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Article

Rising future tropical cyclone-induced extreme winds in the Mekong River Basin

Aifang Chen [a], Kerry A. Emanuel [b], Deliang Chen [a,*], Changgui Lin [a], Fuqing Zhang [c]

[a] *Regional Climate Group, Department of Earth Sciences, University of Gothenburg, Gothenburg 40530, Sweden*
[b] *Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[c] *Department of Meteorology and Atmospheric Science, Center for Advanced Data Assimilation and Predictability Techniques, the Pennsylvania State University, University Park, PA 16802, USA*

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ABSTRACT

The societal impact of extreme winds induced by tropical cyclones (TCs) is a major concern in the Mekong River Basin (MRB). Though no clear trend of landfalling TC intensity along the Vietnam coastline has been observed since the 1970s, climate models project an increasing TC intensity in the 21st century over the Western North Pacific, which is the primary TC source region influencing the MRB. Yet, how future TC activities will affect extreme winds quantitatively in the MRB remains unclear. By employing a novel dynamical downscaling technique using a specialized, coupled ocean-atmospheric model, shorter return periods of maximum wind speed in the MRB for 2081–2100 compared with 1981–2000 are projected based on five global climate models under the RCP8.5 scenario, suggesting increases in the future tropical cyclone intensity. The results point to consistently elevated future TC-related risks that may jeopardize sustainable development, disrupt food supply, and exacerbate conflicts in the region and beyond.

1. Introduction

Tropical cyclones (hereafter TCs) are one of the most devastating natural hazards [1,2], causing about 472,000 deaths and damages worth of 985 billion United States Dollars (USD) globally between 1971 and 2018 [3]. Frequent landfalling TCs threaten the lives of the 60 million residents along the lower Mekong River, which is one of the world's largest rivers [4,5]. These landfalling TCs terrorize those living on the margins of economic development in the riparian countries of the lower Mekong River Basin (MRB), namely: Cambodia, Laos, Myanmar, Thailand, and Vietnam [4,6]. The MRB has been hit by severe TCs such as Nargis (2008) in Myanmar that claimed over 136,000 lives [4], and Ketsana (2009) which caused damage and losses in Vietnam, Cambodia, Laos, and Thailand, totaling 800, 132, 58, and 21 million USD, respectively [7]. The impact of TCs varies from one event to another [2]. However, TC intensity has proven to be a pivotal factor because the majority of losses arises from intense TCs [8,9].

The TCs that influence the MRB primarily originate from the South China Sea, Western North Pacific [10] and North Indian Ocean [11]. Among them, the Western North Pacific is the ocean basin with the greatest TC activity [2]. The TCs often enter the MRB through Vietnam [10]. Despite uncertainties of the Western North Pacific's basin-wide TC activity among the best track datasets, a poleward migration of the TCs generated from the ocean basin has been inferred and has coincided with a decreased TC activity in the South China Sea since the 1980s [12,13]. But there was no clear trend of landfalling TC intensity across Vietnam's coastline for 1977–2010 [8]. Nonetheless, mean TC intensity is predicted to increase during the 21st century [14–16], prominently in the Western North Pacific [14], even though no consensus on the global frequency change of future TCs has been reached. Owing to potentially catastrophic impact, this projected increase in future TC intensity is a threat to the wellbeing of exposed residents. The current study seeks to assess future changes of TC-induced extreme wind events in the MRB region.

Various approaches have been used to simulate TC climatology based on global climate models (GCMs) [14]. Due to the small size of storm cores (~5 km), direct GCM simulations with coarse horizontal resolution of ~100 km generally underestimate TC activity [17–21] and fail to capture high-intensity TCs which often cause the most damage and deaths [14,17,18]. Dynamical downscaling, by embedding high-resolution regional models in the GCMs, is an alternative approach [22]. However, this approach still suffers from inadequate horizontal resolutions (~10–50 km) while remaining

* Corresponding author.
E-mail address: deliang@gvc.gu.se (D. Chen).

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expensive to perform for periods long enough to show statistical significance [20,22]. In this study, we use a variant downscaling technique developed by Emanuel et al. [22,23]. It uses a simpler, embedded model to generate large numbers of synthetic TC events (~10^3), thus providing robust statistics that agree with observations [22,24]. This technique can circumvent the drawback of using low horizontal resolution GCMs [17,22] and is computationally efficient [22]. We apply this technique to assess future TC intensity changes in the MRB for 2081–2100 compared with 1981–2000, with a focus on the associated extreme winds of the TCs. Our results of the future return periods of TC-induced extreme wind events provide useful scientific guidance for adaptation to future climate changes in the MRB.

2. TC downscaling simulations

The downscaling technique applied in the present study generates synthetic TCs by applying the Coupled Hurricane Intensity Prediction System (CHIPS) model to TC tracks that are initiated by randomly seeding in space and time and propagated forward using a beta-and-advection model driven by large-scale flows in which they are embedded [22,23,25]. This technique has been demonstrated to be capable of simulating synthetic TC events with statistical properties compatible with historical TCs [22,26,27]. It has also been used in a wide range of risk assessments; e.g., TC rainfall [28], storm surge [24], and socio-economic damage [29].

To assess future changes in TC intensity, we use climate projections of five GCMs from the Coupled Model Intercomparison Project Phase 5 (CMIP5) [30]. These five models were selected because they have the output required by the downscaling technique [23] and because they have good continuity between the historical period and climate projections [14,28]. The GCMs are GFDL-CM3, HadGEM2-ES, IPSL-CM5A-LR, MIROC5, and MPI-ESM-MR; abbreviated as GFDL5, HadGEM5, IPSL5, MIROC5, and MPI5, respectively. The horizontal resolutions and other details of these GCMs can be found in Table S1 (online). In this study, we assume that the TCs influence the MRB if they pass anywhere within a predefined MRB boundary, with a maximum surface wind speed (hereafter MWS, represents the maximum wind speeds induced by TCs, unless otherwise stated) greater than 30 kt (or 15 m s^{-1}, 1 kt≈0.51 m s^{-1}).

More specifically, historical climate simulations from each GCM are first applied to generate a set of 100 events for each year from 1981 to 2000 that influence the MRB [22,28]. As this technique does not yield an absolute rate of TC genesis [22,24,28], the annual frequency of TCs from each GCM for 1981–2000 is calibrated to match that from the best track data (1.25 events per year) from the Joint Typhoon Warning Center (JTWC, http://www.metoc.navy.mil/jtwc/jtwc.html) for the same period. Hence, a calibration constant (the overall seeding rate) for each GCM is obtained [14,24]. Based on the same respective calibration constants, corresponding sets of synthetic storm tracks for each GCM for the period 2081–2100 are generated under the Representative Concentration Pathway 8.5 scenario (RCP8.5), which corresponds to a high greenhouse gas emission pathway during the 21st century [31]. The annual frequency of storms for the future climate is then predicted by each GCM [22,24,28]. Interested readers can refer to Refs. [22,23], which offer in-depth descriptions of this downscaling technique, along with its advantages and limitations.

Besides the assessment of future TC intensity change (indicated by MWS) on the basin-wide scale, the risks for the four major cities in the MRB have also been assessed (Fig. S1 online); i.e., Can Tho (Vietnam), Phnom Penh (Cambodia), Nakhon Ratchasima (Thailand), and Vientiane (Laos). These cities were selected based on their locations and population (https://en.wikipedia.org/w/index.php?title=List_of_cities_in_ASEAN_by_population&oldid=875520357), representing the most important hotspots in terms of human population in the region. For future TC intensity change, we here focus on projected return periods of the MWS. The return period is defined as the inverse of the annual exceedance probability [28], with a shorter return period of the MWS indicating an upwards shift of tropical cyclone intensity [32].

3. Results

Best track and synthetic return periods of MWS for 1981–2000 in the MRB are compared in Fig. 1. Except for MIROC5 (Fig. 1d), estimates from the best track data all fall within the 90% sampling error confidence interval of MWS calculated from the synthetic storm events. The annual exceedance frequency of MWS from the best track data also displays consistency with that from the synthetic storm events between 50 and 90 kt (Fig. S2 online). Also, most of GCM-based simulations have track densities close to the observed densities (Fig. S3 online). Such consistencies demonstrate the reliable skill of the downscaling technique in simulating the synthetic storm events. Similar reliabilities in simulating statistical properties consistent with those of historical TCs have also been demonstrated in other regions in previous studies [26,27,33]. The estimated MWS from the synthetic storm events increases smoothly when the return period is less than 600 years, while abrupt changes appear when the return period is greater than 600 years, especially for IPSL5 and MPI5. These abrupt changes reveal a limitation for the estimation of storm events with a long return periods longer than about 1000 years owing to the finite sample size [33].

Compared with 1981–2000, the results for 2081–2100 under the RCP8.5 show consistently shorter return periods of MWS from all GCMs in the MRB region (Fig. 2), though the differences for the MPI model are small. In other words, a higher occurrence probability of MWS is predicted. The results disclose a worrying rising trend in the occurrence of intensified TCs for the late 21st century. For example, a MWS of 140 kt, which can cause potentially high catastrophic damage, presently occurs at a median rate of about once every 98.7 years among the results (with 123.2 and 16.4 years at 25th- and 75th-percentiles, respectively). However, for the years 2081–2100, it would occur once every 44.7 years (with 58.5 and 6.7 years at 25th- and 75th-percentiles, respectively) (Table 1). Meanwhile, a MWS of 120 and 100 kt would both occur with shorter return periods. In terms of the changing magnitude of return periods of MWS between the two time periods (defined as: the return period of MWS in 2081–2100 / the return period of MWS in 1981–2000), this varies among the GCMs. In particular, MIROC5 predicts a high increase in extreme wind occurrences, while MPI5 shows relatively smaller changes.

The MWS decreases with latitude in both periods (1981–2000 and 2081–2100) for four selected cities: Can Tho, Phnom Penh, Nakhon Ratchasima, and Vientiane (Fig. 3). Rising extreme wind occurrences with varying magnitudes at Can Tho and Phnom Penh are estimated for 2081–2100 with shorter return periods of MWS. Specifically, it is astonishing that the estimated MWS for 2081–2100 surpasses current peak of the MWS for 1981–2000, implying an immense boosting future tropical cyclone risk particularly in Can Tho. The inconsistency among GCMs is presented by the overlapping shadings for the two periods in Fig. 3, indicating the uncertainties caused by GCMs. The medians of simulations by the five GCMs show shifting patterns of the MWS return periods in particular at Nakhon Ratchasima and Vientiane, with smaller MWS at longer return periods. These shifting patterns indicate that the two cities will experience landfalling TCs with more frequent lower-magnitude MWS, but less frequent high MWS in 2081–2100.

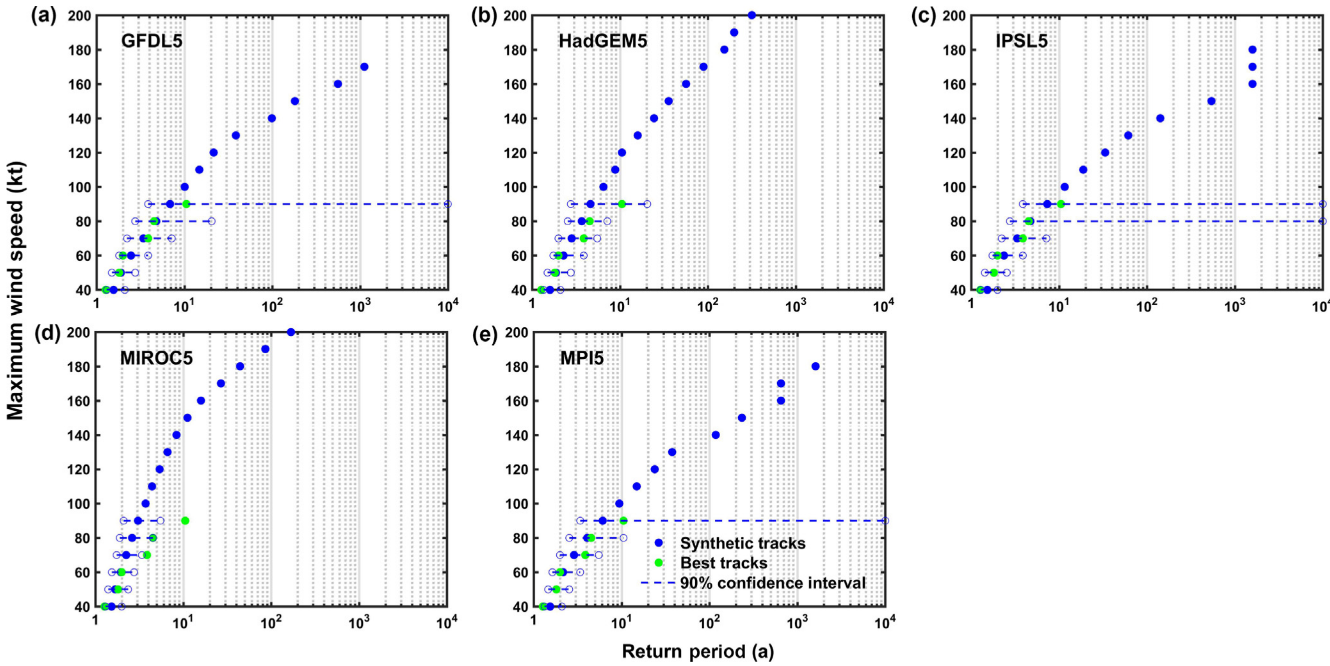

Fig. 1. Comparison of return periods (unit: a) of the maximum wind speeds induced by tropical cyclones in the Mekong River Basin for 1981–2000 based on best track data and historical simulations from each of the five GCMs: GFDL5 (a), HadGEM5 (b), IPSL5 (c), MIROC5 (d), and MPI5 (e). The green dots are for the best track data, and the blue dots are for five GCMs. The blue dashed lines show the 90% confidence interval based on estimated best track data sampling error.

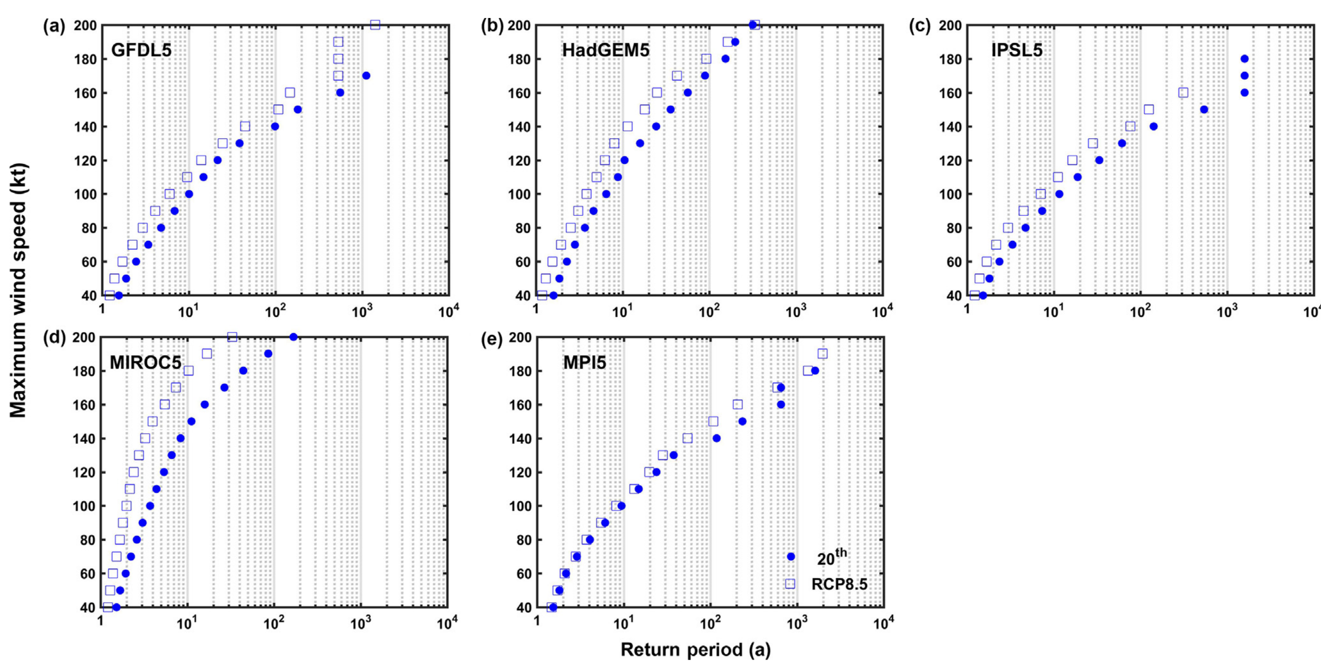

Fig. 2. Return periods (unit: a) of the maximum wind speeds in the Mekong River Basin associated with synthetic tropical cyclones simulated from each of the five models over the period 1981–2000 from historical simulation (solid dots), and 2081–2100 from the RCP8.5 scenarios (hollow squares): GFDL5 (a), HadGEM5 (b), IPSL5 (c), MIROC5 (d), and MPI5 (e).

In addition, increasing MWS at the return period of 100 years from most of the GCMs indicates higher extreme wind occurrences induced by TCs in 2081–2100 at the four cities (Table 2). The highest MWS for 2081–2100 lies in Can Tho with a mean of 106.6 kt which is category 3 on the Simpson Hurricane Wind Scale. This is followed by Phnom Penh, Nakhon Ratchasima, and Vientiane. The changing magnitude of MWS between the two time periods at the four cities also presents a similar sequence, with the largest increase in Can Tho. Return period of 100 years is regarded as high-risk, corresponding to many earlier disaster assessments [34]. Such a rising extreme wind occurrence induced by TCs in 2081–2100 portrays significantly increasing TC risk in the MRB.

Table 1
Return periods (unit: a) of three given maximum wind speeds (MWS) belonging to three strong tropical cyclone categories for present (1981–2000) and future (2081–2100), estimated by the five GCMs. The categories shown in the heading row of the table are defined according to the Saffir-Simpson Hurricane Wind Scale.

GCM	Time period	140 kt (category 5)	120 kt (category 4)	100 kt (category 3)
GFDL5	Present	98.7	21.5	10.1
	Future	44.7	13.9	6.0
HadGEM5	Present	24.5	10.5	6.5
	Future	11.4	6.2	3.8
IPSL5	Present	141.8	33.6	11.6
	Future	76.4	16.3	7.1
MIROC5	Present	8.4	5.4	3.7
	Future	3.3	2.4	2.0
MPI5	Present	118.0	23.9	9.5
	Future	54.3	19.7	8.2
On average[a)]	Present	98.7	21.5	9.5
		(123.2 16.4)	(25.7 8.4)	(10.4 5.4)
	Future	44.7	13.9	6.0
		(58.5 6.7)	(17.1 4.3)	(7.3 3.0)

a) The values is the median percentiles in storm return periods among the five GCMs, with the values in the parentheses showing the 25th- (left) and 75th- (right) percentiles, respectively

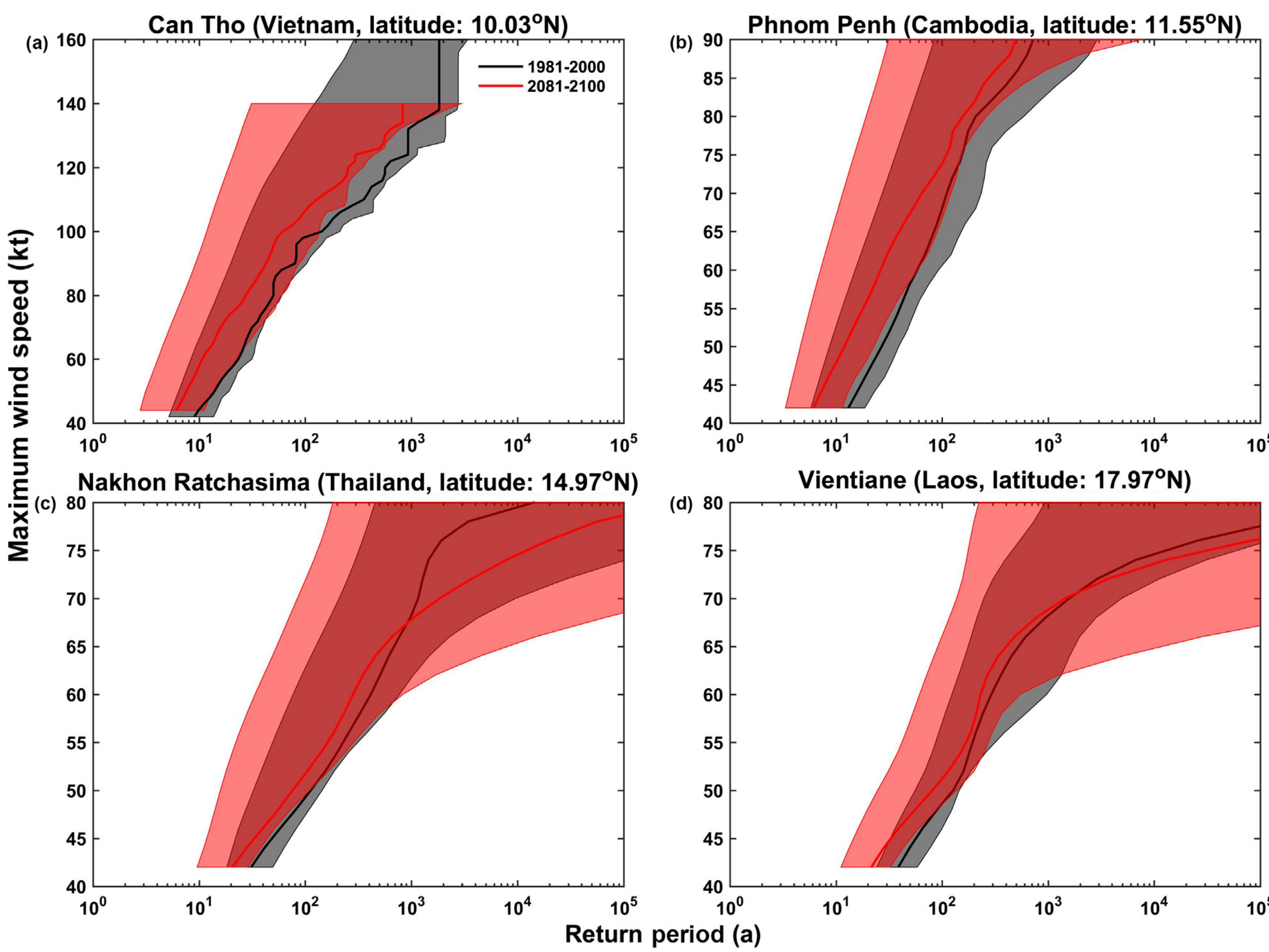

Fig. 3. Return periods (unit: a) of the maximum wind speeds associated with simulated synthetic tropical cyclones from five GCMs over the period 1981–2000 from historical simulations (black), and 2081–2100 from the RCP8.5 scenario simulations (red) at Can Tho (Vietnam, a), Phnom Penh (Cambodia, b), Nakhon Ratchasima (Thailand, c), and Vientiane (Laos, d). The solid lines and left and right shading edges show the median, 25th- and 75th-percentiles, respectively, in storm return periods among five GCMs. The scatter of the return periods is among the models used for the downscaling.

4. Discussion

The projected TC-induced extreme wind occurrences in the MRB region for 2081–2100 based on the CMIP5 simulations are mostly consistent among the five GCMs under the RCP8.5 scenario. However, there are considerable variations in the estimated mean annual TC frequency affecting this region, ranging between 1.41 and 2.32. This difference in the annual TC frequency estimates at least partially reflects the uncertainties in the GCM projections of future climate [22,24]. TC formation and development can be

Table 2
The maximum wind speeds of the tropical cyclones associated with 100-year return period at four cities in the Mekong River Basin (unit: kt) for present (1981–2000) and future (2081–2100), estimated by the five GCMs.

GCM	Time period	Can Tho	Phnom Penh	Nakhon Ratchasima	Vientiane
GFDL5	Present	93.6	68.0	48.6	48.6
	Future	106.6	73.8	51.7	51.2
HadGEM5	Present	131.5	85.1	69.8	45.3
	Future	161.8	97.1	67.1	49.3
IPSL5	Present	76.8	61.1	49.2	54.9
	Future	94.9	63.4	50.5	58.0
MIROC5	Present	149.1	113.6	60.7	62.6
	Future	234.4	151.9	102.2	83.9
MPI5	Present	97.9	58.3	40.5	46.2
	Future	87.3	69.1	42.3	43.4
On average[a)]	Present	97.9 (89.4 135.9)	68.0 (60.4 92.2)	49.2 (46.6 63.0)	48.6 (46.0 56.8)
	Future	106.6 (93.0 180.0)	73.8 (67.7 110.8)	51.7 (48.5 75.9)	51.2 (47.8 64.5)

a) The values is the median percentiles in maximum wind speed among the five GCMs, with the values in the parentheses showing the 25th- (left) and 75th- (right) percentiles, respectively.

strongly influenced by large-scale environmental conditions such as vertical wind shear, potential intensity, and humidity [19,35–37], which may vary significantly among different GCM simulations. There are also inherent uncertainties in the projected changes of the thermodynamic regimes, particularly at regional scales [13,19]. As shown in previous studies [17,22,24], differences in horizontal resolutions, physical parameterizations, and dynamical cores of the GCMs can lead to varied regional climates. Nevertheless, the overall agreement (for both the return periods and annual exceedance frequency of MWS) between synthetic TC events based on the GCM simulations and best track records offer support for the projected future increase of TC-induced extreme wind events in the MRB presented in this study.

On the whole, increases in TC intensity with shorter of the return periods for MWS are simulated for the MRB by 2081–2100 based on the five GCMs. As in Emanuel [14,20], the projected increases in TC intensity are related to increasing potential intensity as the climate warms. Since TCs are driven by surface enthalpy fluxes, climate warming will lead to an increased enthalpy jump at the sea surface and facilitate creation and development of TCs with higher intensity [14]. Smaller vertical wind shear induced by the warming climate scenario is another possible reason for the increases in TC intensity over the Western North Pacific [18].

Meanwhile, the considerable differences among the four cities indicate large spatial heterogeneity in TC-intensity increases in the MRB for 2081–2100, with larger increases in TC intensity for areas closer to the coast. As TCs move over land, they decay due to the absence of a substantial surface enthalpy source [13,23]. Factors related to coastal development, e.g., shipping, coastal tourism, and coastal settlement, that promote a more densely populated coastal area than heretofore [34,38], will lead to higher exposure to TC-induced hazards. Apart from being affected by extreme winds, coastal areas such as Can Tho are also vulnerable to storm surges induced by intense TCs [24,39]. Such storm surges will be further amplified by the projected rising sea levels under warming global climate [13,24] as well as Mekong Delta subsidence [40,41]. Overall, future TC-related risks are likely to increase due to higher exposure and increasing intensity of TCs, particularly in coastal areas of the MRB.

The projected increases in TC intensity may also disturb global food markets by affecting rice production in the MRB, because Thailand and Vietnam are the two most important rice exporting countries in the world [42]. Ultimately, both socioeconomic development and the effects of climate change drive TC-induced losses of life and property damage [29]. Generally, poor people suffer more from natural hazards like those induced by TCs [43]. For the underdeveloped MRB riparian countries [6,7], projected TC intensity increases may jeopardize sustainable development and exacerbate conflicts.

5. Conclusion

In summary, based on the CMIP5 simulations from the five GCMs under the RCP8.5 scenario, this study shows a consistent shorter return period of TC-induced extreme wind in the MRB in 2081–2100, particularly in areas closer to the coast. Our results suggest a rising future TC intensity in the MRB region in the future which may disrupt food supply, and aggravate conflicts in the region and beyond. Facing the extensive and far-reaching impact of intensifying future TCs in the MRB, mitigating greenhouse gas emissions is paramount. Simultaneously, the government needs to take measures to develop resilience strategies for adaptation to future climate change.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Aifang Chen, Kerry A. Emanuel and Deliang Chen designed the research; Kerry A. Emanuel run the model and provided the output data; Aifang Chen, Kerry A. Emanuel and Changgui Lin interpreted the results; all authors contributed to the writing, with Aifang Chen as the lead author.

Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scib.2019.11.022.

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Aifang Chen is a doctoral student at the Department of Earth Sciences at the University of Gothenburg. She is interested in hydroclimate change and risk assessment, with special focus on Mainland Southeast Asia.

Deliang Chen is a climate researcher and August Röhss Chair professor at the University of Gotheburg, elected members of six Academies including the Royal Swedish Academy of Sciences (RSAS) and Chinese Academy of Sciences. He has served on numerous international and national committees, such as chairs of the Nomination Committee of the Stockholm Water Prize and the Earth Science Division of the RSAS, as well as Coordinating Lead Author of IPCC-AR6.