

Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century

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A recently developed technique for simulating large [$O(10^4)$] numbers of tropical cyclones in climate states described by global gridded data is applied to simulations of historical and future climate states simulated by six Coupled Model Intercomparison Project 5 (CMIP5) global climate models. Tropical cyclones downscaled from the climate of the period 1950–2005 are compared with those of the 21st century in simulations that stipulate that the radiative forcing from greenhouse gases increases by $8.5 \text{ W} \cdot \text{m}^{-2}$ over pre-industrial values. In contrast to storms that appear explicitly in most global models, the frequency of downscaled tropical cyclones increases during 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. The increased frequency of events is consistent with increases in a genesis potential index based on monthly mean global model output. These results are compared and contrasted with other inferences concerning the effect of global warming on tropical cyclones.

climate change | natural hazards

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 y ago. The interannual variability of just over nine 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 y 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., refs. 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 χ defined by Emanuel (8):

$$\chi \equiv \frac{h^* - h_m}{h_0^* - h^*}, \quad [1]$$

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, and h_0^* is the saturation moist static energy of the sea surface. (h_m is probably better represented by a pressure-weighted mean over the moist convective layer. In that case, Eq. 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.) Under global warming, both the numerator and the denominator of Eq. 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). Although one may therefore expect χ to increase in the global mean, its trend is highly variable from region to region.

Although 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:

- i) 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

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Conflict of interest statement: The technique used here to estimate the level of tropical cyclone activity in CMIP5-generation climate models is also used by a firm, WindRiskTech LLC, in which the author has a financial interest. That firm applies the technique to estimate tropical cyclone risk for various clients.

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much progress on this (e.g., ref. 10), a single, universally agreed-on algorithm has yet to emerge. A clear advantage of direct simulation is that it requires no additional assumptions or model applications (other than the detection algorithm). An important limitation of this approach is that it severely underresolves 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).

- ii) **Dynamical downscaling:** This technique embeds high-resolution regional or local models within general circulation models (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.
- iii) **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 datasets. 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 Coupled Model Intercomparison Project (CMIP) 3-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 intermodel and interbasin variability in such trends. Most models also predict an increase in precipitation associated with tropical cyclones in most regions (Knutson et al., ref. 7).

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). Although 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 with 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).

Technique and Models

The present work applies the downscaling technique of Emanuel et al. (9) to six CMIP5 global models. Initially, we selected all

seven of the global models that archived all of the output needed by our technique, but discarded one of the models that contains 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), owing to a discontinuity in aerosol content. The six models we selected are the Community Climate System Model 4 (CCSM4) of the National Center for Atmospheric Research (NCAR), the Climate Model 3 (CM3) of the Geophysical Fluid Dynamics Laboratory (GFDL) of the National Oceanic and Atmospheric Administration (NOAA), the Hadley Center Global Environment Model version 2 Earth System (HadGEM2-ES) model of the United Kingdom Meteorological Office Hadley Center, the Max Planck Institution Earth System Model Medium Resolution (MPI-ESM-MR) model of the Max Planck Institution, the Model for Interdisciplinary Research on Climate Version 5 (MIROC5) 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 Meteorological Research Institute Climate General Circulation Model 3 (MRI-CGCM3) of the Meteorological Research Institute of Japan. These models will hereafter be referred to respectively as NCAR, GFDL, MOHC, MPI, MIROC, and MRI. They are listed in Table 1 along with their approximate horizontal resolutions.

Our technique applies a highly resolved, coupled ocean–atmosphere model formulated in angular momentum coordinates (8) to tropical cyclone tracks initiated by random seeding in space and time, and propagated forward using a beta-and-advection model driven by winds derived from the climate model 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 to derive the wind shear that is required by the intensity model. As described in Emanuel et al. (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 specific 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

Table 1. List of CMIP5 models and horizontal resolutions

Modeling center	Institute ID	Model name	Average horizontal resolution, °
National Center for Atmospheric Research	NCAR	CCSM4	1.25 × 0.94
NOAA Geophysical Fluid Dynamics Laboratory	GFDL	CM3	2.5 × 2.0
Met Office Hadley Center	MOHC	HADGEM2-ES	1.875 × 1.25
Max Planck Institute for Meteorology	MPI	MPI-ESM-MR	1.875 × 1.865
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC	MIROC5	1.41 × 1.40
Meteorological Research Institute	MRI	MRI-CGCM3	2.81 × 2.79

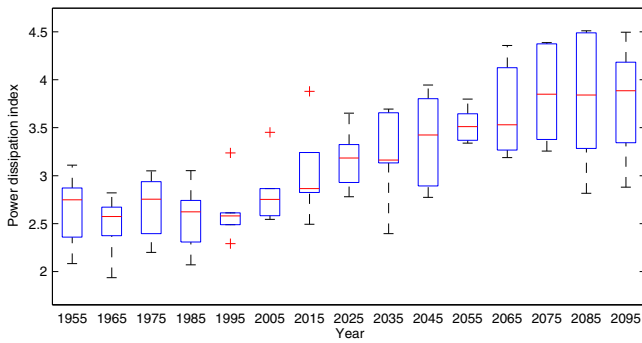


Fig. 3. As in Fig. 1, but for the power dissipation index. Units are $10^{12} \text{m}^3 \text{s}^{-2}$.

tropical cyclone climatology (e.g., refs. 6, 25). Here we use the genesis potential index (GPI) developed by Emanuel (21):

$$GPI \equiv |\eta|^3 \chi^{-\kappa} \text{MAX}((V_{pot} - 35 \text{ m} \cdot \text{s}^{-1}), 0)^2 (25 \text{ m} \cdot \text{s}^{-1} + V_{shear})^{-4}, \quad [2]$$

where η is the absolute vorticity of the 850 hPa flow, V_{pot} is the potential intensity in $\text{m} \cdot \text{s}^{-1}$, V_{shear} is the magnitude of the 850 hPa–250 hPa wind shear (in $\text{m} \cdot \text{s}^{-1}$), and χ is defined by Eq. 1. Genesis indices like the one used here, based on potential intensity, have an intrinsic advantage over those that are based on sea surface temperature over a threshold (e.g., refs. 26–28), in that there is no physical justification for a climate-invariant sea surface temperature threshold. Indeed, when applied to global models under global warming, these sea surface temperature threshold-based indices produce unrealistic increases in activity (27).

We calculate the GPI defined by Eq. 2 for each of the six models, using monthly mean thermodynamic data, 850 hPa vorticity, and 250–850 hPa wind shear. We then sum the GPI over all 12 mo of each year, and over the whole planet. (Note that the GPI vanishes wherever the potential intensity is less than or equal to $35 \text{ m} \cdot \text{s}^{-1}$.) 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. Fig. 5 compares the multimodel mean GPI thus calculated to the mean downscaled global tropical cyclone 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 the models.) Examination of the four individual factors that comprise the GPI as defined by Eq. 2 for each of the six models shows that there is no single dominant factor that explains the GPI trend over the 21st 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. (9). On the other hand, all models have increasing potential intensity and all but NCAR and MRI have decreasing vertical shear; MRI's shear shows no discernible trend, whereas NCAR's trends upward. The vorticity factor in Eq. 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. (9). That study downscaled seven models, five of which were predecessors of models used in the current work, and compared tropical cyclone activity averaged over the last 20 y of the 22nd century simulated under emissions scenario A1b to activity averaged over the last 20 y of the 20th century. The different emissions scenario and different time periods make comparison difficult, but Table 2

compares global trends in frequency and power dissipation of the two generations of models. Clearly the CMIP5 generation of global models shows substantial increases in downscaled tropical cyclone activity compared with the CMIP3 generation. Only the MRI models show roughly consistent results between the two generations. 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 scenarios and time periods, and the different models used.

Our current results may be compared with recent work examining explicit, downscaled, and statistically inferred changes in tropical cyclone activity using CMIP5 models. Camargo (12) diagnosed tropical cyclones simulated explicitly in 14 global model simulations and two emissions scenarios, including the one used here, RCP8.5. She documents a number of serious deficiencies in the climatologies of the explicitly simulated cyclones, including a strong negative bias in the overall frequency of storms, in rough inverse proportion to the horizontal resolution of the model. Of the seven models that had nontrivial numbers of tropical cyclone in the historical climate simulations, only one showed significant upward trends in global tropical cyclone frequency over the 21st 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. The MRI model also had the best agreement between its climatology of tropical cyclones and its GPI.

Villarini et al. (15) applied a statistical downscaling scheme to 17 CMIP5 models and projected that North Atlantic tropical cyclone frequency will increase early in the 21st century, owing mostly to changes in radiative forcing arising from non-greenhouse gas causes. (The 17 models included five of the six models used here, but the authors did not provide a model-by-model breakdown of their results.) At the same time, their technique projects no significant change in North Atlantic tropical cyclone frequency over the 21st 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 not 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 et al. (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

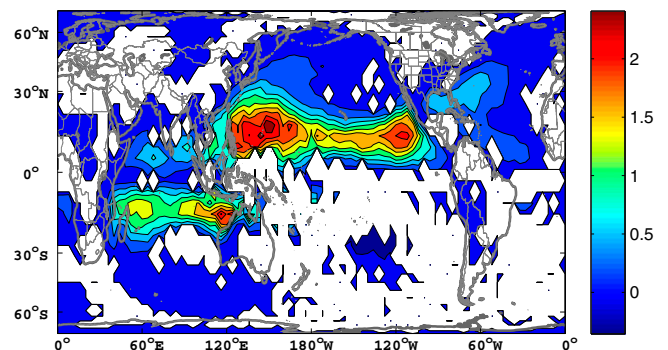


Fig. 4. Change in Power Dissipation Index averaged over the six models, per 4° latitude grid box. This is defined as the difference between power dissipation averaged over the period 2006–2100 and that averaged over 1950–2005. Units are $10^8 \text{m}^3 \text{s}^{-2}$ per $4^\circ \times 4^\circ$ square,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

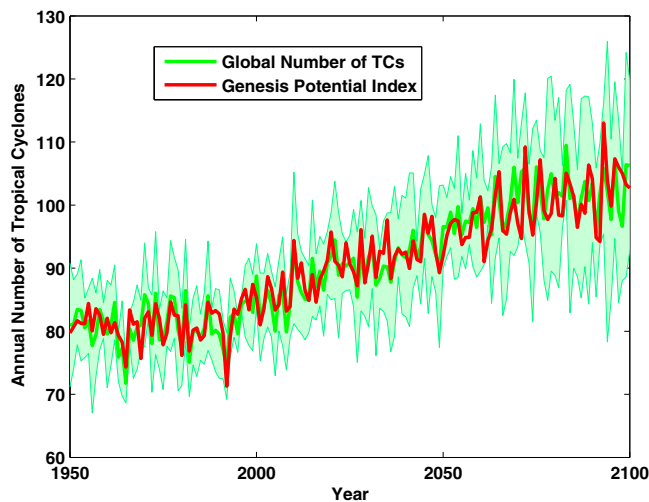


Fig. 5. Annual downscaled global tropical cyclones (green) and GPI given by Eq. 2 (red). Both quantities have been averaged over the six models. The green shading shows one SD up and down among the six downscaled storm counts.

$3 \times 10^{11} \text{m}^3 \text{s}^{-2}$, which can be compared with our six-model mean of $1.2 \times 10^{11} \text{m}^3 \text{s}^{-2}$.

Knutson et al. (14) used regional and local models to downscale both CMIP3 and CMIP5 global simulations in the North Atlantic region. For the CMIP5 models, they examined simulations using the RCP4.5 emission scenario, which is roughly half the radiative forcing used in our study. They downscaled an ensemble average over 18 CMIP5 models using the 18-km-resolution Zetac models, and an ensemble average over 13 CMIP5 models using the 50-km-resolution HiRAM model. They find a modest (~20%) decrease in the projected frequency of North Atlantic tropical cyclones, and although 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 et al. (15) and Camargo (12), who shows essentially no change, and with the current downscaling and application of the GPI defined by Eq. 2 to the five GCMs used here, which indicate a small 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 of 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 et al. (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 more 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. Also, those results are only for the North Atlantic, where the current downscaling shows only a small, although still statistically significant, increase.] 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 Eq. 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 midtropospheric moist static energy used in Eq. 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 MOHC 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 midlevel 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 midlevel moisture and comparing it to the sensitivity of our model may prove enlightening on this issue.

Summary

Application of a tropical cyclone downscaling technique to six 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 generally predict a small decrease of global tropical cyclone frequency, and with recent CMIP5-based projections that show little consistent change in frequency. The few CMIP5-based projections of storm intensity published to date pertain strictly to the North Atlantic

Table 2. Comparison between CMIP3 and CMIP5 changes in downscaled tropical cyclone frequency and power dissipation

Institute ID	CMIP3 model	CMIP5 model	CMIP3 change in global frequency, %	CMIP5 change in global frequency, %	CMIP3 change in global power dissipation, %	CMIP5 change in global power dissipation, %
NCAR	CCSM3	CCSM4	-3	+11	+5	+8
GFDL	CM2.0	CM3	-13	+41	+2	+72
MOHC		HADGEM2-ES		+22		+31
MPI	ECHAM5	MPI-ESM-MR	-11	+29	+4	+57
MIROC	MIROC3.2	MIROC5	-12	+38	+8	+80
MRI	MRI-CGCM2.3.2a	MRI-CGCM3	+2	+13	+22	+26

For CMIP3 models, the listed numbers are percentage changes from the 20-y period 1981–2000 to the 20-y period 2181–2200 under emissions scenario A1b. For the CMIP5 models, the listed numbers represent percentage changes from 1981–2000 to 2081–2100 under radiative forcing scenario RCP8.5.

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.

We show here that the predicted increase in the frequency of tropical cyclones is consistent with increases in a GPI that was developed independently, based on observed seasonal, spatial, and climate variability of tropical cyclones. The good agreement between the downscaled tropical cyclone frequencies and those based on GPI lends further confidence to the technique. Although both the GPI and the random seeding technique used to initiate storms in our downscaling method produce good predictions of spatial, seasonal, and short-term climate variability of tropical cyclones over the past few decades during which measurements of tropical cyclone are of high quality, neither has been tested against truly global climate change. Indeed, no technique, including explicit simulation of tropical cyclones in climate models, has been tested against global climate change.

The present study used six CMIP5 models, the only six 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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