

Tropical cyclone risk in Bangladesh

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सार – हमने पुनः विश्लेषण तथा पाँच CMIP5 और सात CMIP6 जलवायु मॉडलों से निचले पैमाने पर संख्यात्मक अनुकारी उष्णकटिबंधीय चक्रवातों के आधार पर बांग्लादेश में वर्तमान और भविष्य के उष्णकटिबंधीय चक्रवातों के जोखिम का पता लगाया। निचले पैमाने पर उष्णकटिबंधीय चक्रवातों से पवन और वर्षा के जोखिम के सांख्यिकीय रूप से ठोस अनुमान प्राप्त हुए, तथा संकेत मिले कि यदि इस शताब्दी में ग्रीनहाउस गैस उत्सर्जन पर नियंत्रण के लिए कम कार्य किया जाएगा तो ये जोखिम बढ़ सकते हैं। यद्यपि उपयोग किए जाने वाले जलवायु मॉडल में काफी भिन्नता है, फिर भी बहु-मॉडल से सुझाव प्राप्त हुए हैं कि शताब्दी के अंत तक 100 नॉट्स से अधिक तटीय पवनों की संभावना तीन गुनी हो जाएगी, जबकि 150 नॉट्स से अधिक वाले तटीय पवनों में दस गुना अधिक तक वृद्धि हो जाएगी। इसी प्रकार, ढाका में तूफान की कुल वर्षा की आवृत्ति शताब्दी के अंत तक 325 वर्षों में एक बार 500 मि.मी. से अधिक से लेकर 40 वर्षों में एक बार तक बढ़ जाएगी, जबकि एक मीटर से अधिक वर्षा की संभावना लगभग 20 गुना अधिक तक बढ़ जाएगी। इन परिणामों से बांग्लादेश में अगले 80 वर्षों में उष्णकटिबंधीय चक्रवातों से जुड़े जोखिमों में बहुत अधिक वृद्धि का संकेत मिलता है, जिससे वायुमंडल में ग्रीनहाउस गैसों के संचय में पर्याप्त कमी होगी।

ABSTRACT. We explore current and future tropical cyclone risk in Bangladesh using numerically simulated tropical cyclones downscaled from reanalyses and from current and future climate states simulated by five CMIP5 and seven CMIP6 climate models. The downscaled tropical cyclones provided statistically robust estimates of wind and rain risk and how these risks may evolve over this century if little is done to curb greenhouse gas emissions. While there is considerable scatter among the climate models used, the multi-model consensus suggests that the probability of coastal winds exceeding 100 kts will triple, while those in excess of 150 kts will increase by a factor of ten by the end of the century. Likewise, the frequency of storm total rainfall at Dhaka in excess of 500 mm increases from once in 325 years to once in 40 years by the end of the century, while the probability of rainfall in excess of 1 meter increases by a factor of about 20. These results indicate very substantial increases in risks associated with tropical cyclones in Bangladesh over the next 80 years, barring substantial reductions in the accumulation of greenhouse gases in the atmosphere.

Key words – Pre-monsoon rainfall, Hurst Exponent, Lyapunov Exponent, Southwest monsoon, Northeast monsoon.

1. Introduction

With its low-lying floodplains and proximity to very warm ocean waters, Bangladesh is highly susceptible to strong tropical cyclones and accompanying heavy rain and storm surge. Having a densely packed and vulnerable population, it is the site of many of the worst tropical cyclone disasters in world history, including the Bhola Cyclone of 1970, which killed between 300,000 and 500,000 people - the largest loss of life in any tropical cyclone on record globally. The inadequate response of the government of what was then East Pakistan to the disaster was among the factors leading to independence from West Pakistan and the founding of Bangladesh as a nation in 1971.

Fig. 1 shows a tabulation of annual loss of life from tropical cyclones in the region that is now Bangladesh, from 1760 to 2020.

During this period 14 storms killed more than 10,000 people; most recently the 1991 Bangladesh Cyclone, which killed upwards of 150,000. Loss of life has been greatly reduced since the 1991 event by sustained disaster management efforts, including the construction of evacuation shelters and implementation of advanced warning and evacuation strategies (Ahmed *et al.*, 2016). For example, severe Cyclone Amphan struck West Bengal, just west of Bangladesh, in May, 2020 in the midst of the COVID-19 pandemic, with a 5 m storm surge. It proved the costliest cyclone ever recorded in the North Indian Ocean, but the death toll was held to 128.

Yet continued reductions in tropical cyclone mortality are now threatened by climate change, owing to increasing sea level and the possibility of more dangerous cyclones. The region is too small and the historical record too short and incomplete to provide an adequate estimate of historical tropical cyclone risk, let alone future risk in

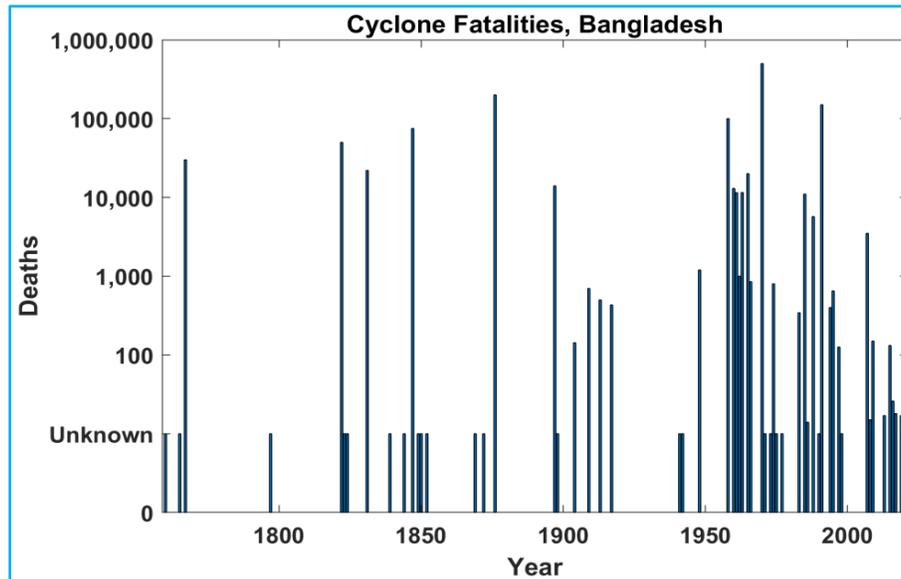


Fig. 1. Annual loss of life from tropical cyclones in the region that is Bangladesh today, from 1760 to the present. Years with no bars have no recorded cyclones, while the shortest bars correspond to years with known cyclones but no recorded fatalities. Data through 2009 from Chowdhury (2012) and post 2009 from Wikipedia_contributors (2020)

the presence of climate change. For this reason, we turn to physical modeling of tropical cyclones to provide quantitative risk assessments.

The main tool for assessing climate change effects on weather risks is the global climate model. However, such models are far from ideal for the task, owing to inadequate spatial resolution. Today's best global climate models have grid spacing of tens of kilometers, whereas experiments with specialized, high-resolution, convection-permitting models show that numerical convergence requires grids spacing on the order of kilometers (Rotunno *et al.*, 2009). While global climate models usually produce facsimiles of tropical cyclones, their structure and intensity are distorted by inadequate spatial resolution. Yet such models continue to be the primary basis for assessments of climate change effects on tropical cyclone risk (*e.g.*, see the review by Knutson *et al.*, 2020).

For the present study, we use the downscaling method developed by Emanuel *et al.* (2006) and Emanuel *et al.* (2008). Tropical cyclone tracks are created by randomly seeding, in space and time, the evolving, global, large-scale environment. This environment is synthetically generated from gridded global reanalyses or climate models in a way that insures that the monthly means of all variables are those of the gridded data (interpolated to the storm positions) and that the monthly mean variances and covariances of the daily atmospheric winds with respect to their monthly means are correct. Finally, the kinetic

energy spectrum of the synthesized large-scale winds obeys geostrophic turbulence scaling.

Once the tracks are created, the Coupled Hurricane Intensity Prediction System (CHIPS; Emanuel and Rappaport, 2000) model is run along each of the randomly generated tracks. The intensity model has very high spatial resolution in the storm core, owing to the use of an angular momentum radial coordinate and has been shown to produce skillful real-time intensity forecasts (Emanuel and Rappaport, 2000). Well over 99% of the seeded tracks dissipate rapidly and are discarded; the survivors constitute the downscaled tropical cyclone climatology of the original reanalysis or climate model. This technique has been shown to accurately simulate all the salient features of the current climatology of tropical cyclones when applied to global reanalysis data (Emanuel *et al.*, 2008).

There are several advantages to this technique in comparison to conventional downscaling using regional models. The use of angular momentum coordinates allows increasing spatial resolution of the storm core as its intensity increases, thus each storm's intensity is limited by the physical properties of its environment rather than by numerical resolution. Because the tropical cyclone model is driven by the statistics of the global model or reanalysis, an arbitrarily large number of events can be simulated in a given climate and the seeding is global so there is no need to pre-select sub-domains.



Fig. 2. Filter used in the creation of synthetic tracks affecting Bangladesh. The centers of all the simulated tropical cyclones passed over one (or possibly both) of the two line segments shown in orange. Rainfall was calculated at Dhaka, at center near the top of the map

TABLE 1

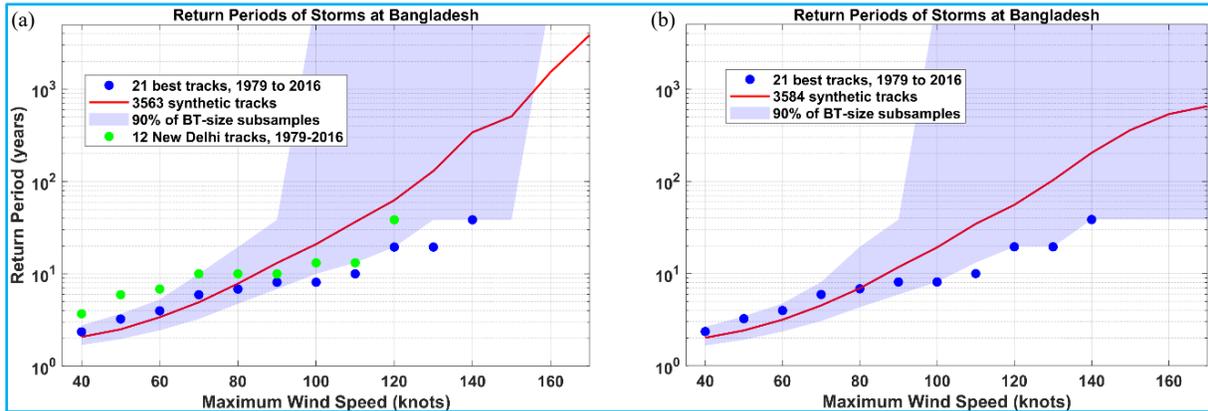
Global Climate models used in this study

Institution	Model	Atmospheric Resolution*	Reference
National Center for Atmospheric Research	CCSM4	1.25 × 0.94 degree	(Lawrence <i>et al.</i> , 2011)
NOAA Geophysical Fluid Dynamics Laboratory	CM3	2.5 × 2.0 degrees	(Donner <i>et al.</i> , 2011)
Met Office Hadley Center	HADGEM2-ES	1.875 × 1.25 degree	(Collins <i>et al.</i> , 2011)
Institut Pierre Simon Laplace	CM5A-LR	3.75 × 1.89 degrees	(Dufresne <i>et al.</i> , 2013)
Max Planck Institute for Meteorology	MPI-ESM-MR	1.875 × 1.865 degree	(Giorgetta <i>et al.</i> , 2013)
Canadian Centre for Climate Modelling and Analysis	CanESM5	2.8 × 2.8 degrees	(Swart <i>et al.</i> , 2019)
EC-Earth consortium	EC-Earth3	0.7 × 0.7 degree	
Institut Pierre Simon Laplace	IPSL-CM6A-LR	1.25 × 2.5 degrees	(Hourdin <i>et al.</i> , 2016)
Center for Climate System Research; University of Tokyo; Japan Agency for Marine-Earth Science and Technology; National Institute for Environmental Studies	MIROC6	1.4 × 1.4 degree	(Tatebe <i>et al.</i> , 2019)
Max Planck Institute	MPI-ESM1-2-HR	0.94 × 0.94 degree	(Müller <i>et al.</i> , 2018)
Meteorological Research Institute (Japan)	MRI-ESM2-0	1.12 × 1.125 degree	(Yukimoto <i>et al.</i> , 2019)
United Kingdom Met Office	UKESM1-0-LL	1.25 × 1.875 degree	(Sellar <i>et al.</i> , 2020)

* - This is the resolution of the output used to drive the downscaling; it may not correspond exactly with the native resolution of the GCM

For the present analysis, we created sets of synthetic tropical cyclones whose centers passed over either (or both) of the line segments displayed in Fig. 2. This

captures most storms that affect Bangladesh, though a few may pass through or near the nation by entering from the west; these would have travelled over some land before



Figs. 3(a&b). (a) Return periods of tropical cyclone winds on the Bangladesh coastline determined from the synthetic track set (red) and from historical data (blue dots). The return periods are the inverse of the annual exceedance probabilities and (b) As in (a) but incorporating salinity stratification in to the ocean mixing model (see text) used in the creation of the synthetic tracks. The blue shading in the figure represents limits within which 90% of the return periods based on the subsamples lie.

affecting the region. We downsampled 3,800 synthetic tracks over the period 1979-2016 from NCAR-NCEP reanalyses and 2,000 tracks for each of five CMIP-5-generation and seven CMIP-6-generation global climate models for each of two periods: 1981-2000 from historical simulations and 2081-2100 from RCP 8.5 simulations (CMIP5) and SSP5 8.5 simulations (CMIP6). In total, 51,800 tropical cyclone events were created. Table 1 summarizes the reanalysis and climate models used. Storm total rainfall was calculated at Dhaka using the algorithm described in detail in Feldmann *et al.* (2019).

2. Results

Figs. 3(a&b) displays the return periods (inverse annual exceedance probabilities) of maximum surface winds accompanying tropical cyclones whose centers were crossing the line segments shown in Fig. 2 (these may be considered the maximum winds experienced along the coastline of Bangladesh during the life of each storm). The red curve is derived from 3,800 cyclones downsampled from NCAR/NCEP reanalyses over the period 1979-2016 and the blue dots represent return periods estimated from 21 historical storms that crossed the line segments shown in Fig. 2. The historical tracks are from the U.S. Navy's Joint Typhoon Warning Center (JTWC) and were accessed through the IBTrACS historical tropical cyclone archive (Knapp *et al.*, 2010). To estimate sampling error, we created many subsamples of the full synthetic data set at the rate of the historical tracks in each wind speed bin. The blue shading in the figure represents limits within which 90% of the return periods based on the subsamples lie.

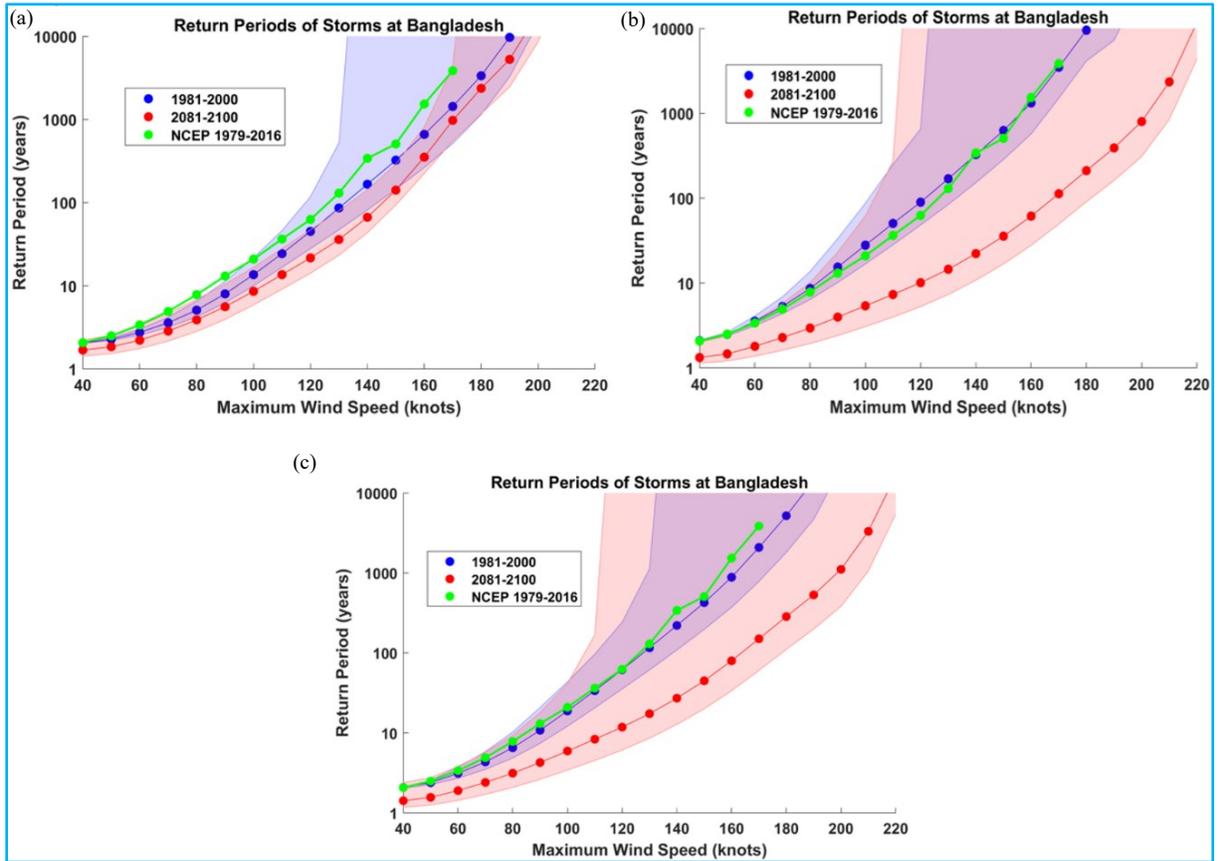
The synthetic tracks significantly underestimate the frequency of high intensity events striking Bangladesh.

This is not a bias we see in other regions and so indicates problems with the synthetic downscaling and/or historical data peculiar to this region.

There is considerable uncertainty in estimating tropical cyclone wind speed in regions, like the Bay of Bengal, that are not surveyed by reconnaissance aircraft. The data plotted as blue dots in Fig. 3(a) were assembled by JTWC, which uses a 1-minute average wind speed, but several other agencies do their own analyses and may use different conventions. As an example, Fig. 3(a) also shows, in green dots, return periods based on winds assembled by the Regional Specialized Meteorological Center (RSMC) in New Delhi, India. They record only 12 events passing over the coast of Bangladesh during this period, in contrast to 21 events recorded by JTWC. Apparently, RSMC ignores many weak storms included in the JTWC data (Bhardwaj and Singh, 2020), and moreover RSMC New Delhi uses a 3-minute wind averaging convention, which tends to record wind speeds that are smaller than JTWC's 1-minute average winds.

The New Delhi analyses shown by the green dots in Fig. 3(a) have fewer total events and also fewer very strong events, more in line with the return periods of strong events indicated by the synthetic tracks.

Yet part of the problem may also lie in the synthetic track model. In particular, the ocean mixing model, an important component of the intensity model that accounts for the effect of wind-driven turbulent mixing, which brings colder water to the surface, does not account for salinity effects on density. But the Bay of Bengal has strong salinity gradients, especially in summer, owing to a combination of monsoonal rains and river runoff



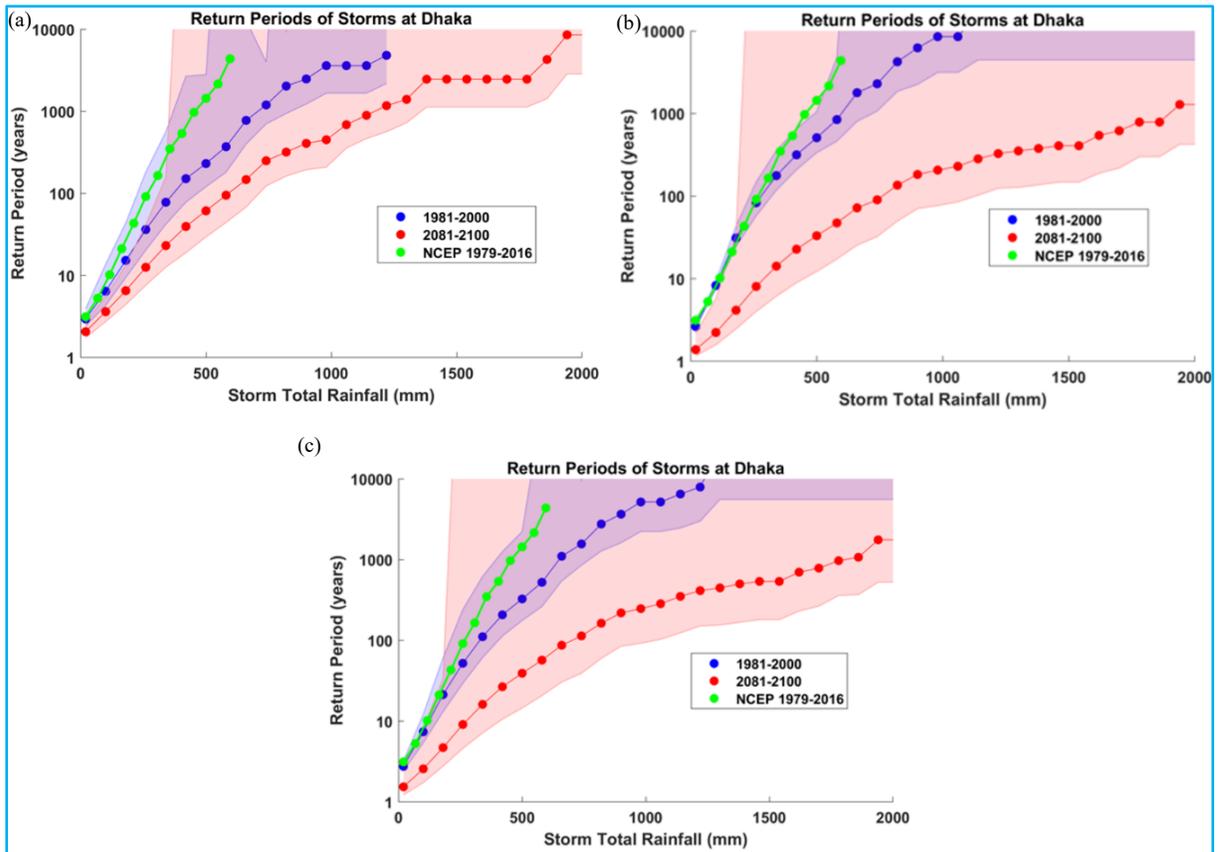
Figs. 4(a-c). Return periods of tropical cyclone winds on the Bangladesh coastline from downscaling. (a) CMIP5 models, (b) CMIP6 models and (c) both together. The green curve in all three panels is from downscaled NCCAR/NCEP tropical cyclones for the period 1979-2016, as in Fig. 3(a). The blue curves are the 1981-2000 results from downscaling the historical simulations, while the red curves represent the period 2081-2100 from RCP 8.5 (CMIP5) and SSP5 8.5 (CMIP6), The shading represents one standard deviation up and down (in annual exceedance frequency) among models downscaled

(Vinayachandran *et al.*, 2002) and there are even indications that the salt stratification is increasing, leading to more intense cyclones (Fan *et al.*, 2020). Stronger density stratification reduces vertical mixing, leading to stronger cyclones, all other things being equal.

To test whether such an effect makes a difference in our intensity model, we modified it to include the effects of salinity on potential density. [The original ocean mixing model is described in detail in Emanuel *et al.* (2004)]. For this purpose we used the long-term monthly mean upper ocean climatology of Levitus (1982), which does not, however, take into account any change in the upper ocean thermal and salinity structure in recent decades. The downscaling model was re-run with this one change and the effect on wind return periods is shown in Fig. 3(b). While, as expected, there is hardly any effect on weak storms, the frequency of stronger storms is indeed increased, though not enough to account, by itself, for the

discrepancy between the downscaled results and the JTWC-analyzed historical events.

Figs. 4(a-c) displays the return periods of maximum surface winds accompanying tropical cyclones whose centers were crossing the line segments shown in Fig. 2, downscaled from climate models. The left panel shows the results of the CMIP5 model downscaling, the right panel shows CMIP6 and the bottom panel shows return periods based on the combination of CMIP5 and CMIP6 downscaling. Each panel also shows (in green) the return periods of tropical cyclones downscaled from NCCAR/NCEP reanalyses over the period 1979-2016, as in Fig. 3(a). The blue curves are from the CMIP model historical simulations 1981-2000 and the red from the RCP 8.5 (CMIP5) and SSP5 8.5 (CMIP6) simulations, 2081-2100. The shading shows one standard deviation (in exceedance frequency) among the five CMIP5 and seven CMIP6 models.



Figs. 5(a-c). Return periods of tropical cyclone storm total rainfall at the city of Dhaka, from downscaling. (a) CMIP5 models, (b) CMIP6 models and (c) both together. The green curve in all three panels is from downscaled NCCAR/NCEP tropical cyclones for the period 1979-2016. The blue curves are the 1981-2000 results from downscaling the historical simulations, while the red curves represent the period 2081-2100 from RCP 8.5 (CMIP5) and SSP5 8.5 (CMIP6). The shading represents one standard deviation up and down (in annual exceedance frequency) among models downscaled

The multi-model consensus shows appreciable increase in tropical cyclone wind risk resulting from global warming; more so among the CMIP6 models than the CMIP5 models. For example, for the combined results, the multi-model mean return period of 150 kts at the coast decreases from 425 years in the historical period to 45 years by the end of this century, a nearly ten-fold reduction. The frequency of hurricane-force winds doubles from once in four years to once in two years.

It is evident from Figs. 4(a-c) that the overall frequency of tropical cyclones crossing the coast of Bangladesh increases in the multi-model consensus. If we artificially hold the overall frequency constant and recalculate the return periods, the high intensity events still increase in frequency. For example, the return period of 150 kts still decreases from 425 years in the historical period to 110 years by the end of the century (not shown), an increase of roughly a factor of four. Thus we may conclude that the increase frequency of high intensity

events is owing both to an overall increase in tropical cyclone frequency and to a shift to greater storm intensity.

We calculated storm total rainfall at Dhaka, the capital and largest city of Bangladesh, located about 300 km inland from the coast, using the technique described in Feldmann *et al.* (2019). The return periods of storm total rainfall are displayed in Figs. 5(a-c), in the same format as Fig. 4. The return periods of rainfall downscaled from NCCAR/NCEP [green curves in Figs. 5(a-c)] are in this case nearly one standard deviation higher than the multi-model mean of the historical simulations from the CMIP models but nevertheless well within the scatter among those models.

As with the winds, the changes in storm total rainfall wrought by global warming are larger in the CMIP6 models than in CMIP5. The projected percentage increases in rainfall are quite large, owing to the compound effects of increased frequency and intensity of

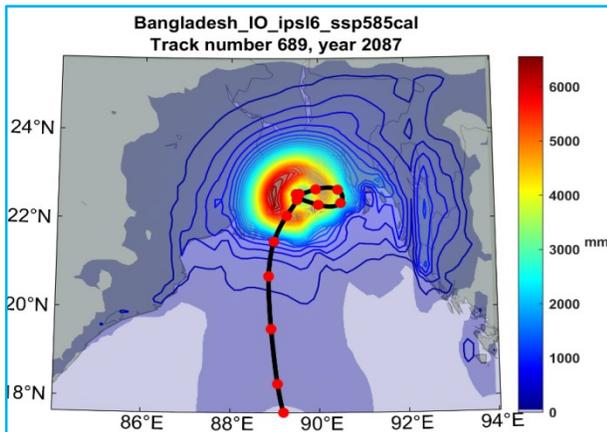


Fig. 6. Map of storm total rainfall for an event downscaled from the CMIP6 IPSL model, that stalls over southern Bangladesh in September 2087. Contours show storm total rainfall (mm) according to scale at right. Black curve shows track of storm center with red dots at 12-hour intervals

storms together with the greater availability of moisture in the warmer atmosphere. For example, the annual probability of a storm total rainfall of at least 1 m increases from once in 5200 years to once in 250 years, while the annual probability of rainfall in excess of 500 mm increases from once in 325 years to once in 40 years. The return period of 100 mm of rain decreases from 7 years in the late 20th century to 3 years by the end of this century.

Return periods of heavy rains at a specific location will underestimate the risk of heavy rain somewhere in Bangladesh and flooding will depend on area-integrated rainfall. Fig. 6 maps the storm total rainfall for an event that produced just over a meter of rain at Dhaka in mid-September of 2087, downscaled from the IPSL model. The storm, which is intense and wet, stalls over southern Bangladesh and produces over 6 m of rain in some places. The 1 meter of rain in Dhaka would be a 250-year event for the city, but the 250-year rain event for Bangladesh as a whole would produce somewhat more than 1 m of rain.

3. Summary

Bangladesh has suffered immensely from tropical cyclones, with much of the damage and loss of life resulting from storm surge and freshwater flooding. Here we show that the combination of rising sea level, more atmospheric moisture and worsening storms, all resulting from global warming, pose very high risk for the nation moving forward into this century. In particular, we downscaled 5 CMIP-5 and 7 CMIP-6 models, as well as NCAR-NCEP reanalyses, to produce nearly 52,000 synthetic tropical cyclone events and used these to estimate current and future wind and rain risk to

Bangladesh. These downscaled tropical cyclone account for changing genesis frequency and location, changing tracks, moisture availability and storm intensity and size as climate changes, but with much uncertainty tracing to the differing projections by the various climate models we used. While advances in climate science and improvements in climate models offer the prospect of reduced uncertainty, the risk as currently assessed warrants determined action to mitigate and adapt to existing and future tropical cyclones.

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