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Third assessment on impacts of climate change on tropical cyclones in the Typhoon Committee Region − Part II: Future projections

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Abstract

This paper assesses published findings on projections of future tropical cyclone (TC) activity in the ESCAP/WMO Typhoon Committee Region under climate change scenarios. This assessment also estimates the projected changes of key TC metrics for a 2 °C anthropogenic global warming scenario for the western North Pacific (WNP) following the approach of a WMO Task Team, together with other reported findings for this region. For projections of TC genesis/frequency, most models suggest a reduction of TC frequency, but an increase in the proportion of very intense TCs over the WNP in the future. However, some individual studies project an increase in WNP TC frequency. Most studies agree on a projected increase of WNP TC intensity over the 21st century. All available projections for TC related precipitation in the WNP indicate an increase in TC related precipitation rate in a warmer climate. Anthropogenic warming may also lead to changes in TC prevailing tracks. A further increase in storm surge risk may result from increases in TC intensity. The most confident aspect of forced anthropogenic change in TC inundation risk derives from the highly confident expectation of further sea level rise, which we expect will exacerbate storm inundation risk in coastal regions, assuming all other factors equal.

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

1. Introduction

This is the second part (part II) of a two-part series which summarizes the third assessment of tropical cyclones (TCs) and climate change in the western North Pacific (WNP) basin. The assessment was requested by the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP) and the World Meteorological Organization (WMO) Typhoon Committee. While part I of the series reviewed the evidence for past trends of TC activity in the WNP and the detection and attribution aspects (Lee et al., 2019), part II assesses the future projections of TC activity in the WNP.

Future changes of TC activity with climate change are a big concern due to the large societal impacts of TCs on coastal communities around the world, especially in the Asia Pacific region. Since the publication of the Second Assessment Report (SAR) on the influence of climate change on tropical cyclones in the Typhoon Committee region (Ying et al., 2012), a number of additional studies of potential changes in TC activity have been carried out, using dynamical models and

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diagnostic approaches. A particular focus has been on the potential influence of anthropogenic global warming on the changes in TC genesis and intensity, as recommended by the Typhoon Committee expert team in 2012. Moreover, in recent years, several new higher resolution dynamical modeling studies have attempted to address the issue on future changes in TCs activity, and confidence in their findings has been enhanced by the use of higher model resolution (requiring more advanced computational resources).

A WMO Task Team on Tropical Cyclones and Climate Change (hereafter referred to as the WMO Task Team) has recently conducted a global assessment of the impacts of climate change on TCs (Knutson et al., 2019a; 2019b). While the focus of that assessment was on global activity, they also prepared some regional TC/climate change assessment statements and summaries for the WNP basin. For TC projections, the WMO Task Team estimated the general range of modeled changes quantitatively by rescaling the raw projections from different studies-which often had assumed different climate change scenarios. All projections were rescaled to be consistent with a 2 °C anthropogenic global warming scenario (Knutson et al., 2019b). In the third assessment for the WNP, our Typhoon Committee Expert Team used the same approach to estimate projected changes of several key TC metrics expected under a 2 °C warming scenario for the WNP (see Section 3).

This paper summarizes key projected changes in TC activity over the WNP, as an update to Ying et al. (2012). Section 2 provides a review of new studies of future projections of TC activity with a special focus on TC frequency, intensity, precipitation rate, shifts in track patterns and storm surge risk in the WNP. Section 3 presents projected changes of several key TC metrics expected under a 2 °C warming scenario for the WNP. Uncertainties in the model projections will be discussed in Section 4. A summary of findings and recommended future studies are included in Section 5.

2. Future TC activity projections in the WNP

2.1. Frequency

Modeling studies published since the previous assessment (in 2012) on the projections of TC genesis/frequency mostly suggest a reduction of TC frequency over the WNP, but a future increase in intense TC proportion. However, there are still individual studies that project an increase in TC frequency or a decrease in intense TC numbers. Specific results of relevant model experiments are summarized in the following paragraphs.

Murakami et al. (2012a) investigated uncertainties in future projected changes in TC activity using ensemble global warming projections under the Intergovernmental Panel on Climate Change (IPCC) A1B scenario for 2075−2099. Their ensemble model experiments were performed using three different cumulus convection schemes and four different assumptions for prescribed future SST patterns. All experiments consistently projected reductions in global and WNP TC frequency. However, TC frequency of occurrence (TCF) and TC genesis frequency (TGF) increased in the central Pacific. Their results implied that differences in SST spatial patterns can cause substantial variations and uncertainties in projected future changes of TGF and TC numbers at ocean-basin scales. In IPCC Fifth Assessment Report (IPCC AR5), Christensen et al. (2013) provided a synthesis of global and regional projections of future TC climatology for 2081−2100 relative to 2000−2019. Globally, their consensus projection was a decrease in TC frequency by approximately 5−30%. Ogata et al. (2016) found that changes of intense TC frequency are not robust to ocean model treatment. By comparing a coupled atmosphere-ocean general circulation model (AOGCM) and atmosphere-only model (AGCM) they found that future climate TC projections are not robust in the region 120−160°E, 25−40°N because of large internal variability there. However, both models showed a significant decrease in TC frequency and an increase in intense TC frequency in the region 120−160°E, 10−25°N. Sugi et al. (2016) projected changes in the frequency of very intense (Category (Cat.) 4−5, $V_{max} \geq 59\,ms^{-1}$) TCs that are not uniform over the globe. The frequency is projected to increase in most regions but decrease in the southwestern part of the WNP. Tang and Camargo (2014) used a ventilation index as a metric to assess possible changes in TC frequency in the Climate Model Intercomparison Project Phase 5 (CMIP5) models. They suggested that by the end of the 21st century there will be an increase in the seasonal ventilation index, implying less favorable conditions for TC genesis or rapid intensification in the majority of TC basins.

With a view to studying the impact of model resolution on high-impact climate features such as TCs, Roberts et al. (2015) simulated 27 years of global TC activity for both the present climate and an end-of-century future climate, at resolutions (grid-spacing) of N96 (130 km), N216 (60 km), and N512 (25 km). In the future climate ensemble, there is a slight decrease in the frequency of TCs in the Northern Hemisphere and a shift in the Pacific with peak intensities becoming more common in the Central Pacific. There is also a change in TC intensities, with the future climate having fewer weak storms and proportionally more stronger storms. Manganello et al. (2014) investigated future changes in the WNP TC activity projected by multidecadal simulations using the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS) at 16-km and 125-km grid spacing. They found that, for the simulations by the higher-resolution version of the IFS there is a significant increase in the frequency of typhoons and very intense (Cat. 3−5) typhoons which is accompanied by a corresponding reduction in the frequency of weaker storms. Wu et al. (2014) simulated present-day (1980−2008) and projected (late twenty-first century; CMIP3 A1B scenario) TC activity in the WNP using an 18-km-grid Geophysical Fluid Dynamics Laboratory (GFDL) regional atmospheric model. The model simulations suggested a weak tendency for decreases (−7%) in the number of WNP TCs and for increases in the more intense TCs. Regionally, the simulations projected an increase in TC activity north of Taiwan, which would imply an increase in TCs making landfall in northern China, the Korean Peninsula, and Japan. Yamada et al. (2017) simulated TCs under present-day and warmer climate conditions using a version of NICAM (Nonhydrostatic Icosahedral Atmospheric Model). Future changes in TC activity and structure were investigated using a 14-km mesh climate simulation. The model projected a decrease in the global frequency of TCs by 22.7% (a decrease of 11.2% in the WNP) under warmer climate conditions. Satoh et al. (2015) further investigated the mechanisms for the reduction in the global frequency of TCs under global warming. Simulation results obtained by using the 14 km mesh global nonhydrostatic model (NICAM) showed that the reduction in the global frequency of TCs is much larger than that of the total tropical convective mass flux. This study suggested the importance of the changes in the intensities of TCs in explaining the future changes of TC frequency in the model.

Knutson et al. (2015) adopted a regional nested dynamical downscaling approach to investigate the response of TCs to a climate change scenario obtained from a multi-model ensemble of CMIP5 models (the Representative Concentration Pathway 4.5 (RCP4.5) scenario) in all basins. The features of the late-twenty-first-century projected changes include a substantial reduction in global TC frequency (−16%), but an increase in the frequency of the most intense storms (+28% for Cat. 4−5 and + 59% for TC with maximum winds exceeding 65 ms^{-1}), but there were not significant changes projected for the WNP. Murakami et al. (2014) examined 25-yr present-day simulations and future projections for the last quarter of twenty-first century obtained from 10 Meteorological Research Institute (MRI) AGCMs under the A1B scenario and 11 CMIP5 models under the RCP4.5 and RCP8.5 scenarios using in each case a pair of simulations (a present day simulation (1979−2003) and a global-warmed future projection (2075−99)). Overall, the models projected statistically significant decreases in basin-total frequency of occurrence of TCs and TC genesis frequencies globally (by −15% to −29% for A1B; by −6% to −23% for RCP4.5; and by −13% to −40% for RCP8.5). Tsou et al. (2016) simulated tropical storm (TS) activity using a version of the HiRAM model with 20-km grid-spacing, focusing on the WNP and Taiwan/East Coast of China (TWCN) at the present time (1979−2003) and future climate (2075−2099) under the RCP 8.5 scenario. During 2075−2099, both TS genesis numbers and TS frequency over the WNP and TWCN are projected to decrease consistent with the IPCC 5th assessment report (AR5). However, the rate of decrease (−49%) is much greater than that projected in IPCC AR5.

Tory et al. (2013a) examined changes in TC frequency under anthropogenic climate change using an Okubo−Weiss−Zeta parameter (OWZP) TC-detection method with a selection of CMIP3 models. They reported a global reduction of TCs between about −6% and −20%, with a much larger spread of results (about +20% to −50%) in individual basins. Further study by Tory et al. (2013b) using CMIP5 models reported that the eight models with a reasonable TC climatology all projected decreases in global TC frequency varying between −7% and −28%.

Camargo et al. (2014) concluded that many genesis indices developed for the present climatology are not able to capture the reduction of global TC activity in a warmer climate, at least within the context of the GFDL HiRAM (High Resolution Atmospheric Model). They tried to gain further insights into the reasons for the global mean decrease in TC number in the model using SST changes derived from greenhouse gas−forced warming scenarios. Their results suggested that the reductions in global TC frequency in warmer climates simulated by GFDL HiRAM are attributable to increasing saturation deficits, as temperature increases while relative humidity stays approximately constant. This effect is partially offset by increases in potential intensity (PI), which reduces the magnitude of the decrease in TC frequency.

Mori et al. (2013) performed ensemble numerical experiments of near-future projections in the WNP targeted for the period of 2016−2035, using three versions of a coupled atmosphere-ocean global climate model, the Model for Interdisciplinary Research on Climate (MIROC). Near-future projections (2016−2035) indicated significant reductions (approximately −14%) in TC number, especially over the western part of the WNP, even under scenarios with less prominent global warming than that at the end of this century. Zhang and Wang (2017) studied the late twenty-first-century changes of tropical cyclone activity over the WNP under global warming conditions using WRF-ARW with an improved cumulus parameterization scheme. Future projections under the RCP4.5 and RCP8.5 scenarios suggested an overall reduction of TC genesis frequency over the western part of the WNP. Similar changes are found for the frequency of TC occurrence and the accumulated cyclone energy (ACE).

In contrast to other studies which generally project a reduction in TC frequency in WNP, by applying a statistical/dynamical tropical cyclone downscaling technique to six CMIP5 global climate models running under historical conditions and under RCP8.5 scenario, Emanuel (2013) projected a large increase in global TC activity, most evident in the North Pacific region. However, this result for CMIP5 models contrasted with that obtained by applying the same downscaling technique to CMIP3 models, which generally projected a small decrease of global TC frequency. Moreover, Park et al. (2017) showed that an ensemble mean of CMIP5 models projects an increase in TC activity in the WNP under the RCP8.5 scenario, which is due to enhanced subtropical deep convection and favorable dynamic conditions therein in conjunction with an expansion of the tropics. Zhang et al. (2017) also found that, under global warming, the TC-track density and PDI both exhibited robust and significant increasing trends over the North Pacific basin, especially over the central subtropical Pacific, and the positive trends are more significant in the RCP8.5 experiments than in the RCP4.5 experiments. The increase in North Pacific TCs is primarily manifest as increases in both the intense and the relatively weak TCs, whereas there is only a slight increase in the number of moderate TCs.

2.2. Intensity

Most TC intensity projections using relatively high resolution models (60 km grid or finer grid spacing) agree on an increase in the intensity of strong TCs by the late 21st century in response to projected 21st century warming. In the IPCC AR5 (Christensen et al., 2013) the consensus A1B-like scenario late 21st century projection was for an increase (0 to +25%) in the global frequency of categories 4 and 5 storms, with an increase of a few percent in typical lifetime maximum intensity.

Tsuboki et al. (2015) analyzed to what extent the intensity of super typhoons in the WNP could change in the globally warmed climate of the late 21st century by re-simulating a series of historical cases using altered environmental conditions. High resolution downscaling experiments using a 20 km mesh MRI-AGCM for twelve super typhoon cases revealed that the super typhoons for the present climate simulation attained an average central pressure of 877 hPa and an average maximum surface wind speed of 74 ms^{-1}. In comparison, the super typhoons under warmer climate conditions attained average wind speeds of 88 ms^{-1} and minimum central pressures of 857 hPa.

Mei et al. (2015) developed a statistical projection using an observation-based regression model that considers both the effects of SST and subsurface stratification and found that upper ocean temperatures in the low-latitude northwestern Pacific (LLNWP) and SSTs in the central equatorial Pacific control the seasonal average lifetime peak intensity by setting the rate and duration of typhoon intensification, respectively. Continued LLNWP upper-ocean warming as predicted under a moderate (RCP4.5 scenario) is expected to further increase the average typhoon intensity by an additional 14% by 2100. Knutson et al.'s (2015) CMIP5 multimodel dynamical downscaling study projected an increase in average TC intensity both globally and in the WNP. They also projected an increase the number and occurrence days of very intense category 4 and 5 storms, globally, but with no significant change in the WNP. Tsou et al. (2016), using 20 km grid-spacing model, projected that for the late 21st century (RCP8.5 scenario) TS intensity would increase. Wu et al. (2014), using an 18-km-grid model, projected a weak tendency for increases in the frequency of more intense WNP TCs. Averaged ACE of individual events is expected to increase 5.6%, and the model projected enhancements of the mean TC intensity for both lifetime-mean maximum wind speeds (1.4% increase) and lifetime-maximum wind speed (2.6% increase). Yamada et al. (2017), using a 14-km mesh model, projected that the ratio of intense TCs increases by 6.6% globally (and increases by 17.8% in the WNP) under warmer climate conditions. Manganello et al. (2014) suggested that, for the higher-resolution version of the IFS model simulations, the frequency of typhoons and very intense (Cat. 3–5) typhoons increases significantly in the future climate scenario and this change is accompanied by a reduction in the frequency of weaker storms.

Using Super Typhoon Haiyan (2013) as a case study, Nakamura et al. (2016) explored potential future typhoon intensity and storm surges around the islands of Samar and Leyte in the Philippines, taking into account monthly mean sea surface temperatures (SST), atmospheric air temperature (AAT), and relative humidity (RH) from MIROC5 according to four RCP scenarios proposed by IPCC AR5. Accounting for all of these factors, the intensity increased, with a MSLP decrease of −13 hPa. The results of this study supported earlier studies that found that while increases in SSTs can contribute to the intensification of future typhoons, when other associated environmental changes (increases in tropospheric temperatures and relative humidity) are included, the intensification of TCs is moderated compared to the case of SST warming in isolation.

2.3. Precipitation rates

Kanada et al. (2013) studied composite patterns of hourly TC-related precipitation projected by 20 km mesh MRI-AGCM and 2 km mesh non-hydrostatic model for the present-day and future climate. They simulated smaller radii of azimuthally averaged maximum precipitation in the future climate than in the present-day climate, and the hourly precipitation exceeding 50 mm h^{-1} was concentrated in a narrow region within a radius of 60 km in the future climate. In addition, their simulations included spirally elongated precipitation patterns, with rainfall rates exceeding 10 mm h^{-1} south of the TC center in the future climate. As projected by a CMIP5 13-model ensemble under the RCP4.5 scenario, Knutson et al. (2015) reported a pronounced increase in TC precipitation rates in the warmer climate, including in the WNP basin. The physical mechanism suggested by the results is that enhanced tropospheric water vapor in the warmer climate enhances moisture convergence and thus TC rainfall rates. Villarini et al. (2014) simulated an increase in TC rainfall rates on the order of 10–20% globally in response to a uniform increase of 2 K in SST (both alone and in combination with CO_2 doubling) using a set of idealized high-resolution atmospheric model experiments.

Tsou et al. (2016), using a 20 km grid atmospheric model, projected that the late 21st century (RCP8.5) mean precipitation rate within 200 km of the storm center at LMI time (LMI; the maximum intensity achieved during a storm's lifetime) over the WNP at the end of the 21st century would increase by 22% (RCP8.5 scenario). The projected increase around Taiwan and East Coast of China was even larger (+54%) at the end of the 21st century. Yamada et al. (2017) projected that the precipitation rate within 100 km of the TC center increased by 12% under warmer climate conditions.

Utsumi et al. (2016) analyzed the relative contributions of different weather systems (i.e., TCs, extratropical cyclones including fronts, and others) to changes in annual mean and extreme precipitation in the late 21st century using multimodel projections of CMIP5. According to the models, total precipitation from TCs decreases (increases) in the tropics (subtropics). In contrast, an increase in rainfall rates associated with individual TCs is a common response of numerical models under greenhouse warming (Knutson et al., 2013; Kim et al., 2014; Villarini et al., 2014). Projected increases in TC rainfall typically range from −1% to 20% across different TC basins in the downscaling study (RCP4.5 late 21st century scenario) by Knutson et al. (2015) with relatively large changes (around +20%) in the WNP basin. In addition, the quantitative changes will also depend on the details of the TC precipitation metric chosen and on the particular future emission scenario assumed.

2.4. Shifts in track pattern and landfalling

Using a high-resolution global climate model for a suite of future warming experiments (2075—2099), Murakami et al. (2013) projected an increase in future TC occurrence around the Hawaiian Islands. They concluded that the substantial increase in the likelihood of TC frequency is primarily associated with a northwestward shift of TC tracks over the ocean southeast of the islands. Wu et al. (2014) projected a weak (80% significance level) tendency for WNP TC activity to shift poleward under global warming. Lok and Chan (2017) simulated the number of TCs making landfall in South China using a nested regional climate/mesoscale modelling system and projected a northward migration of TC activity in the WNP throughout the twenty-first century. Their study also projected fewer but more intense landfalling TCs in South China for the late twenty-first century. Projections of WNP TCs simulated by, and downscaled from, an ensemble of numerical models from CMIP5 by Kossin et al. (2016) showed a continuing poleward migration over the twenty-first century using the projections under the RCP8.5 scenario. The projected migration causes a shift in regional TC exposure that is similar in pattern to the past observed shift which is robust in the WNP Ocean.

Manganello et al. (2014) projected that in a future climate scenario, a southward (southwestward) shift of the main genesis region takes place in the T1279 (T159) IFS, with a smaller and less significant increase in the genesis density over the South China Sea. These changes are consistent with a small change in the basinwide seasonal mean TC frequency in both models. Colbert et al. (2015) explored the impact of natural and anthropogenic climate change on TC tracks in the WNP using a beta and advection model (BAM). The BAM captured many of the observed changes in TC tracks due to El Niño—Southern Oscillation (ENSO). Potential changes in TC tracks over the WNP due to anthropogenic climate change were also assessed for 17 CMIP3 models and 26 CMIP5 models. Statistically significant decreases (by −4 to −6% in westward moving TCs) and increases (5—7% in re-curving ocean TCs) were found. Wang and Wu (2015) assessed future track and intensity changes of TCs based on the projected large-scale environments for the 21st century from a selection of nine CMIP5 climate models under the RCP4.5 scenario. The projected changes in mean steering flows suggested a decrease in the occurrence of TCs over the South China Sea area with an increase in the number of TCs taking a northwestward track. There was also considerable inter-model variability in the changes in prevailing tracks and their contribution to the basin-wide intensity changes. Nakamura et al. (2017) analyzed the WNP TC model tracks in two large multimodel ensembles and identified two potential changes in track types in a warming climate. The first is a statistically significant increase in the north-south expansion, which can also be viewed as a poleward shift, as TC tracks are prevented from expanding equatorward due to the weak Coriolis force near the equator. The second change is an eastward shift in the storm tracks that occurs near the central Pacific, indicating a possible increase in the occurrence of storms near Hawaii in a warming climate.

2.5. Sea level rise and storm surge

‘Sea level rise and TC-induced storm surge can cause extreme economic damage and loss of life. Mase et al. (2013) and Yasuda et al. (2014) explored future storm surge risk in East Asia using the results of MRI-AGCM to directly force a storm surge simulation model. The simulation suggested that there will be slight change in the location of severe storm surges in the Yellow Sea, moving from Bohai Bay to the Shandong Peninsula. The East China Sea is projected to remain a vulnerable area due to a significant number of intense TCs passing through it in the future climate. Neumann et al. (2015) assessed future population change in the low-elevation coastal zone and trends in exposure to 100-year coastal floods based on four different sea-level and socio-economic scenarios and showed that the number of people living in the low-elevation coastal zone, as well as the number of people exposed to flooding from 1-in-100 year storm surge events, is highest in Asia. China, India, Bangladesh, Indonesia and Viet Nam were estimated to have the highest total coastal population exposure in the baseline year and this ranking was expected to remain largely unchanged in the future. Hoshino et al. (2016) explored inundation risk in different areas of Japan due to the impacts of future sea level rise and increase in the intensity of TCs and concluded that the level of defenses around many areas of Tokyo Bay could be inadequate by the end of the 21st century.

Vitousek et al. (2017) used extreme value theory to combine sea-level projections with wave, tide, and storm surge models to estimate increases in coastal flooding at a global scale. They found that regions with limited water-level variability, i.e., short-tailed flood-level distributions, located mainly in the Tropics, will experience the largest increases in flooding frequency. They concluded that the 10—20 cm of sea-level rise expected no later than 2050 will more than double the frequency of extreme water-level events in the Tropics, impairing the developing economies of equatorial coastal cities and the habitability of low-lying Pacific island nations. The review by Woodruff et al. (2013) also highlighted that, although sea level rise rates, storm intensification, and time periods differ among previous studies, the general consensus is for an increase in future extreme flood elevations. They concluded that increasing rates of sea level rise will cause increased flooding by TCs, and that future storm damage will be greatest not where TC activity is the highest, but rather where rapidly evolving coastlines and increasing coastal populations greatly enhance storm impacts.

Lloyd et al. (2016) explored the influences of climate change-associated sea-level rise and socioeconomic development on future storm surge mortality risk using a statistical global-level storm surge mortality risk model under the A1B scenario. They suggested that climate change is expected to increase storm surge mortality risk, with the impacts concentrated in regions such as South and South-East Asia. However, given the lack of model validation and the unreliability of the mortality estimates, they pointed out that the projections are best interpreted qualitatively. Moreover, the plausible increase in TC induced extreme wind waves due to the projected increase in TC intensity may further aggravate the impacts of storm surge and sea level rise on coastal structures (Timmermans et al., 2017, 2018).

Nakamura et al. (2016) projected future changes in storm surge due to TC intensification using a regional model simulation of Super-typhoon Haiyan (2013) as input to a separate off-line storm surge model. When they re-simulated Haiyan using modified boundary conditions based on a late 21st century RCP8.5 scenario of the MIROC5 climate model, their downscaling model projected a 0.7 m increase in storm surge, associated with a more intense typhoon (13 hPa lower central pressure).

2.6. Casualties and economic losses

Ranson et al. (2014) assessed existing studies of future tropical and extratropical cyclone damages under climate change, where they considered monetary damages and unmonetized “loss potential” damages, but excluded mortality. They formed an ensemble of 478 estimates of temperature-damage relationships from existing studies, and estimated a probability distribution for the dependence of future storm damages on atmospheric temperatures. Their framework suggested that a 2.5 °C increase in global surface air temperature would lead to a 28% increase in TC damages in the WNP. Gettelman et al. (2018) projected future TC damage with a high resolution global climate model (CLIMADA) in the different regions (US, Central America and Caribbean, East Asia, Indian Ocean and Pacific Islands). According to their study, the East Asia region is projected to experience a large increase in storm damage with future storms.

3. Assessment for the WNP by a WMO Task Team on TCs and climate change

A WMO Task Team has recently conducted an assessment of tropical cyclone/climate change projections similar to our assessment for the WNP, but from a global perspective (Knutson et al., 2019b). For TC projections, in addition to attempting to establish the sign of future change compared to present-day, the WMO Task Team also presented quantitative ranges of projected changes for a 2 °C anthropogenic warming scenario. For these quantitative ranges, they rescaled the various raw projections from existing studies (which had used a range of different climate change scenarios, including IPCC A1B, RCP4.5, RCP8.5, and 2xCO2). The rescaling attempted to make all projections roughly compatible with a 2 °C anthropogenic global warming scenario. For example, for the IPCC AR4 A1B scenario, Knutson et al. assumed a global mean temperature change of 2.65 °C, based on Table 10.5 of IPCC et al. (2007). Then all A1B scenario TC projections were rescaled by the factor 2.0/2.65 to be approximately consistent with a 2 °C global warming scenario. Similarly, for IPCC AR5, the previously published RCP4.5 and RCP8.5 scenario TC projections were rescaled using factors of 2.0/1.8 (RCP4.5) and 2.0/3.7 (RCP8.5), respectively, as adopted from Table SPM.2 of IPCC (2013). The use of this approximate rescaling method introduces some additional uncertainty into the projections, although these additional uncertainties are very likely smaller than the large uncertainties already present associated with the projections obtained from different studies.

Also, to provide some context on the approximate timing of a 2 °C global warming, Knutson et al. (2019b) noted that CMIP5 models on average project a 2 °C global warming, relative to 1986−2005, by around year 2055 under the RCP8.5 scenario, while IPCC AR5 concluded with medium confidence that 21st century global warming will remain below 2 °C for the RCP2.6 scenario (IPCC, 2013). We note that the 2 °C global warming projections in Knutson et al. (2019b) and our current report can be rescaled to other global warming levels (e.g., 1.5 °C, 3 °C) using the ratio of these warming levels to our 2 °C benchmark, since that level of approximation is already present in our rescaled results.

Based on the rescaled analyses, Knutson et al. (2019b) concluded that a 2 °C anthropogenic global warming is projected to impact TC activity at the global level as follows:

i) The most confident TC-related projection is that sea level rise accompanying the warming will lead to higher storm inundation levels, assuming all other factors are unchanged.
ii) For TC precipitation rates, there is at least medium-to-high confidence in an increase globally, with a median projected increase of 14% (range 6−22%).
iii) For TC intensity, there is at least medium-to-high confidence that the global average will increase. The median projected increase in lifetime maximum surface wind speeds is about 5% (range 1−10%).
iv) For the global proportion of TCs that reach very intense (Cat. 4−5) levels, there is at least medium-to-high confidence in an increase, with a median projected change of +13%.

Confidence levels were relatively lower for the following three projections:

v) a further poleward expansion of the latitude of maximum TC intensity in the WNP;
vi) a decrease of global TC frequency, although this is projected in most current studies; and
vii) a global increase in very intense TC frequency (Cat. 4−5), as is seen most prominently in higher resolution models.

In our current assessment for the WNP, our Expert Team also estimated the projected changes of several key TC metrics in the WNP basin under a 2 °C anthropogenic global warming scenario. For this purpose, we used the approach and relevant data from the assessment of Knutson et al. (2019b) as well as a few additional relevant studies for the WNP region. Our quantitative estimates of the projected changes for TC frequency, TC intensity, frequency/proportion of very intense (Cat. 4−5) TCs, and TC precipitation rates for the WNP are summarized in Fig. 1 and Tables S1 to S5 of the supplementary information. The projections of these metrics for the WNP are generally consistent with the corresponding assessment for the WNP contained in Knutson et al. (2019b). Further details of the projections based on the 2 °C warming assessment for WNP are summarized below:

(a) TC frequency

Among the 140 estimates for the WNP, the median change of TC frequency is about − 10% with a 10th − 90th percentile range of −26% to +11%.

(b) TC intensity

The median change of TC intensity across the 26 estimates for the WNP is about +5% with a 10th − 90th percentile range of +2% to +9%, and with a large majority of models projecting an increase in the TC intensity.

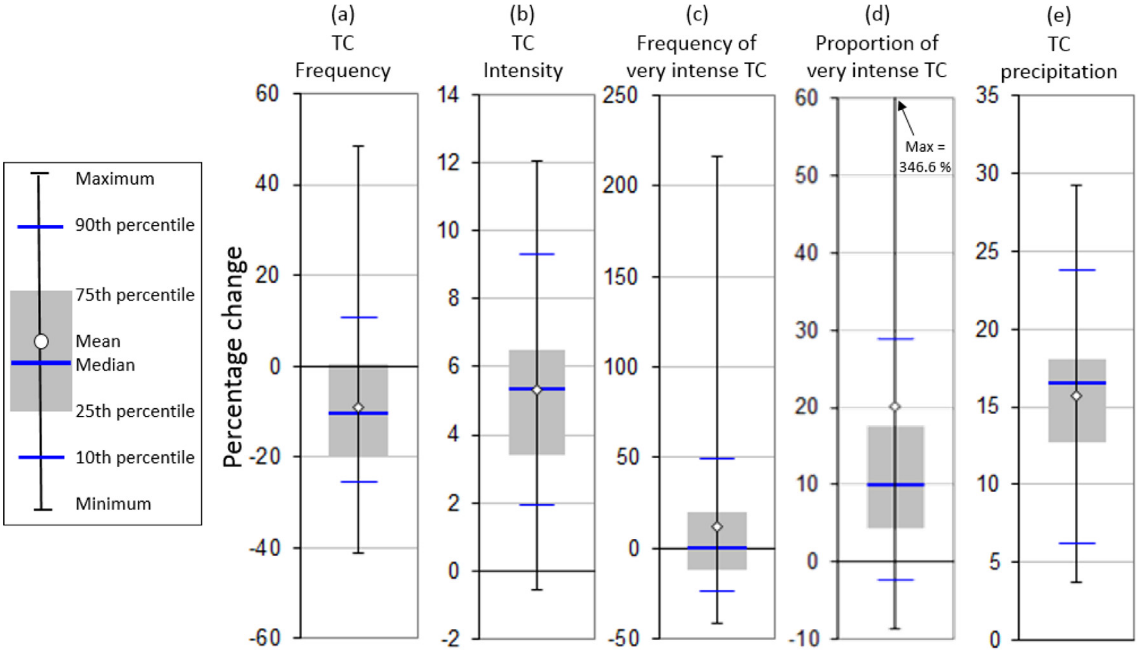
(c) Frequency and proportion of very intense TCs (Cat. 4−5)

The median change in Cat. 4−5 TC frequency across the 37 available estimates for the WNP is about 0% with a 10th − 90th percentile range of −24% to +50%. This suggests no clear tendency in the sign of change in very intense TC frequency, compared with the overall TC frequency in (a). As pointed out by Knutson et al. (2019b), most of the decreased very intense TC frequency projections are from relatively coarse resolution models.

We also examined the change in proportion of very intense TCs, which removes the influence of the overall decrease in TC frequency. Available model projections across 37 estimates suggest that there is a clear tendency for an increase, with a median change of about +10%, and a 10th to 90th percentile range of −2 to +29%. This generally agrees with the global findings for this metric by the WMO Task Team (global projected change of about +13%), but for the WNP projection there is slightly more uncertainty regarding the sign of change.

(d) TC precipitation

Among the 16 estimates for the WNP, the median change is about +17% with a 10th − 90th percentile range of +6% to +24%. All estimates are positive, suggesting a robust tendency for a projected increase in TC precipitation rates in studies to date.



Maximum	48.3	12.1	216.2	346.6	29.2
90th percentile	10.6	9.3	49.6	28.8	23.8
75th percentile	0.4	6.6	20.0	17.7	18.3
Median (Mean)	-10.3 (-8.9)	5.3 (5.3)	0.0 (12.3)	10.0 (20.2)	16.5 (15.7)
25th percentile	-20.0	3.2	-12.1	3.9	12.1
10th percentile	-25.5	1.9	-23.5	-2.3	6.3
Minimum	-41.3	-0.5	-41.1	-8.8	3.7
No. of estimates	140	26	37	38	16

Fig. 1. Summary distributions for the WNP of projected changes in (a) TC frequency, (b) TC intensity, (c) frequency of very intense TCs (Cat. 4−5), (d) Proportion of very intense TCs (Cat. 4−5) and (e) near-storm TC precipitation rates. The table below the diagrams gives the values of the box and whisker plots.

4. Uncertainties

This section outlines some of the uncertainty sources for the projections of TC activity using numerical and empirical models. Understanding and considering these uncertainty sources is important for climate change assessment. We emphasize that discussion of the uncertainties in climate change does not imply that existing climate change research is of little value for decision making. Rather this can help with the assessment of the quality of each projection covered by assessment and helps us evaluate existing studies more comprehensively and appropriately.

4.1. Future trend

One way to anticipate future trends in TC activity due to climate change is to identify and detect emerging human-induced trends in the historical TC observational data. Alternatively, model simulations and projections provide a means to quantify potential future TC changes under certain assumptions about future climate forcing and climate change. Such simulations or projections are typically based on numerical models. Due to difficulties in directly solving complex systems of dynamical equations and limitation in understanding of various physical processes of the climate system, numerical models will include various hypotheses and parameterization schemes. These simplifications, in turn, cause discrepancies between the modeled climate and the real-world climate, especially as related to dynamical and moisture processes (e.g. Shepherd, 2014).

For TCs, the presently known uncertainty sources include model resolution, parameterization schemes for convection, future SST pattern uncertainty, and a variety of other related environmental climate parameters (e.g. global temperature sensitivity, lapse rate changes, changes in the vertical temperature gradient in the upper ocean, atmospheric circulation changes, etc.), as well as TC detection schemes applied to model data (Horn et al., 2014; Murakami et al. 2012a, 2012b; Walsh et al., 2016; Wehner et al., 2015). Due to differences among models and post-processing approaches, biases relative to TC observations may be found in metrics such as annual TC numbers, tracks, intensities, duration, size, precipitation rates, and other metrics (Camargo and Wing, 2016; Gettelman et al., 2018; Walsh et al., 2016). The fidelity of the relationship between simulated TCs and the simulated environments is another source of uncertainty (Camargo et al., 2007; Wehner et al., 2015). This implies that an evaluation of confidence in simulated or projected TC activity should consider not only a model's performance in reproducing the large-scale air-sea system, but also to what extent a given model simulates or includes the important physical processes that operate in the real climate. These are highly dependent on our understanding of the physics of natural and anthropogenic climate change.

Moreover, as Wehner et al. (2015) suggested, “projections of future tropical cyclogenesis obtained from metrics of model behavior that are based solely on changes in long-term climatological fields and tuned to historical records must also be interpreted with caution”. In other words, empirical TC genesis potential indices based on historical observations should be applied to the projection of numerical models with caution, since the simulated relationship between TCs and various environmental factors was reported to be different from one model to the next (Camargo et al., 2007), and may also not be stationary across different climate states. An advantage of dynamical approaches (e.g., Wehner et al., 2015; Knutson et al., 2008) is that the physics within the model is designed to consistent across different climate states and leads to a dynamically based prediction of the change in TC genesis in the altered climate state. However, dynamical modeling approaches contain other assumptions (limited model resolution, treatment of TC-ocean interaction, physics parameterizations, etc.). Regardless of the approach used, one should carefully examine and evaluate the reasonableness of any assumptions of particular technique, because such assumptions may introduce uncertainties (e.g., Walsh et al., 2016; Tory et al., 2014).

As compared with results for global TC activity, researchers found an even larger divergence of results between model projections for some metrics for individual basins (Camargo, 2013). Bacmeister et al. (2018) suggested that the large uncertainties of projected basin-scale TC activity, which were as large as the effects of using an RCP8.5 vs. RCP4.5 scenario (van Vuuren et al., 2011), can be attributed to uncertainties in future SSTs. Nakamura et al. (2017) suggested that projected changes in future TC track patterns were model- and scenario-dependent, and they emphasize the importance of multi-model ensembles for more robust future projections.

4.2. Precipitation

Advances were reported in reducing precipitation uncertainties in CMIP5 models as compared to CMIP3 models (Woldemeskel et al., 2016). However, Woldemeskel et al. (2016) also found large uncertainties in heavy rain regions, as well as mountainous and coastal areas. Despite this, as indicated in Section 3, there is a strong consensus among available TC projection studies that rainfall rates of TCs will increase in a greenhouse warmed climate. The potential uncertainty sources for TC rainfall include the contribution of uncertainties in SST patterns, locations of convection and convergence associated with the SST patterns, and land-sea thermal contrasts (Endo et al., 2017; Kent et al., 2015). For example, Knutson et al. (2015) reported no significant change in projected TC precipitation rates in the southwest Pacific basin, which they noted was the basin with the smallest projected SST increase of any TC basin. This suggests the potential importance of SST pattern changes for TC rainfall rate responses at the regional scale. Recently, Kendon et al. (2017) suggested that the changes in rainfall intensity in general (not just for TCs), as well as daily and hourly rainfall extremes, show remarkable differences in summertime projections between coarse- and high-resolution models in which cumulus convection was treated differently.

4.3. Storm surge

Storm surge and ocean models are usually driven by atmospheric winds, pressure fields, air-sea fluxes of moisture and so forth. One of the challenging issues is adequately specifying these driving forces under TC conditions, which introduces the first aspect of uncertainties in storm surge evaluation (e.g. Yang et al., 2016; Yasuda et al., 2014). When remote effects are considered, the storm surge is also highly dependent on TC tracks and intensities, propagation speed, the distances relative to coasts (Wada et al., 2018), and basin geometry. In addition to the atmospheric component of driving forces, the ocean or wave models play the essential roles in projecting storm surge. Ocean or wave models, as examples of numerical models, exhibit the same general kinds of uncertainties as atmospheric models but for different essential physical processes and boundary conditions. Storm surge risk may also be affected by long-term changes of TC activity or by sea-level rise (Resio and Irish, 2015). In particular, sea level rise generally leads to higher coastal flooding inundation levels, assuming all other factors equal.

5. Summary

5.1. Projected changes

The results of this assessment on the projections of TC activity in the WNP are generally consistent with those of the SAR published 2012 and with projections for the WNP basin as summarized in the recent global assessment conducted by the WMO Task Team on Tropical Cyclones and Climate Change (Knutson et al., 2019b). With our focus on just the WNP basin, we are able to present more detailed description of projection studies relevant to the WNP basin than was in Knutson et al. (2019b). Compared with the SAR, the general conclusions of increased TC intensity in most modeling studies and increased TC precipitation rates in all available studies remains unchanged, though with confidence increased some by the confirming results of multiple new studies. We explicitly analyze the proportion of TCs reaching Category 4 and 5 intensity in available studies and show that this is projected to increase in most studies. We now have enough studies available to allow for a calculation of the 10th to 90th percentile ranges on projections of several metrics (after rescaling for consistency). Below we summarize the quantitative multi-study-based projections of changes of key TC metrics, scaled to a 2 °C anthropogenic global warming scenario.

For TC genesis/frequency over the WNP, most recent studies using higher resolution dynamical models projected a reduction of TC numbers (median: -10%; 10th to 90th percentile: -26% to +11%), but an increase in the proportion of very intense TCs (Cat. 4–5) (+10%; −2% to +29%). Note there are still individual studies projecting an increase in overall TC frequency. Most TC intensity projection studies agree on an increase in intensity of WNP TCs in response to a 2 °C global anthropogenic warming scenario (+5%; +2% to +9%). All available projections for TC related precipitation also indicated an increase in TC related precipitation rate in a warmer climate (+17%; +6% to +24%). Anthropogenic warming may lead to potential changes in TC prevailing tracks, although details vary among studies. Climate models continue to predict future increases in sea level and this will increase coastal inundation levels assuming all other factors equal. Storm surge risk may also be increased by the projected increase in TC intensity. However, some studies also suggest a possible decrease in storm numbers in the WNP in the future, which could contribute toward decreasing surge risk, assuming all other factors equal. In summary, the most confident aspect of change in storm inundation risk with global warming comes from the highly confident expectation of further sea level rise, which would exacerbate storm inundation risk, assuming all other factors equal.

5.2. Recommendations for future work

With a view to gaining further confidence in future projections of TC activity in the WNP basin, Typhoon Committee Members and research community are also encouraged to conduct additional research to:

(i) Investigate TC extreme events under climate change scenarios in support of vulnerability assessments
(ii) Continue to evaluate the sensitivity of TC projections to the details of climate and/or TC downscaling models
(iii) Enhance the use of statistical significance testing, evaluation of present-day simulations (including interannual variations), and multi-model ensemble experiments with models with enhanced resolution and physics to better quantify uncertainty in future projections.
(iv) 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.
(v) Reduce or quantify uncertainties to the extent possible in the 21st century projections of regional SST patterns and the vertical structure of the atmospheric (temperature, winds, moisture) and oceanic changes as these differences can lead to large differences in regional TC projections.
(vi) Continue research to better understand the basic physical mechanisms that cause the observed or modeled changes in TC activity (including TC track/genesis position changes) in the basin.
(vii) Make use of historical TC observations and paleoclimate proxy data, together with models, to detect possible anthropogenic influence on past TC activity and evaluate the consistency of historical model simulation with the observed changes, in order to gain further confidence in future projections.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tcrr.2020.04.005.

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