circ}\) × 5\(^{\circ}\) latitude-longitude grid box) for all TCs, WTCs, and ITCs over the WNP based on the JTWC best track dataset during 1980–2016. Orange (blue) color indicates areas where the positive (negative) trend is statistically significant at the 90\% confidence level by the \(F\) test.

(Ref : Zhan R.F. and Y.Q. Wang, Weak tropical cyclones dominate the poleward migration of the annual mean location of lifetime maximum intensity of Northwest Pacific tropical cyclones since 1980, J. of Climate, published online. Doi : 10.1175/JCLI-D-17-0019.1)
Intensification of landfalling TCs using JTWC and adjusted JMA dataset

Analysis using adjusted JMA dataset to cater for the changes in the JMA analysis methodology (Mei and Xei, 2016) from 1977 to 2013

Tracks and intensity evolution of typhoons in Cluster 1 – eastern China, Taiwan, Korean and Japan

Annual mean typhoon lifetime peak intensity and annual mean typhoon intensification rate as a function of time from the JTWC (black curve) and adjusted JMA (red curve) data for Cluster 1. Thick dashed lines show linear trends during 1977–2013.

(Ref : Mei and Xei, 2016 : Intensification of landfalling typhoons over the northwest Pacific since the late 1970s, Nature GeoScience, DOI: 10.1038/NGEO2792)
Analysis results for Cluster 2

Tracks of typhoons of Cluster 2 – affecting South China Sea

Annual mean typhoon lifetime peak intensity and annual mean typhoon intensification rate as a function of time from the JTWC (black curve) and adjusted JMA (red curve) data for Cluster 2. Thick dashed lines show linear trends during 1977–2013.

(Ref: Mei and Xei, 2016: Intensification of landfalling typhoons over the northwest Pacific since the late 1970s, Nature GeoScience, DOI: 10.1038/NGEO2792)
Destructiveness of TCs landfalling in China

Li et al. (2017) reveals that TCs making landfall over East China have tended to be more destructive in recent decades (1975-2014), with a significant increase in PDI after landfall. Such an increase in the PDI of TCs landfalling over East China is associated with concomitant enhancement in landfall frequency as well as landfall intensity over East China.

Changes in the PDI of TCs making landfall over South China are less apparent. Composite analysis suggested that the reduction in TC occurrence over South China offsets considerably the positive effects of the intensity and the nonlinear term.

Linear trends of (a) PDI ($10^5$ kt$^3$/decade) for TCs making landfall over East China and the contribution of the (b) frequency effect, (c) intensity effect, and (d) nonlinear effect to the PDI trend during 1975–2014.

Regions with trends that are significant at 90% confidence are shaded by dots.

(Ref : Li, C.Y., W. Zhou, C.M. Shun and T.C. Lee, 2017 : Change in Destructiveness of Landfalling Tropical Cyclones over China in Recent Decades, Journal of Climate, published online, http://dx.doi.org/10.1175/JCLI-D-16-0258.1)
Changes in Tropical Cyclone Rainfall in China

Linear trends in annual (a) and summer (b) mean TC precipitation (mm year⁻¹) and in annual (c) and summer (d) extreme precipitation (mm year⁻¹) for each TC during 1965-2009 with crosses and squares indicating stations that are statistically significant at the 95% level.

Time series of annual average precipitation (mm) for each TC during 1965-2009.

The rainfall variability in Hong Kong is considerably affected by the TC rainfall, which has a decreasing trend in recent decades. Taking out the TC rainfall from the total rainfall reveals that there is an increasing trend in daily rainfall frequency and intensity for non-TC rainfall in Hong Kong.

Annual maximum daily rainfall (mm) and mean daily rainfall intensity (mm/day) associated with (a), (b) total rainfall; (c), (d) TC rainfall; and (e), (f) non-TC rainfall in Hong Kong during 1961–2012.

(Ref: Li et al., 2015: Climatological Characteristics and Observed Trends of Tropical Cyclone–Induced Rainfall and Their Influences on Long-Term Rainfall Variations in Hong Kong, MWR, 143, 2192-2205)
Future projections of tropical cyclone activities in WNP
What will the future hold?

Theoretically, with the climate getting warmer due to climate change, more energy will be available to fuel the storm in the future, especially under suitable dynamical conditions. In the western North Pacific (WNP), a number of model simulations have been conducted by different research groups to investigate the possible effects of climate change on tropical cyclone activities in WNP in the 21st century.

The 2nd Assessment of Typhoon Committee and other recent publications generally suggest that:

• Most model studies suggest a decrease in tropical cyclone frequency in WNP.

• Most of the studies report an increase in the number of intense tropical cyclones and related rainfall rate in the WNP in a warmer climate.

• The possible influence of climate change on the shift of tropical cyclone track and formation location over the WNP is also noted in some studies.

• Sea level rise will likely contribute toward increased storm surge risk.

<table>
<thead>
<tr>
<th>Study reference</th>
<th>Model details</th>
<th>WNP (changes: %, significance in bold)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugi et al. (2002)#</td>
<td>JMA, T106 L21 (~120 km)</td>
<td>-66</td>
</tr>
<tr>
<td>McDonald et al. (2005)* #</td>
<td>HadAM3, N144 L30 (~100 km)</td>
<td>-30</td>
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<tr>
<td>Hasegawa and Emori (2005)#</td>
<td>CCSR/NIES/FRC GC T106 L56 (~120 km)</td>
<td>-4</td>
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<tr>
<td>Oouchi et al. (2006)#</td>
<td>MRI/JMA, T106 L21 (~120 km)</td>
<td>-38</td>
</tr>
<tr>
<td>Stowasser et al. (2007)#</td>
<td>NCAR CCSM2 IPRC regional model (downscaling)</td>
<td>+19</td>
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<tr>
<td>Bengtsson et al. (2007)#</td>
<td>ECHAM5 T213 (~60 km) T319 (~40 km)</td>
<td>-20 (T213) -28 (T319)</td>
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<tr>
<td>Gualdi et al. (2008)#</td>
<td>SINTEX-G coupled model T106 (~120 km)</td>
<td>-20</td>
</tr>
<tr>
<td>Zhao et al. (2009)</td>
<td>GFDL AM2.1, (~ 50 km)</td>
<td>-29 (CMIP3 Ensemble), -5 (CM2.1), -12 (HADCM3), -52 (ECHAM5)</td>
</tr>
<tr>
<td>Sugi et al. (2009)#</td>
<td>JMA/MRI AGCM, (~20km, ~60 km)</td>
<td>-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)</td>
</tr>
<tr>
<td>Murakami and Sugi (2010)</td>
<td>MRI/JMA-AGCM TL95 (180 km), TL159 (120 km), TL319 (60 km), TL959 (20 km)</td>
<td>-18.5 (TL95), -26.0 (TL159), -11.7 (TL319), -26.8 (TL959)</td>
</tr>
<tr>
<td>Murakami et al. (2011b)</td>
<td>MRI--AGCM, (60 km)</td>
<td>+8, -1, -5, -22, -22, -25, -28, -30, -35, -35, -40, -45</td>
</tr>
<tr>
<td>Murakami et al. (2011c)</td>
<td>MRI--AGCM v3.2 and v3.1, (20 and 60 km)</td>
<td>-27 (v3.1 20km), -23 (v3.2 20km), -20 (v3.1 60km), -28 (v3.2 60km)</td>
</tr>
</tbody>
</table>

# Cited in the first assessment report (Lee et al., 2010).
### Summary of projections results of the nine available studies on the WNP TC intensity

(Extracted and simplified based on Table 5.2 of the 2nd Assessment Report)

<table>
<thead>
<tr>
<th>Study reference</th>
<th>Model details</th>
<th>WNP (changes: %, significance in bold)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knutson and Tuleya (2004)#</td>
<td>Regional model downscale (~9km grid) of TCs in idealized (e.g., no shear) environments</td>
<td>+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</td>
</tr>
<tr>
<td>Hasegawa and Emori (2005)#</td>
<td>JMA, T106 L21 (~120 km)</td>
<td>Decrease (all intensity)</td>
</tr>
<tr>
<td>Oochi et al. (2006)#</td>
<td>MRI/JMA TL959 L60 (~20km)</td>
<td>+4.2 (average lifetime MSW) -2.0 (average annual max MSW)</td>
</tr>
<tr>
<td>Stowasser et al. (2007)#</td>
<td>NCAR CCSM2 IPRC Reg. Model downscale (~50km)</td>
<td>+50 (PDI and intensity in July to October)</td>
</tr>
<tr>
<td>Vecchi and Soden (2007)</td>
<td>CMIP3 18 models</td>
<td>+2.9 (-3.1, 12.6) PI</td>
</tr>
<tr>
<td>Emanuel et al. (2008)</td>
<td>(CCSM3, CNRM-Mk3.0, CSIRO-Mk3.0, ECHAM5, GFDL-CM2.0, MIROC3.2, MRI-CGCM2.3.2a)</td>
<td>+4.1 (MSW, PDI)</td>
</tr>
<tr>
<td>Yu et al. (2009)</td>
<td>CMIP3</td>
<td>Pl: +1.3 ms⁻¹ (-0.1 to 2.4 ms⁻¹), i.e., +2.0% (-0.2 to 3.9%). DPI: +2.3% (13 out of 15 models show an increase).</td>
</tr>
<tr>
<td>Murakami et al. (2011a)</td>
<td>MRI/JMA-AGCM (20 km mesh)</td>
<td>+7.4 (East Japan, 95% confidence) +7.2 (West Japan, 95% confidence)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+1.8 (Korea), +4.4 (North China), +1.1 (Central China)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+7.4 (South China, 99% confidence), +1.0 (Taiwan)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+5.8 (Southeast Asia, 90% confidence), +8.7 (Philippines, 95% confidence)</td>
</tr>
<tr>
<td>Murakami et al. (2011c)</td>
<td>MRI-AGCM v3.2 and v3.1 (20 km)</td>
<td>+18.1 (v3.1, mean MSW, 99% confidence) +7.1 (v3.2, mean MSW, 99% confidence)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+15.5 (v3.1, lifetime max MSW, 99% confidence)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+6.2 (v3.2 lifetime max MSW, 95% confidence)</td>
</tr>
</tbody>
</table>

# Cited in the first assessment report (Lee et al., 2010). ** MSW: mean sustained wind speed; MCP: minimum central pressure.
Some TC related rainfall projections assessed during the Typhoon Committee 2\textsuperscript{nd} Assessment

Table 3. Summary of projections of change percentage (\%, significant change is in underlined bold) in the TC-related rainfall for approximately the late 21st century. Some results are shown for multiple-basin estimates that include the WNP basin. The “NH” and “ENP” are acronyms of the Northern Pacific and eastern North Pacific, respectively. See Knutson et al. (2010) for further details.

<table>
<thead>
<tr>
<th>Study reference</th>
<th>Model details</th>
<th>GHG</th>
<th>Global or NH</th>
<th>WNP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hasegawa and Emori (2005)</td>
<td>CCSR/NIES/FRCGC AGCM, T106 (~120km)</td>
<td>5 x 20 years at 1 x CO\textsubscript{2} 7 x 20 years at 2 x CO\textsubscript{2}</td>
<td>–</td>
<td>+8.4 (with radius of 1000km)</td>
</tr>
<tr>
<td>Yoshimura et al. (2006)</td>
<td>JMA GSM9603 AGCM, T106</td>
<td>10 years 1 x CO\textsubscript{2}, 2 x CO\textsubscript{2}</td>
<td>+10 (Global, Arakawa-Schubert, with radius of 300 km) +15 (Global, Kuo, with radius of 300 km)</td>
<td>–</td>
</tr>
<tr>
<td>Bengtsson et al. (2007)</td>
<td>ECHAM5/MPI-OM, ECHAM5; T213 (~60 km), T319 (~60 km)</td>
<td>A1B</td>
<td>+21 (all TCs in NH)</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+30 (TYs in NH)</td>
<td></td>
</tr>
<tr>
<td>Knutson and Tuleya (2008)</td>
<td>GFDL Hurricane model (idealized)</td>
<td>CMIP2+</td>
<td>+22 (Atlantic, ENP, and WNP combined, with radius ~100km)</td>
<td>+ 20 (with radius of ~100 km)</td>
</tr>
<tr>
<td>Gualdi et al. (2008)</td>
<td>SINTEX-G (SXG) AOGCM, T106 (~120 km)</td>
<td>30 years 1 x CO\textsubscript{2}, 2 x CO\textsubscript{2}</td>
<td>+11 (global, with radius of 100 km, time of max winds) +4.9 (with radius of 400 km, time of max winds)</td>
<td>–</td>
</tr>
</tbody>
</table>
**Table 4. Summary of projections of changes in the WNP TC activity regions and track patterns for approximately the late 21st century.**

<table>
<thead>
<tr>
<th>Study reference</th>
<th>Model details</th>
<th>GHG</th>
<th>WNP</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yokoi and Takayabu (2009)</td>
<td>Five CMIP3 models</td>
<td>40 years</td>
<td>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).</td>
<td>Detect TC-like vortex as Yokoi et al. (2009) GP (Emanuel and Nolan, 2004) was used to analyze the environmental conditions</td>
</tr>
<tr>
<td>Kim et al. (2011)</td>
<td>HadCM3 (full dynamics ocean model), HadSM3 (mixed layer ocean model). 1.25°×1.25°, L20</td>
<td>1×CO₂, 1981–2000, 2×CO₂, 20 years</td>
<td>Increase in east of the Philippines in DJFMAM (HadSM3), Increase in the north and east of the genesis center in JJASON (HadSM3)</td>
<td>Seventeen-member ensemble, genesis potential index ConvGP (Royer et al., 1998) is used in assessment.</td>
</tr>
<tr>
<td>Li et al. (2010)</td>
<td>ECHAM5 T319 (~40km)</td>
<td>A1B</td>
<td>TC activity would shift from the western to central Pacific</td>
<td>High resolution model projections</td>
</tr>
<tr>
<td>Murakami et al. (2011a)</td>
<td>MRI/JMA-AGCM (~20 km)</td>
<td>A1B</td>
<td>Eastward shift of two prevailing northward recurving TC tracks during July-October, –44 (for TC frequency approaching coastal regions of the Southeast Asia)</td>
<td>High resolution model projections</td>
</tr>
<tr>
<td>Murakami et al. (2012)</td>
<td>MRI-AGCM v3.2 and v3.1 (20 and 60 km)</td>
<td>A1B</td>
<td>Northward shift of the most intense TC (category 5)</td>
<td>High resolution model projections</td>
</tr>
<tr>
<td>Wang et al. (2011)</td>
<td>CCCma CGCM3.1 GFDL CM2.0 MIROC3.2(medres) HadGE M1 HadCM3</td>
<td>IPCC AR4 1965–1998 (1965–2009) 2001–2040</td>
<td>The increasing TC influence over the subtropical East Asian and decreasing TC activity over the South China Sea will continue through 2040.</td>
<td>Five-point smoothed TC frequency, large scale steering flow and SST, analyzed by the SVD method.</td>
</tr>
</tbody>
</table>
General consensus assessment of the numerical experiments. All values represent expected percent change in the average over period 2081–2100 relative to 2000–2019, under an A1B-like scenario, based on expert judgment after subjective normalization of the model projections. Four metrics were considered: the percent change in (I) the total annual frequency of tropical storms, (II) the annual frequency of Category 4 and 5 storms, (III) the mean Lifetime Maximum Intensity (LMI; the maximum intensity achieved during a storm’s lifetime) and (IV) the precipitation rate within 200 km of storm centre at the time of LMI. (Figure 14-17, IPCC AR5 WG1)
More tropical cyclones in a cooler climate?

The 25 year present climate experiment was conducted using the 60 km resolution MRI-AGCM3.2 with observed SST for the period 1979–2003.

The 4K-cooler (warmer) climate experiment, the SST was uniformly decreased (increased) by 4K globally.

Mean annual global TC numbers in 4K-cooler (warmer) and present climate experiments.

Annual SST frequency distribution at the time and location of TC genesis for observation (green dashed), 4K-cooler climate (blue solid), present climate (green solid), and 4K-warmer climate (red solid).

Projected changes in TC activity in CMIP5 model

Changes in tropical cyclone (TC) frequency under anthropogenic climate change are examined for 13 global models from phase 5 of the Coupled Model Intercomparison Project (CMIP5), using the Okubo–Weiss–Zeta parameter (OWZP) TC-detection method (Tory et al., 2013). Changes in TC frequency are determined by comparing TC detections in the CMIP5 historical runs (1970–2000) with high emission scenario (representative concentration pathway 8.5) future runs (2070–2100).

The eight models with a reasonable TC climatology all project decreases in global TC frequency varying between 7% and 28%.

![Graph showing percentage change in mean TC frequency](image_url)

**FIG. 4.** Percentage change in mean TC frequency between the late-twentieth and late-twenty-first centuries for the CMIP5 models deemed to have reasonable global TC climatology (i.e., within 50% of that observed). Changes that are significant at 95% and 90% confidence levels are indicated by asterisk and plus symbols, respectively.

(Ref: Tory et al., 2013: Projected Changes in Late-Twenty-First-Century Tropical Cyclone Frequency in 13 Coupled Climate Models from Phase 5 of the Coupled Model Intercomparison Project, J of Climate, 26, 9946-9959)
Global Projections of Intense TC Activity for the Late 21st Century from Dynamical Downscaling of CMIP5/RCP4.5 Scenarios by Knutson et al. 2015

Projections indicate fewer tropical cyclones globally in a warmer late-twenty-first-century climate, but also an increase in average cyclone intensity, precipitation rates, and the number and occurrence days of very intense category 4 and 5 storms.

Simulated occurrence of tropical cyclones of at least category-4 intensity for (a) present-day or (b) late-twenty-first-century (RCP4.5; CMIP5 multimodel ensemble) conditions; unit: storms per decade.

(Ref : Knutson et al. 2015 : Global Projections of Intense Tropical Cyclone Activity for the Late Twenty-First Century from Dynamical Downscaling of CMIP5/RCP4.5 Scenarios, J of Climate, 28, 7203-7223)
Tropical cyclone activity (percent change) statistics from downscaling experiments for CMIP5 multimodel ensembles (future vs present day). The future scenarios use RCP4.5 averaged conditions for late twenty-first century and are compared to the “present-day” simulations for 1982–2005 climatological SST conditions.

(Ref : Knutson et al. 2015 : Global Projections of Intense Tropical Cyclone Activity for the Late Twenty-First Century from Dynamical Downscaling of CMIP5/RCP4.5 Scenarios, J of Climate, 28, 7203-7223)
Projection of future changes in the frequency of intense TCs

PD experiments (1979–2003)
GW experiments (2075–2099)

Changes in occurrence frequency (TC days) of tropical cyclones in various intensity categories.
- All tropical storms (cat 0–5),
- Hurricane intensity storms (cat 1–5),
- Major hurricanes (cat 3–5) and
- Very intense tropical cyclones (cat 4–5)

(Ref: Sugi et al., 2016: Projection of future changes in the frequency of intense tropical cyclones, Clim Dyn, DOI 10.1007/s00382-016-3361-7)
Change in steering flow (black vectors) and the associated change in frequency of TC occurrence (shading) compared to the historical run for (a) 2010–39, (b) 2040–69, and (c) 2070–99 derived from the selected model ensemble.

Percentage changes in (a) the lifetime maximum intensity and (b) the number of intense TCs derived from each selected climate model.

(Ref: Wang and Wu, 2015: Influence of Future Tropical Cyclone Track Changes on Their Basin-Wide Intensity over the Western North Pacific: Downscaled CMIP5 Projections, Advances in Atmospheric Sciences, 32, 613–623)
Storm Surge

Storm surge is an abnormal rise of water generated by a storm, over and above the predicted astronomical tide.

Storm tide is the water level rise during a storm due to the combination of storm surge and the astronomical tide.

- **Strong winds piling up the sea water near the coast**
- **Low atmospheric pressure of the tropical cyclone uplifts the sea surface on its path**
Projected maximum storm surges in East Asia with a return period of 100 years

(Ref: Yasuda et al., 2014: Evaluation of future storm surge risk in East Asia based on state-of-the-art climate change projection, Coastal Engineering, 83, 65-71.)
Sea level rise

- Over the period 1901–2010, global mean sea level rose by 0.19m.
- The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia.

(Reference: IPCC AR5 WGI SPM [http://www.climatechange2013.org/]
CU Sea Level Research Group [http://sealevel.colorado.edu/content/global-mean-sea-level-time-series-seasonal-signals-removed])
Sea-level rise will likely make existing storms significantly more damaging, increasing the likelihood of occurrence of extreme sea level due to tropical cyclones (i.e. shorter return period).
Summary (1)

• Existing four best track datasets continue to show significant inter-decadal variations in basin wide TC frequency and intensity in the WNP.

• While most of the best track datasets depicted a decreasing trend in basin wide TC frequency, the observed trend and its statistical significance are still highly depending on which best track dataset is used, on the analysis period chosen and other analysis details.

• For TC intensity, while differences in TC best track datasets for the WNP may cause uncertainty in the detection of a long term trend in this basin, some progress have been made to improve the consensus on this subject in recent years.

• Amid a general decrease in overall TC frequency, a number of studies using various statistical methods to reduce the uncertainty in intensity assessment among datasets suggested an increase in the number and intensification rate for intense TCs, such as Cat. 4-5, in the WNP since mid-1980s.

• Moreover, spatial and cluster analysis of TC intensity depicted inhomogenous trends in different regions of the WNP with an observed intensification of landfalling typhoons since late 1970s.
Summary (2)

- Significant northwestward shift in TC tracks and poleward shift in the average latitude where TCs reach their peak intensity in the WNP since 1980s have also been reported. The prevailing track changes also resulted in an increase in the exposure of TC passage and landfalling in some regions, including eastern China, Japan, and Korean Peninsula in the last few decades.

- Climate models mostly predict a future decreases in global and the WNP TC frequency. Most of the model simulations also report an increase in the number of intense TCs and the TC rainfall rate in the WNP in a warmer climate. Some studies also suggested the observed track changes in the last few decades may continue in the 21st century.

- Sea level rise and more intense TCs will likely contribute toward increased storm surge risk to coastal cities in the future. The combined changes in prevailing track and intensity may have significant implications to the future tropical cyclone risk in some regions in the WNP.

- Recent studies using observational analysis and model simulations also provide better understanding on the possible connections between climate change and TC activities.

- Climate change and tropical cyclone is a topic of on-going research, in particular on attribution and detection, future impacts, and projection uncertainty aspects.