Increased Global Tropical Cyclone Activity from Global Warming: Results of Downscaling CMIP5 Climate Models

Kerry Emanuel

Program in Atmospheres, Oceans, and Climate Department of Earth, Atmospheric and Planetary Sciences Massachusetts Institute of Technology

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A recently developed technique for simulating large (O(104)) numbers of tropical cyclones in climate states described by global gridded data is applied to simulations of historical and future climate states simulated by five CMIP5 global climate models run in support of the upcoming IPCC report. Tropical cyclones downscaled from the climate of the period 1950-2005 are compared to those of the 21st Century in simulations that stipulate that the radiative forcing from greenhouse gases increases by over the course of the century. In contrast to storms that appear explicitly in most global models, the frequency of downscaled tropical cyclones increases over the 21st century in most locations. The intensity of such storms, as measured by their maximum wind speeds, also increases, in agreement with previous results. Increases in tropical cyclone activity are most prominent in the western North Pacific, but are evident in other regions except for the southwestern Pacific. These results are compared to and contrasted with other inferences concerning the effect of global warming on tropical cyclones.

Climate change | Global warming | Natural hazards | Tropical cyclones

1. Introduction

Some 90 tropical cyclones develop around the world each year, and this number has been quite stable since reliable records began at the dawn of the satellite era, about 40 years ago. The interannual variability of just over 9 storms per year is not distinguishable from a Poisson process. The physics behind these numbers remains enigmatic, and the general relationship between tropical cyclone activity and climate is only beginning to be understood.

It has been known for at least 60 years that tropical cyclones are driven by surface enthalpy fluxes (1, 2), which depend on the difference between the saturation enthalpy of the sea surface and the moist static energy of the subcloud layer. On time scales larger than that characterizing the thermal equilibration of the ocean's mixed layer (roughly a year), this enthalpy difference is controlled by the net radiative flux into the ocean, the net convergence of ocean heat transport, and the mean speed of the surface wind (3). An increase of the net surface radiative flux, brought about by increasing greenhouse gas concentrations, should result in an increase in the enthalpy jump at the sea surface, enabling tropical cyclones of greater intensity. Calculations with a single-column model (4) confirm that increasing greenhouse gas content increases the enthalpy jump, and with it, the potential intensity of tropical cyclones. Experiments with general circulation models also show that the intensity of the most intense tropical cyclones, which are usually close to their thermodynamic intensity limit, generally increases as the planet warms (e.g. 4, 5).

Although global warming increases the thermodynamic potential for tropical cyclones, the frequency and to some extent the intensity of such storms respond to several other environmental factors, first elucidated by Gray (6). These include the vertical shear of the horizontal wind, environmental vorticity, and the humidity of the free troposphere. The response of one or more of these additional factors to global climate change generally results in a reduction of the global frequency of tropical cyclones as the climate warms, seen in many explicit and downscaled simulations using global climate models (7). The most likely explanation for this decrease is the increase in the saturation deficit of the free troposphere as represented by the nondimensional parameter χdefined by Emanuel (8):

$$\chi \equiv \frac{h^* - h_m}{h_0^* - h^*}, \qquad (1)$$

where h^* is the saturation moist static energy of the free troposphere (nearly constant with altitude in a moist adiabatic atmosphere), $h_m$is a representative value of the actual moist static energy of the middle troposphere[1], and h_0^* is the saturation moist static energy of the sea surface. Under global warming, both the numerator and the denominator of (1) increase, but the former increases somewhat faster than the latter. At constant relative humidity, the numerator increases with temperature following the Clausius-Clapeyron relation, while the denominator increases in proportion to the surface turbulent enthalpy flux, which in the global annual mean is constrained to balance the net radiative cooling of the troposphere, which increases only slowly with global warming (9). While one may therefore expect χ to increase in the global mean, its trend is highly variable from region to region.

While theory and models indicate that both potential intensity and χ will increase with global mean temperature, leading to the expectation that storm intensity will increase while storm frequency will decrease, one must rely on numerical simulations to produce more detailed and quantitative information on how these storms might respond to climate change. The starting point for most estimates of climate change effects on tropical cyclones is the global climate model. Three techniques have been used to estimate tropical cyclone climatology from global models:

1. Direct simulation. Most climate models today directly simulate tropical cyclones, although they are poorly resolved. It proves not entirely straightforward to detect tropical cyclones in the output of global models, and although there has been much progress on this (e.g. 10), a single, universally agreed-on algorithm has yet to emerge. A clear advantage of direct simulation is

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[1] is probably better represented by a pressure-weighted mean over the moist convective layer. In that case, (1) can be interpreted as the ratio of the time scale for surface fluxes to saturate the troposphere to the time scale for surface fluxes to bring the whole troposphere into thermodynamic equilibrium with the ocean.

that it requires no additional assumptions or model applications (other than the detection algorithm). An important limitation of this approach is that it severely under-resolves tropical cyclones, resulting in a substantial truncation of the intensity spectrum of simulated storms, even at 50-km grid spacing (11), and usually produces fewer events than observed (12).

2. **Dynamical downscaling**. This technique embeds high-resolution regional or local models within GCMs, producing more highly resolved tropical cyclones. It has the advantage of providing high spatial resolution, but suffers from a number of disadvantages, including problems arising from a mismatch of the regional model physics with those of the global model (13) and the lack of feedback of the simulated storms to the global climate system. Nevertheless, we apply a variant of this technique in the present paper.

3. **Genesis indices**. This technique, pioneered by Gray (6), empirically relates observed frequencies of tropical cyclogenesis to large-scale environmental factors as provided by climatological or global model data. These indices have the advantage of a strong empirical foundation and easy applicability to model or reanalysis data sets. On the other hand, they only predict genesis locations and frequencies and do not account for changes in tracks or intensity; moreover, they are usually developed and calibrated to capture regional variability and may not respond accurately to global changes.

A comprehensive listing of these three techniques applied to CMIP3-generation climate models is provided in the supplementary information accompanying Knutson*, et al.* (7), who also summarize the main results of the applications of these techniques. Taken together, they imply a global decrease in the frequency of weaker events but an increase in high-intensity cyclones. On the other hand, there is large inter-model and inter-basin variability in such trends. Most models also predict an increase in precipitation associated with tropical cyclones in most regions (Knutson et al., 2010).

Early results from CMIP5 model simulations show mixed results for global and Atlantic tropical cyclone frequency (12, 14, 15) and some indication of an increase in North Atlantic tropical cyclone intensity (16). While there are too few results to make any decisive statements, these early papers suggest less decrease – and perhaps no decrease – in tropical cyclone frequency, compared to earlier results based on CMIP3-generation models. The only CMIP5-based intensity projections so far pertain to the North Atlantic and these suggest increasing intensity (16).

2. Technique and Models

The present work applies the downscaling technique of Emanuel, Sundararajan and Williams (9) to five CMIP5 global models. Initially, we selected all seven of the global models that archived all of the output needed by our technique, but discarded two of the models that contain large discontinuities between the end of simulations representing the historical period (1950-2005) and the beginning of simulations representing climate projections into the 21st century (2006-2100). The five models we selected are the CM3 model of the Geophysical Fluid Dynamics Laboratory (GFDL) of the National Oceanic and Atmospheric Administration (NOAA), the HADGEM2-ES models of the United Kingdom Meteorological Office Hadley Center, the MPI-ESM-MR model of the Max Plank Institution, the MIROC5 model of the Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute of the University of Tokyo and the National Institute for Environmental Studies, and the MRI-CGCM3 model of the Meteorological Research Institute of Japan. These models will hereafter be referred to respectively as GFDL, HADGEM, MPI, MIROC, and MRI.

Our technique applies a highly resolved, coupled ocean-atmosphere model phrased in angular momentum coordinates (8) to tracks initiated by random seeding in space and time, and propagated forward using a beta-and-advection model driven by winds derived from the AGCM simulations. The intensity model is integrated along each track. In practice a large majority of the events suffer declining intensity from their onset and are discarded; the survivors constitute the tropical cyclone climatology of the model.

The downscaling model relies on large-scale winds both to drive the beta-and-advection track model and for deriving wind shear that is required by the intensity model. As described in Emanuel, Ravela, Vivant and Risi (17), the winds are derived from synthetic time series of winds constrained to have the same monthly means as those produced by the global model, as well as the same monthly mean covariances among the wind components at two model levels, where the fluctuations are defined in terms of departures of daily means from monthly means. The wind time series are also constrained to have power spectra that fall off with the cube of the frequency. The thermodynamic input to the intensity model consists of monthly mean potential intensity and 600 hPa temperature and relative humidity derived from the global models. The ocean component of the intensity model requires ocean mixed layer depth and sub mixed layer thermal stratification; in the simulations described here we use present day climatology for both these quantities. Thus the effect of global warming on the thermal stratification of the upper ocean is not considered here. When driven by NCAR/NCEP reanalyses during the period 1980-2006, this downscaling technique produces results that explain as much of the observed variance in North Atlantic tropical cyclone activity as do certain global models (11, 18) and the regional downscaling model of Knutson, Sirutis, Garner, Held and Tuleya (19), which was also driven by NCAR/NCEP reanalysis data. The technique captures well the observed spatial and seasonal variability of tropical cyclones around the globe, as well as the effects of such climate phenomena as ENSO and the Atlantic Meridional Mode. Thus there are objective reasons to have some confidence in the ability of the downscaling technique to simulate the effects of climate and climate change on tropical cyclone activity. An important advantage of this technique over explicit simulation with global and regional models is that its high resolution of the storm core allows it to capture the full intensity spectrum of real storms.

Our downscaling technique requires a single global calibration of the rate of seeding. Here we calibrate the seeding rate used by each model so as to produce 80 events globally with maximum 1-minute winds at 10 m altitude exceeding 40 knots, averaged over the historical period 1950-2005. Since some of the events included in our data set have maximum winds less than 40 knots, the total storm frequencies shown here may have 1950-2005 averages slightly larger than 80. It should also be noted that, in contrast to Emanuel et al. (2008), we downscale each year of model data separately. We ran 600 events per year globally, for each of the years in the span 1950-2100, using historical simulations for the period 1950-2005 and the RCP8.5 scenario for the period 2006-2100. This large number of events keeps the strictly random (Poisson) interannual variability of global storm counts at less than 5%.

3. Results

Figure 1 shows a box plot of the global frequency of downscaled tropical cyclones, averaging each simulation over 10-year blocks. An increase in global mean frequency during roughly the first three quarters of the 21st century is indicated, with a total increase in the range of 10-40%. Figure 2, displaying the change in track density averaged over the five models, shows that most of the increase in frequency is in the North Pacific, but with substantial increases in the North Atlantic and South Indian oceans as well. The only coastal region that experiences a substantial decline in track crossings is the southeast coast of Australia.

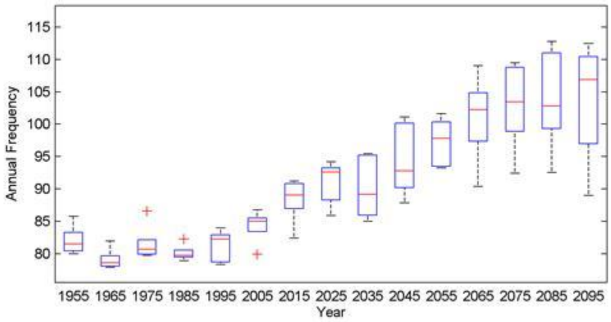

Figure 1: Global annual frequency of tropical cyclones averaged in 10-year blocks for the period 1950-2100, using historical simulations for the period 1950-2005 and the RCP8.5 scenario for the period 2006-2100. In each box, the red line represents the median among the 5 models, and the bottom and tops of the boxes represent the 25th and 75th percentiles, respectively. The whiskers extent to the most extreme points not considered outliers, which are represented by the red + signs. Points are considered outliers if they lie more than 1.5 times the box height above or below the box.

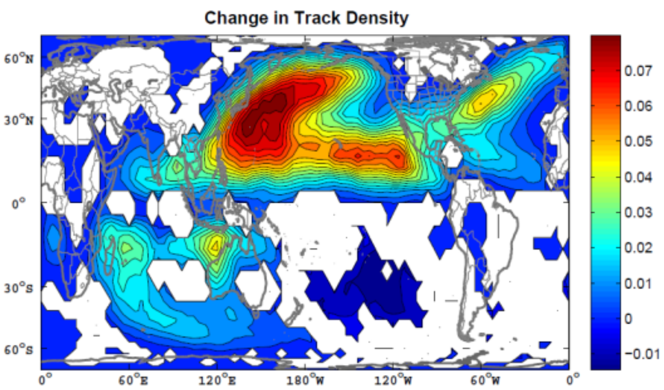

Figure 2: Change in track density, measured in number of events per 4° X 4° square per year, averaged over the five models. The change is the average over the period 2006-2100 minus the average over 1950-2005. The white regions are where fewer than 4 of the 5 models agree on the sign of the change.

One distinct advantage of our downscaling technique is that it captures the full spectrum of storm intensity (17), in contrast with direct global model simulations, which truncate the high intensity events (11) that do a disproportionate amount of total tropical cyclone damage (20, 21). One convenient measure of tropical cyclone intensity is the power dissipation index, an estimate of the total amount of kinetic energy dissipated by tropical cyclones over their lifetimes (22). The power dissipation index is the integral over the lifetime of the storm of its maximum surface wind cubed. Here we also accumulate global power dissipation over each ten-year block from 1950 to 2100 and display the result in Figure 3. Averaged over the 5 models, power dissipation increases by about 50% over the 21st century. Of this increase, very nearly half comes from the increase in the frequency of events discussed previously; the other half comes from an increase in the cube of the surface winds. This is reflected in a 40% increase globally in hurricanes of Saffir-Simpson category 3 and higher.

The spatial distribution of the increase in power dissipation is illustrated in Figure 4. Consistent with the increase in track density, most of the increase in power dissipation is in the North Pacific, but with substantial increases in the western part of the North Atlantic and in the South Indian Ocean as well. Averaged over the 5 models, the power dissipation at landfall[2] increases by about 55% over the 21st century, consistent with the increase in basin-wide power dissipation.

Overall, these results project substantial increases in tropical cyclone activity under the RCP8.5 emissions pathway, at least for the 5 models used here. In the next section, these results are analyzed and compared to and contrasted with previous work.

4. Analysis and comparison to previous work

Although the physics underlying the frequency of tropical cyclogenesis are not well understood, several indices have been developed that empirically relate observed tropical cyclogenesis rates to environmental variables thought to be important in controlling tropical cyclone climatology (e.g. 6, 23). Here we use the genesis potential index (GPI) developed by Emanuel (24):

$$GPI \equiv |\eta|^3 \chi^{-4/3} MAX\left(\left(V_{pot} - 35\, ms^{-1}\right), 0\right)^2 \left(25\, ms^{-1} + V_{shear}\right)^{-4}, \qquad (2)$$

where η is the absolute vorticity of the 850 hPa flow, V_{pot} is the potential intensity in ms^{-1} , V_{shear} is the magnitude of the 850 hPa-250 hPa wind shear (in ms^{-1}), and χ is defined by (1).

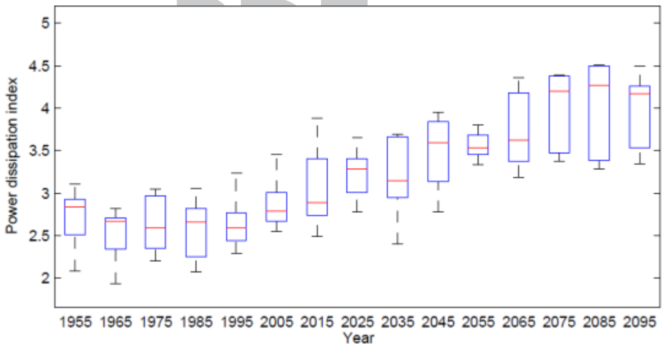

Figure 3: As in Figure 1, but for the power dissipation index. Units are $10^{12} m^3 s^{-2}$.

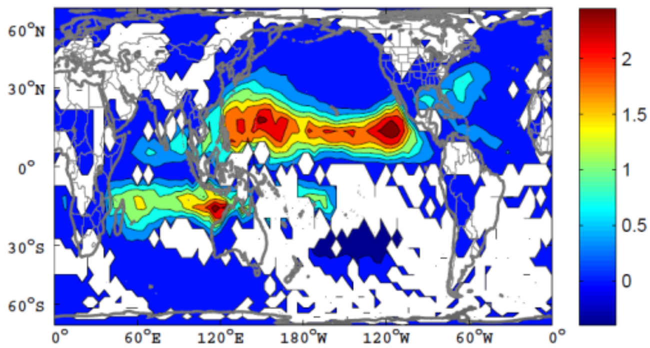

Figure 4: Change in Power Dissipation Index averaged over the 5 models, per 4° latitude square. This is defined as the difference between power dissipation averaged over the period 2006-2100 and that averaged over 1950-2005. Units are $10^8 m^3 s^{-2}$, and white areas show regions in which fewer than 4 of the 5 models agree on the sign of the change.

We calculate the genesis potential index defined by (2) for each of the 5 models, using monthly mean thermodynamic data,

[2] Landfall power dissipation is defined at the cube of the surface winds at the last two-hour snapshot of a tropical cyclone before landfall. Landfall is defined in terms of ¼ x ¼ degree bathymetry.

850 hPa vorticity, and 250-850 hPa wind shear. We then sum the GPI over all 12 months of each year, and over the whole planet. (Note that the GPI vanishes wherever the potential intensity is less than or equal to $35\ ms^{-1}$.) This is done both for the historical simulations over the period 1950-2005 and the RCP8.5 simulations over 2006-2100. The resulting GPI is scaled by a constant multiplicative factor to match the number of downscaled events for each model averaged over the period 1950-2100. Figure 5 compares the multi-model mean GPI thus calculated to the mean downscaled global tropical cyclone counts.

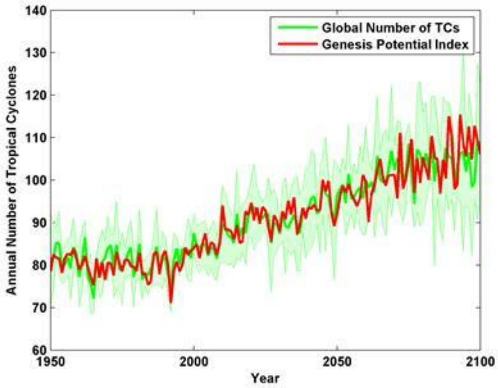

Figure 5: Annual downscaled global tropical cyclones (green) and genesis potential index given by (2) (red). Both quantities have been averaged over the 5 models. The green shading shows one standard deviation up and down among the 5 downscaled storm counts.

The mean GPI well captures the upward trend in global tropical cyclone counts. (Individual model storm counts are also highly correlated with the GPI based on them.) Examination of the 4 individual factors that comprise the GPI as defined by (2) for each of the 5 models shows that there is no single dominant factor that explains the GPI trend over the 21^{st} century for all models. In all but the MPI model, the thermodynamic inhibition of tropical cyclones, χ, increases as the planet warms, as discussed by Emanuel et al. (2008). On the other hand, all models have increasing potential intensity and all but MRI have decreasing vertical shear; MRI's shear shows no discernible trend. The vorticity factor in (2) does not contribute in any significant way to the GPI trends.

The results presented here differ significantly from those derived by applying the same downscaling to CMIP3-generation climate models, as described in Emanuel et al. (2008). That study downscaled 7 models, 4 of which were predecessors of models used in the current work, and compared tropical cyclone activity averaged over the last 20 years of the 22^{nd} Century simulated under emissions scenario A1b to activity averaged over the last 20 years of the 20^{th} Century. Although there was considerable variation from one downscaled model to the next, on average a small decrease in global mean frequency and a small increase in mean intensity were predicted. Although there have been small changes in the downscaling technique, most of the differences between that study and the current one arise from the different emissions scenario and the different models used.

Our current results may be compared to recent work examining explicit, downscaled and statistically inferred changes in tropical cyclone activity using CMIP5 models. Camargo (12) diagnosed tropical cyclones simulated explicitly in five global model simulations and two emissions scenarios, including the one used here, RCP8.5. Of these five models, only one showed significant upward trends in global tropical cyclone frequency over the 21^{st} Century; the others showed little significant change. Interestingly, the one global model that did show an upward trend, the MRI model also used here, was the only model that came close to simulating the observed number of events (~85) in the current climate; the other models simulated less than half this number.

Villarini and Vecchi (15) applied a statistical downscaling scheme to 17 CMIP5 models and projected that North Atlantic tropical cyclone frequency will increase early in the 21^{st} Century, owing mostly to changes in radiative forcing arising from non-greenhouse gas causes. At the same time, their technique projects no significant change in North Atlantic tropical cyclone frequency over the 21^{st} Century as a whole. (By contrast, our results do indicate a robust increase in the frequency of North Atlantic tropical cyclones.) Their method uses only global and North Atlantic sea surface temperature as statistical predictors and does explicitly account for changes in humidity or wind shear, thus it is not surprising that their results differ from our explicit downscaling or from those based on the GPI used here. Villarini and Vecchi (16) extended their earlier work to examine changes in North Atlantic power dissipation index. For the RCP8.5 scenario, they project an increase of about $3\times10^{11} m^3 s^{-2}$, which can be compared to our 5-model mean of $1.3\times10^{11} m^3 s^{-2}$.

Knutson*, et al.* (14) used regional and local models to downscale both CMIP3 and CMIP5 global simulations. For the latter, they examined simulations using the RCP4.5 emission scenario, which is roughly half the radiative forcing used in our study. They find a robust decrease in the projected frequency of North Atlantic tropical cyclones, and while they also find some increase in high intensity events, this increase was not deemed statistically significant. The projected decrease in the numbers of Atlantic tropical cyclones may be contrasted with the results of Villarini and Vecchi (15) and Camargo (12), who shows essentially no change, and with the current downscaling and application of the GPI defined by (2) to the five GCMs used here, which indicate an increase in Atlantic tropical cyclone frequency. In comparing these results, it should be remembered that different models and/or emission scenarios have been used, so the comparison is not uniform.

Among all the CMIP5-related techniques and results, ours appears to be the only one that projects a significant increase in global tropical cyclone frequency (although tropical cyclones modeled explicitly by the MRI model also appear to increase (12)). It is not surprising to see differences with the statistical downscaling of Villarini and Vecchi (15,16), who used only sea surface temperatures as predictors; nor is it surprising to see differences with storms modeled explicitly by GCMs (12) given that, with the exception of the MRI model, the models significantly underpredict real storm counts in the current climate. It is surprising, on the other hand, that our results differ qualitatively from the application of dynamical downscaling (14) to GCMs, given that these are based on high resolution physical models. (An important caveat here is that the models used in that dynamical downscaling constitute a different (but overlapping) set, and the RCP4.5 emissions scenario was used, rather than the RCP8.5 scenario we used.) There are, of course, limitations and areas of concern for both the dynamical downscaling used by Knutson et al. (14) and the technique used here. Focusing on the latter, and making use of the observation that the GPI given by (2) predicts well the number of downscaled events, one area of concern is the somewhat arbitrary choice of 600 hPa as the level at which to estimate the mid-tropospheric moist static energy used in (1) and also by the downscaling model. Emanuel et al. (9) showed that downscaled tropical cyclone activity is sensitive to χ, so the choice of level is important.

As a preliminary step to address this, we calculated χ using the moist static energy at 500 and 700 hPa, rather than at 600 hPa, for the RCP8.5 simulation using the HADGEM model, which shows a robust increase in downscaled tropical cyclone activity over the 21st Century. The increases over the 21st Century in the value of χ calculated using the moist static energies at 500 and 700 hPa were noticeably less than that using 600 hPa, so had we chosen either of these two alternative levels, we would have obtained an even larger increase in tropical cyclone frequency. It may be true, on the other hand, that our simple intensity model is less sensitive to mid-level moisture than is, e.g., the GFDL hurricane model used Knutson et al.'s (14) dynamical downscaling. Experiments aimed at quantifying the sensitivity of the GFDL hurricane model to mid-level moisture and comparing it to the sensitivity of our model may prove enlightening on this issue.

5. Summary

Application of a tropical cyclone downscaling technique to 5 CMIP5-generation global climate models run under historical conditions and under the RCP8.5 emissions projection indicates an increase in global tropical cyclone activity, most evident in the North Pacific region but also noticeable in the North Atlantic and South Indian Oceans. In these regions, both the frequency and intensity of tropical cyclones are projected to increase. This result contrasts with the result of applying the same downscaling technique to CMIP3-generation models, which predict a small decrease of global tropical cyclone frequency, and with recent CMIP5-based projections that range from little change to a significant decline in frequency. The few CMIP5-based projections of storm intensity published to date pertain strictly to the North Atlantic and suggest some increase in intensity and power dissipation, consistent with the present work. It should be borne in mind, however, that each of the CMIP5-based studies used different sets of models, different (or no) downscaling techniques, and, in some cases, different emissions pathways, so they may not be strictly comparable.

The present study used five CMIP5 models, the only five that provided the output needed to apply our downscaling and that did not have large discontinuities between the recent historical and near-term projected climates. The differences between our results, those arrived at by applying the same technique to CMIP3 models, and the conclusions of other groups using different models and/or using different methods suggest that projections of the response of tropical cyclones to projected climate change will remain uncertain for some time to come.

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