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Fewer, but More Intense, Future Tropical Storms Over the Ganges and Mekong Basins

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Key Points:

- We used multiple CMIP6 HighResMIP models and two trackers to estimate the change in the Tropical Storms (TS) characteristics over the Ganges and Mekong basins
- Our results show a decline in the future frequency of TS but increase in the future intensity and Available Cyclone Energy of TS over both basins
- Both tracking algorithms produce qualitatively similar but quantitatively different results

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Understanding climate change impacts on Tropical Storm (TS) activity is crucial for effective adaptation planning and risk assessment, particularly in densely populated low-lying delta rivers basins like the Ganges and Mekong. The change to TS characteristics with warming is uncertain due to limitations in global climate model resolution and process-representation and storm tracking algorithms (trackers). Here, we used 13 HighResMIP models and two trackers to estimate the uncertainty in projections of TS characteristics. We found different trackers producing qualitatively similar but quantitatively different results. Our results show a decline (median ∼52%) in the frequency of TS but increase in the strongest TS and Available Cyclone Energy (ACE) of TS over both basins. The higher-resolution models extract TS with much higher intensity and ACE values compared to the lower-resolution models. These results have implications for adaptation planning and risk assessment for TS and suggest the need for further high-resolution modeling studies.

Plain Language Summary Tropical Storms (TS) are one of the world's most damaging natural hazards which result in colossal socio-economic losses to life, infrastructure, and property, especially in low-lying delta rivers basins like the Ganges and Mekong. Knowledge of changes to TS activity under climate change can therefore be helpful in better disaster risk mitigation and climate adaptation. Previous modeling studies have used coarse-resolution global climate models unable to capture key TS characteristics. In this study, we utilized finer resolution (up to ∼25 km at six hourly time-steps) CMIP6 HighResMIP models and two different tracking algorithms (trackers) to resolve a part of this uncertainty. Our results project a decline to the frequency of future TS but an increase in the strength of TS (in terms of intensity and Available Cyclone Energy, qualitatively similar for both trackers). These findings can be used to assess the future resilience of existing infrastructure systems to Tropical Storms across these densely populated basins.

1. Introduction

The water vapor from the ocean in the tropics leads to tropical disturbances, which can sustain wind speeds (WS) greater than 17.4 m/s classified as Tropical Storms (TS), and when WS exceeds 33 m/s, they are classified as Tropical Cyclones (TC). Very intense TS or TC (WS > 33 m/s) originating in the North Indian Ocean (NIO) account for about 7% of global TCs, mostly forming in the Bay of Bengal rather than the Arabian Sea (Dube et al., 1997). Annually, ∼90 Tropical Storms are formed around the world, with most causing major disasters (Murakami et al., 2013) if they make landfall. Very intense TS are one of the most damaging natural hazards and can result in massive socio-economic losses to life, infrastructure and property, especially in low-lying delta systems in Bangladesh, Vietnam and the east coast of India (Gupta et al., 2018) where there is limited adaptive capacity and preparedness. Understanding and predicting future changes in the frequency or intensity of Tropical Storms will improve forecasts, and risk assessment and is vital for climate change adaptation. This understanding is crucial in the development of management approaches to prevent and reduce the losses caused by intense Tropical Storms.

Besides strong winds, Tropical Storms also lead to intense rainfall. Chen et al. (2019) found a 12.4% contribution of TS-induced rainfall to annual total rainfall in the lower eastern Mekong basin. Moreover, the rainfall rate associated with intense Tropical Storms is projected to increase under the warming climate (Knutson et al., 2015). Tropical Storms also play an important role in providing freshwater resources, through a significant contribution to regional rainfall totals (Franco-Díaz et al., 2019), and the vital transport of sediment to delta regions, especially in the Mekong basin (Chen et al., 2019). Rainfall induced by Tropical Storms is also useful for irrigation and the recharge of groundwater tables in the cultivation regions of Bangladesh.

The influence of climate change and anthropogenic activities on Tropical Storm genesis remains uncertain (Bianchi & Malki-Epshtein, 2021). Some previous studies have shown an increasing trend in the frequency of severe Tropical Storms over the NIO (Singh et al., 2000, 2001). Moreover, studies based on high-resolution dynamical models (e.g., Christensen et al., 2013; Knutson et al., 2010) suggest that global warming will have a strong impact on TCs, resulting in an increase in their intensity of 2%–11% by 2100. Additionally, modeling studies (Knutson et al., 2010; Roberts et al., 2020b) project a decrease in the global average frequency of TCs by some 6%–34%, but predict a substantial increase in the frequency of the most intense cyclones associated with heavy precipitation within 100 km of the storm center. Although it is debatable whether the number of Tropical Storms will increase or decline, their impacts are expected to increase enormously in the future (Hoque et al., 2019).

Projections from global multimodel simulations can be helpful to understand Tropical Storm activity; however, their performance is often questionable due to their lack of horizontal resolution. Most of the models from the Coupled Model Intercomparison Project (CMIP6, Eyring et al., 2016) have model grid spacing typically coarser than 100 km, which might fail to simulate TS characteristics (Gentry & Lackmann, 2010). Although studies have examined the impact of improved horizontal resolution (discussed in Roberts et al. (2020a)), their comparison of results is unfair as their model differs from others in experimental design, model parameters and tracking algorithms. This issue is solved by the CMIP6 High-Resolution Model Intercomparison Project (HighResMIP, Haarsma et al., 2016) which provides a common protocol for multimodel and multiresolution ensembles.

Here, we examine changes to TS characteristics over the Ganga-Brahmaputra-Meghna (Ganges) and Mekong basins in the NIO using the European Union Horizon 2020 project PRIMAVERA models; these utilize the HighResMIP protocol and are available at up to 25 km resolution. Although the NIO experiences relatively few TS per year, its densely populated basins are highly vulnerable to TS and are adversely affected by them through damages to property, crops, and livestock, placing greater stress on health services and providing risks to life. We estimate TS characteristics in the two selected basins in the NIO using TS tracks based on two different tracking algorithms to address the following key science questions:

1. How well are TS represented in high-resolution models (HR-MODELS)?
2. How robust are different tracking algorithms in identifying TS across all models?
3. How are TS characteristics projected to change in the future?

2. Data and Methods

2.1. Data

We obtained Tropical Storm tracks using simulations from the multimodel ensemble of climate models produced as part of the High-Resolution Model Intercomparison Project (HighResMIP, Haarsma et al., 2016). HighResMIP is one of the sub-projects of the Coupled Model Intercomparison Project (CMIP6, Eyring et al., 2016) but is more focussed on smaller scale processes and features like storms (Roberts et al., 2020b). Also, HighResMIP provides higher-resolution models (up to 25 km) giving much more realistic information on the modeled storms at a finer spatial scale which is not extracted by the coarser CMIP6 models (Dong & Dong, 2021; Roberts et al., 2020a). However, the simulations only span 1950–2050 and fewer ensembles are available for most models which might lead to a weaker signal-to-noise ratio. The HighResMIP models provide both atmosphere-only and coupled atmosphere-ocean simulations. We used coupled model simulations in this study as they are a much more self-consistent system despite being influenced by SST biases.

Notwithstanding these limitations, we used simulations from 13 models to test the robustness of the forcing-response change across different models and resolutions. These models include HadGEM3-GC31 (Roberts et al., 2020b), EC-Earth3P (Haarsma et al., 2020), CNRM-CM6-1 (A Voldoire et al., 2019), MPI-ESM1-2 (Gutjahr et al., 2019), and CMCC-CM2-(V)HR4 (Cherchi et al., 2019). More details on the models can be found in Table S1 in Supporting Information S1. The future (2015–2050) simulations are based on the high-emission SSP585 scenario (similar to the CMIP5 RCP8.5, Roberts et al., 2020b). The tropical storm tracks and associated meteorological variables (at six hourly steps) for different HighResMIP models are available as a part of the PRIMAVERA project (Roberts et al., 2020a) and can be accessed through the CEDA Archive (https://data.ceda.

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ac.uk/badc/highresmip-derived/data/storm_tracks/). Roberts et al. (2020b) assessed the ability of these models to extract TS; from the selected models, they found very few TCs for MPI-ESM1-2 models, too many TCs for HadGEM3-GC31-HM and CMCC-CM2-VHR4, close to the observations for CNRM-CM6-1-HR.

To check the consistency of our results with the HighResMIP models we also used two reference data sets for the comparison: IBTrACS (Knapp et al., 2010) and ERA5 data (Hersbach et al., 2020). More details on these datasets can be found in Supporting Information S1.

To check the sensitivity (robustness) of different tracking algorithms (trackers) in identifying Tropical Storm tracks, we used two trackers: TRACK (Hodges et al., 2017) and TempestExtremes (Ullrich & Zarzycki, 2017; TempExt hereafter). More details on the trackers can be found in Supporting Information S1.

We have used the periods 1980–2010 (historic period) and 2020–2050 (future period) to compare the changes in future projections against historic simulations. Models with relatively higher resolution (25–50 km grid) are categorized as HR-MODELS and those with lower resolution (100–250 km grid) are categorized as low-resolution models (LR-MODELS) (Table S2 in Supporting Information S1). Also, for TempExt, TS tracks that make landfall in the Ganges are available for only nine models (Table S3 in Supporting Information S1). Therefore, to check consistency between the two trackers we present the same nine models in our main results; results from all models are discussed in Supporting Information S1.

2.2. Metrics

We used three metrics to understand the changes to Tropical Storm activity in the future compared to the historic period: frequency, intensity and Accumulated Cyclone Energy (ACE). The frequency is the TS count per year and is very sensitive to the model resolution and the tracking algorithm used. Intensity is based only on wind velocities (not precipitation rates) and is calculated using the standard method of using 10 m wind speed at the time when the TS obtains its lifetime maximum wind speed at 925 hPa. The ACE index defines the strength of TS activity and is calculated by summing the square of maximum wind speed (at 925 hPa) every 6 hr throughout the lifetime of the storm during its warm core phase (Camp et al., 2015).

The frequency change is different for models with different mean intensity and grouping the intensities of all TS together might add complexity to interpreting their PDFs. Notwithstanding this limitation, we used a non-parametric Kernel density method to estimate PDFs to compare the probability density function of the intensity/ACE for the different models (HR-, LR-MODELS) and period combinations. The details on the study region can be found in Supporting Information S1.

3. Results and Discussion

3.1. Tropical Storm Frequency Changes

We first evaluated the CMIP6 HighResMIP models in simulating TS against reference data sets like IBTrACS and ERA5 data. Figure 1a shows the comparison between HighResMIP (using TRACK algorithm) and IBTrACS best track data in simulating the frequency of TS over the Ganges basin for 1950–2020 period. Three out of five HR-MODELS show a better agreement in estimating number of TS per year. For the 25 km resolution models (CMCC-CM2-VHR4 and HadGEM3-GC31-HH) and IBTrACS data, the average number of TS per year is 1.46 and 1.70 respectively for models and 1.39 for IBTrACS data. The majority of LR-MODELS overestimate TS/year as compared to the IBTrACS data. We also (for the first time) used TS tracks from the ERA5 reanalysis for the TRACK tracker (derived in the same way as for the HighResMIP simulations) to examine the agreement between the reanalysis and the HighResMIP simulations for the historic period (1979–2020) over the Ganges basin. Our results show that the frequency/magnitude of variability in ERA5 is in better agreement with the HR-MODELS as compared to the LR-MODELS (Figure 1b). In summary, our results show that models at 25 km resolution extract a similar number of TS per year as compared to two reference data sets.

We next performed an inter-comparison of different trackers and models in simulating TS frequency in the Ganges basin for 1980–2050 (Figure 2). We found that for HR-MODELS both trackers show a very small increase in the annual frequency of TS until the early 2010s and then a decline into the future (Figures 2a and 2c). This trend is not visible in the LR-MODELS and may emphasize the need for HR-MODELS for conducting

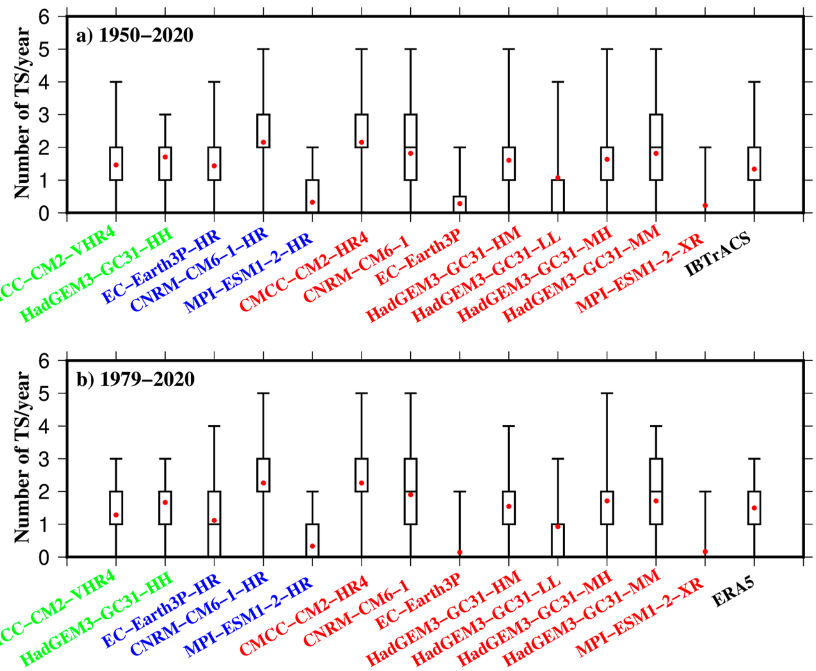

Figure 1. Annual Frequency of Tropical Storm that make landfall in the Ganges basin for CMIP6 HighResMIP models using the TRACK tracking algorithm and (a) IBTrACS data during 1950–2020 period and (b) ERA5 data during 1979–2020 period. Boxes represent median, lower, and upper quartiles; whiskers extend from minimum to maximum values and red dots represent mean values. The models name in green, blue, and red colors are at 25, 50, and coarser than 50 km atmospheric nominal resolution, respectively.

such studies (Figures 2b and 2d). The total number of TS for TempExt is less than for the TRACK algorithm (Figures 2e and 2f), with greater disparities for lower resolution (LR-models); consistent with the findings of Roberts et al. (2020b). We also checked the significance of our results using the Bootstrap Percentile Method as the results presented in Figure 2 can be sensitive to the choice of the time period. Bootstrap results for the change in TS frequency over the Ganges basin are shown in Figure S2 in Supporting Information S1. The sign for the change in the frequency of TS is positive for all distribution of periods. That means these models project a significant (at least 95% confidence interval) decline in the frequency of TS in the future. Moreover, for all models (except CMCC-CM2-HR4 and CNRM-CM6-1), there is a projected decline in TS for more than 75% of the period combinations. We also estimated the TS frequency over the Mekong basin and found a future decline in the frequency of TS for the Mekong basin using both trackers (Figure S3 in Supporting Information S1). The number of TS extracted by TRACK in the Mekong is greater than for TempExt, where the latter tracker fails to extract TS for a majority of the models.

The mechanism leading to the decrease in TS frequency in the warming future is still debatable. The frequency of TS mainly depends on the balance between atmosphere stability (DeMaria et al., 2001), CAPE (Chen et al., 2019), and environmental factors including vorticity, vertical shear of the horizontal wind and the saturation deficit of the free troposphere (Emanuel, 2013). The projected increase in the CAPE in the future will act as a large source of energy for cyclone genesis (Emanuel, 2005) and should increase the frequency/intensity of TS in the future. On contrary, the atmospheric stability and saturation deficit of the free troposphere are projected to increase in the future due to global warming. These factors will inhibit the formation of storms and dampen the increases in the frequency of future TS (Bianchi & Malki-Epshtein, 2021; Emanuel, 2013; Fowler et al., 2021).

Our analysis, based on the evaluation of different climate models, highlights model bias in producing TS simulations. TS simulations are highly dependent on the ability of models to adequately reproduce the changes in large-scale processes that affect TS development (Knutson et al., 2010). We found a quantitative difference in the frequency changes from the different trackers. TempExt most likely misses the weaker storms as they use different detection variables and criteria (mean sea-level pressure) whereas TRACK uses vorticity, spectrally truncated at T63, thus identifying larger-scale features and less sensitive to model grid resolution. Despite producing

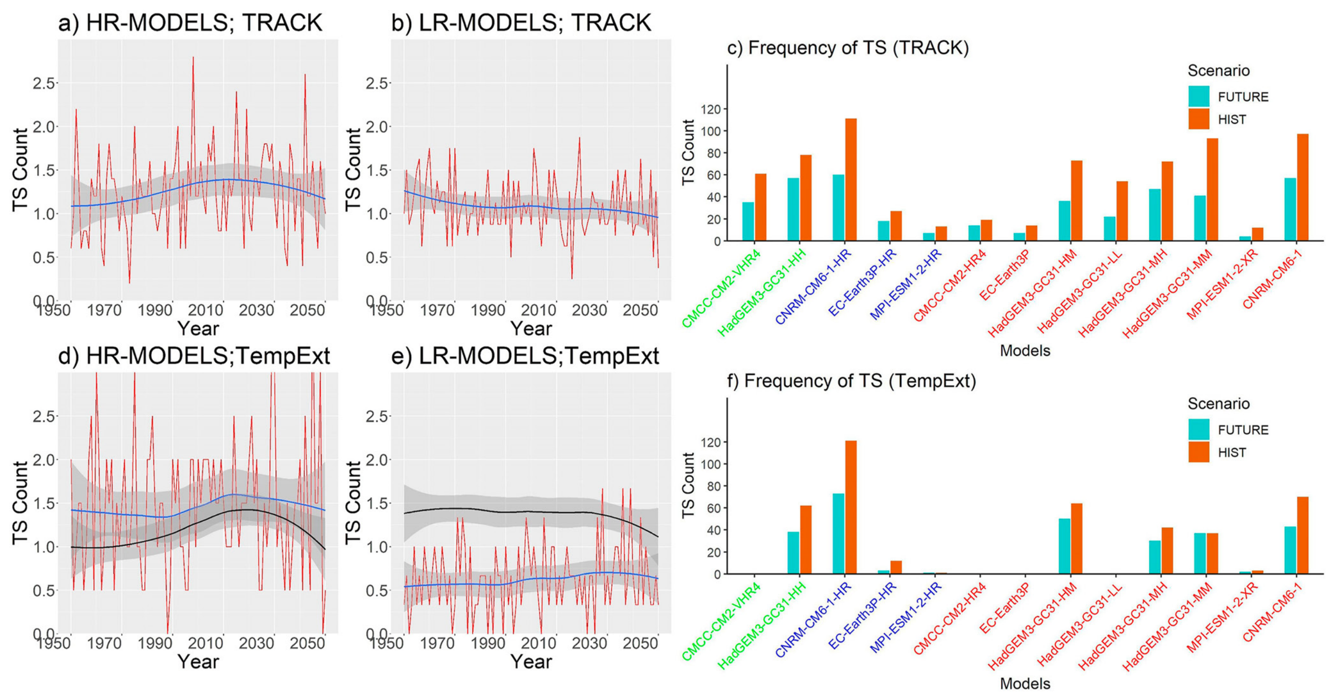

Figure 2. Annual Frequency of Tropical Strom (TS) that make landfall in the Ganges basin using the TRACK tracking algorithm for (a) high-resolution models, (b) low-resolution models, (c) frequency of TS for 1980–2010 (HIST, orange color) and 2020–2050 (FUTURE, cyan color) using TRACK, and (d–f) same as (a–c) but using the TempExt tracker. Detailed information on the models is in Tables S1–S3 in Supporting Information S1. The red lines (a, b, d, and e) show ensemble mean values, the blue lines show a loess curve, and the gray region shows 95% confidence limits. The black lines show a loess curve for TRACKS using only models for which data is available for TempExt. The model names in green, blue, and red colors are at 25, 50, and coarser than the 50 km atmospheric nominal resolution, respectively.

different quantitative results, arising from the different specifications of the tracking algorithms, both trackers produce similar qualitative results. Our results are consistent with the findings of Müller et al. (2022), where they used four different trackers but on precipitation fields; they concluded that all four trackers are reliable analysis tools for atmospheric research and that each tracker gives similar conclusions.

3.2. Tropical Storm Intensity Changes

We next performed an inter-comparison of the trackers and models in estimating the intensity of TS in the Ganges (Figure 3). Our results show higher intensification of the strongest TS in the future (2020–2050) compared to the historical (1980–2010) period for both trackers as compared to the moderate TS. Importantly, HR-MODELS extract more intense TS when compared to LR-MODELS (Figures 3c and 3d). The finest resolution models (CMCC-CM2-VHR4 and HadGEM3-GC31-HH) extract the most intense TS. Kernel density plots for the HR-MODELS show the heavy-tailed distribution of TS intensity for the future period for both trackers. The significance of these results is further evaluated using the bootstrap analysis on all TS and very intense (greater than 95th percentile intensity) TS over the entire period (1950–2050) keeping 30 years period to estimate the change. Bootstrapping results show a significant (at least 95% confidence interval) higher increase in the intensity of very intense TS for the majority of the HR-MODELS as compared to all TS (Figure S4 in Supporting Information S1). The increase in intensity for the most intense TS is up to median 19.2% for HR-MODELS (Figure S4b in Supporting Information S1).

Similarly, for the Mekong, our results indicate more intense TS in the future using TRACK (Figures S5a and S5c in Supporting Information S1). We note here the limitations in the TempExt tracking algorithm in capturing insufficient TS across the Mekong basin; this significantly influences intensity results (Figure S5b in Supporting Information S1). To summarize, our analysis shows clear disparities in the changes to TS intensity from different models and trackers but we find that all models and trackers show consistently more intense TS in the future across the Ganges and Mekong basins.

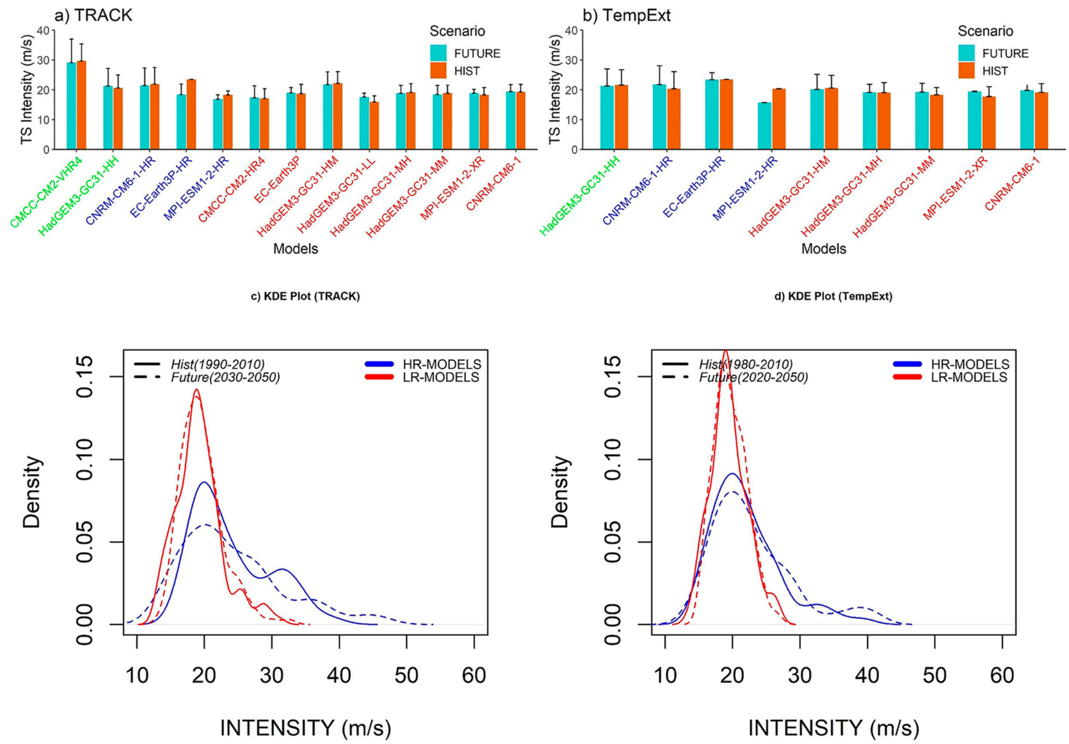

Figure 3. Intensity (in m/s) of Tropical Strom (TS) that make landfall in the Ganges basin for 1980–2010 (HIST, orange color) and 2020–2050 (FUTURE, cyan color) using (a) TRACK tracker, (b) TempExt tracker, (c) Kernel density plot of Intensity of TS using TRACK tracker for high-resolution models (blue) and low-resolution models for HIST (1980–2010, solid lines) and FUTURE (2020–2050, dashed lines), and (d) same as (c) but for TempExt tracker. The bars in panel (a, b) show median intensity values and the whiskers show standard deviation. The model names in green, blue, and red colors are at 25, 50, and coarser than the 50 km atmospheric nominal resolution, respectively.

Davis (2018) have argued that models with resolution of 0.25° or coarser fail to produce very intense (category 4 and 5) TS as coarser grids are not able to sample higher WS as compared to HR-MODELS. Furthermore, Gentry and Lackmann (2010) suggested at least 2 km grid models for studying physical processes in the TC eyeball and at least 3 km resolution models for operational prediction. However, given the limitations in the availability of the large-scale HR-MODELS simulations, Roberts et al. (2020b) showed that HR-MODELS (ranging between 20 and 50 km resolutions) are able to extract more intense TS and go toward observations.

The physical causes for the projected increases in the intensities of TS are increasing SSTs and changes to the upper atmosphere conditions in terms of maximum wind speed (Emanuel, 2000; Wing et al., 2015). TS will derive more energy from the heat (energy) stored on the ocean surface, leading to more intense and damaging storms in the future (Wing et al., 2007). Also, the changes in TS intensity are dominated by thermodynamic air-sea disequilibrium (Wing et al., 2015). This is also supported by climate modeling studies which indicate that although there is uncertainty in projecting changes to future TS climatology, the intensities of the strongest TS will further increase (Emanuel, 2017; Kossin et al., 2013).

3.3. Tropical Storm ACE Changes

We find a future increase in ACE in the Ganges for both trackers across the majority of models. TRACK identifies stronger (higher ACE) TS, as compared to TempExt, and the projected increase in ACE is also greater for TRACK than for TempExt (Figure 4). Moreover, the HR-MODELS extract TS associated with higher ACE than the LR-MODELS. For instance, the CMCC-CM2-VHR4 model (finest; at 25 km resolution) extracts TS with the highest ACE values in its historical simulation, which further increases in the future period. Similarly, for the Mekong basin, we found TS were associated with higher ACE values in the future than for the historical period (Figure S6 in Supporting Information S1).

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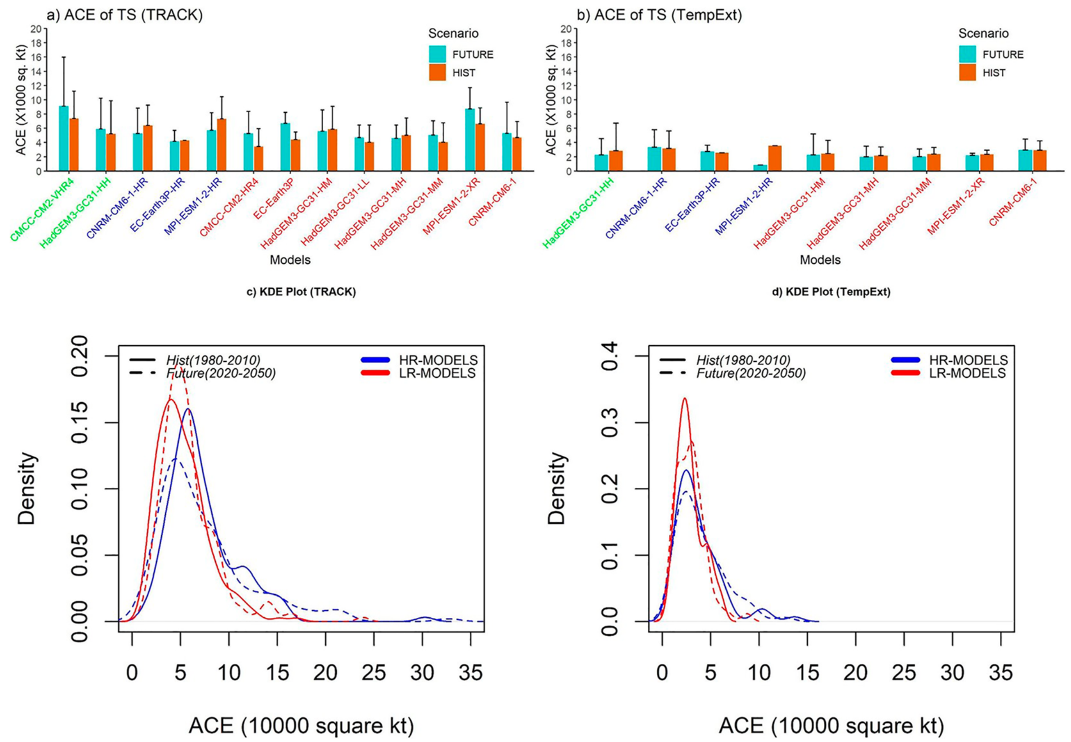

Figure 4. Available Cyclone Energy (ACE) of Tropical Strom (TS) that make landfall in the Ganges basin for 1980–2010 (HIST, orange color) and 2020–2050 (FUTURE, cyan color) using (a) TRACK tracker, (b) TempExt tracker, (c) Kernel density plot of ACE of TS using the TRACK tracker for high-resolution models (blue) and low-resolution models for HIST (1980–2010, solid lines) and FUTURE (2020–2050, dash lines), and (d) same as (c) but for TempExt tracker. The whiskers in panel (a, b) show median values and the bars show standard deviation. The model names in green, blue, and red colors are at 25, 50, and coarser than the 50 km atmospheric nominal resolution, respectively.

Figure S7 in Supporting Information S1 summarizes the change to TS characteristics between the historical (1980–2010) and future (2020–2050) periods across the HR- and LR-MODELS in the Ganges and the Mekong basins. The majority of models project a decline in TS frequency but an increase in storm strength (intensity and ACE) for both trackers and basins for the majority of models; however, the change is not systematic (Bourdin et al., 2022). The rate of increase in the ACE (function of maximum wind speed and the lifetime of TS) is more than the intensity (function of maximum wind speed only) due to the increase in the lifetime of TS in the future (Figure S8 in Supporting Information S1).

4. Conclusion

Understanding the future evolving characteristics of TS is extremely challenging due to uncertainties associated with global climate model structures and resolutions. We have partially resolved this here by using the CMIP6 HighResMIP protocols using multi models, and different tracking algorithms to extract TS. Here, we compared two different storm tracking algorithms and evaluated multi models from the PRIMAVERA project in simulating TS across the Ganges and the Mekong basins. We conclude that:

1. TS frequency increased until the early 2010s but frequencies are projected to decline (by a median of 52%) for the high-resolution (HR-MODELS) models across both basins. TRACK extracts more TS compared to TempExt for both basins.
2. The majority of models show an increase in the intensity of TS in the future across both basins. HR-models extract more intense TS compared to LR models and show larger increases in the most intense TS in future projections.
3. Both tracking algorithms indicate a future increase in ACE for TS across the majority of models over both basins. TRACK identifies TS associated with higher ACE values compared to the TempExt tracker; the future increase in ACE is greater for TRACK than for TempExt (except for HR-MODELS for the Mekong basin).

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Our understanding of the future changes in TS characteristics is hindered by the limitations in model configurations for simulating realistic TS. The biggest challenge in using climate models (like the CMIP5 GCMs) is in their ability to extract severe storms, limited by their coarse resolution. Our study solves a part of this problem by utilizing fine-resolution HighResMIP models which show smaller biases against wind speed observations and therefore should produce more realistic estimates of future changes to intensity.

Despite similar qualitative results (i.e., fewer but stronger TS in the future), the quantitative differences in projected changes to TS characteristics using different trackers and models highlight the need for more studies on uncertainties associated with storm tracking algorithms and using multimodel ensembles, including more trackers and many more high-resolution climate models with longer runs into the past and future. Our study is based on a limited "ensemble of opportunity" and relatively short simulations. Also, assumptions made in the comparison of the two tracking algorithms may lead to uncertainty in our results. However, our findings will be useful for assessing the future resilience of existing infrastructure systems to Tropical Storms and in developing climate adaptation policies across two overpopulated and important delta basins.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

This article draws on data that will be made available via Newcastle University's Research Repository (https://data.ncl.ac.uk/). The data will be available from March 2025 onwards, as part of the data generated by the GCRF UKRI-funded Living Deltas Hub (2019–2024) under Grant Reference NE/S008926/1. https://doi.org/10.25405/data.ncl.c.6288033.v1.

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