Projected Increases in North Atlantic Tropical Cyclone Intensity from CMIP5 Models

GABRIELE VILLARINI
IIHR-Hydroscience and Engineering, The University of Iowa, Iowa City, Iowa

GABRIEL A. VECCHI
National Oceanic and Atmospheric Administration/Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey

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ABSTRACT

Tropical cyclones—particularly intense ones—are a hazard to life and property, so an assessment of the changes in North Atlantic tropical cyclone intensity has important socioeconomic implications. In this study, the authors focus on the seasonally integrated power dissipation index (PDI) as a metric to project changes in tropical cyclone intensity. Based on a recently developed statistical model, this study examines projections in North Atlantic PDI using output from 17 state-of-the-art global climate models and three radiative forcing scenarios. Overall, the authors find that North Atlantic PDI is projected to increase with respect to the 1986–2005 period across all scenarios. The difference between the PDI projections and those of the number of North Atlantic tropical cyclones, which are not projected to increase significantly, indicates an intensification of North Atlantic tropical cyclones in response to both greenhouse gas (GHG) increases and aerosol changes over the current century. At the end of the twenty-first century, the magnitude of these increases shows a positive dependence on projected GHG forcing. The projected intensification is significantly enhanced by non-GHG (primarily aerosol) forcing in the first half of the twenty-first century.

1. Introduction

The projected damage arising from tropical cyclones (TCs) in a future climate, particularly as anthropogenic global warming continues, is a topic of scientific and societal interest, and will be influenced by changes in storm intensity, population, and vulnerability (e.g., Mendelsohn et al. 2012; Peduzzi et al. 2012). The most intense hurricanes (category 3–5) are responsible for the vast majority of the tropical cyclone damage in the United States, even though they represent only one-fourth of the overall landfalling tropical cyclone activity (e.g., Pielke et al. 2008). Theoretical considerations (e.g., Emanuel 1987; Holland 1997) and high-resolution modeling studies (e.g., Knutson and Tuleya 2004; Oouchi et al. 2006; Emanuel et al. 2008; Bender et al. 2010; Knutson et al. 2010) generally suggest an increase in the intensity of tropical cyclones in a warming climate. High-resolution models can represent the most intense storms directly, but the required computational expense generally limits them to single-model runs and/or time slice experiments. At the present time, it is unclear what outcome we would get by running these high-resolution models in a multimodel fashion over the entire twenty-first century. An alternative approach to counting the number of the most intense storms is to employ the seasonally integrated power dissipation index (PDI; Emanuel 2005, 2007), which is a metric that convolves storm duration, frequency, and intensity. Storm intensity is accounted for by taking the third power of the wind speed. Emanuel (2005) found that there was a high correlation between PDI and tropical Atlantic sea surface temperature (SST). Swanson (2008) obtained a higher correlation using the difference between tropical Atlantic SST\textsubscript{Atl} and tropical-mean SST\textsubscript{Trop}. Vecchi et al. (2008b) showed that projections of PDI based on relative SST (the difference between SST\textsubscript{Atl} and SST\textsubscript{Trop}) are in better agreement with results from dynamical models than using SST\textsubscript{Atl} alone. Recently, Villarini and Vecchi (2012a) developed a statistical model in which SST\textsubscript{Atl} and SST\textsubscript{Trop} are used as predictors (see section 2). We have also recently shown that this statistical model can be used to make...
retrospective skillful forecasts of seasonally integrated North Atlantic PDI from November of the previous season, allowing the skillful forecast of the upcoming season as the current one is still coming to an end (Villarini and Vecchi 2013).

Here, we apply the model of Villarini and Vecchi (2012a) to outputs from 17 global climate models (GCMs) produced under phase 5 of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012; Table 1) to address questions related to future changes in North Atlantic tropical cyclone intensity.

2. Methodology

The methodology used to create the projected North Atlantic PDI time series is based on the model described in Villarini and Vecchi (2012a). Here we provide only a brief overview and point the interested reader to the original reference for a more in-depth discussion. The PDI record \( y \) can be modeled according to a gamma distribution \( f_y(\mu, \sigma) \) (\( \mu \) is the location parameter, \( \sigma \) is the scale parameter, and \( G \) is the gamma function):

\[
f_y(y | \mu, \sigma) = \frac{1}{(\sigma^2 \mu)^{1/\sigma^2}} \exp[-y/(\sigma^2 \mu)] \Gamma(1/\sigma^2),
\]

in which the logarithm of the location parameter \( \mu \) is a linear function of SST\(_\text{Atl} \) and SST\(_\text{Trop} \):

\[
\log(\mu) = 0.76 + 1.94 \text{SST}_\text{Atl} - 1.78 \text{SST}_\text{Trop},
\]

and \( \log(\sigma) \) is constant and equal to \(-0.57\). The predictor SST\(_\text{Atl} \) represents the tropical Atlantic SST anomalies computed over \(10^\circ-25^\circ\)N and \(80^\circ-20^\circ\)W, while SST\(_\text{Trop} \) represents the tropical-mean SST computed over \(30^\circ\text{S}-30^\circ\)N. The SST anomalies are computed with respect to the period 1982–2005, and we use the extended reconstructed SST dataset from the National Oceanic and Atmospheric Administration (NOAA), version 3b (ERSSTv3b; Smith et al. 2008), averaged over the period June–November as reference input dataset. As discussed in Villarini and Vecchi (2012a), it is worth clarifying that PDI is a proxy for the overall tropical storm power dissipation (Bister and Emanuel 1998), which is based on the history of tropical cyclone activity each season. The calculations are performed in R (R Development Core Team 2008) using the freely available Generalized Additive Models for Location, Scale, and Shape (GAMLSS) package (Stasinopoulos et al. 2007).

This parsimonious model can describe well the interannual and decadal variability and change of the PDI record over the period 1949–2006 (cf. red and blue lines in Fig. 1; Villarini and Vecchi 2012a) and allows for century-scale reconstructions of PDI (orange line Fig. 1).

The statistical frameworks modeling Atlantic hurricane activity using SST\(_\text{Atl} \) relative to SST\(_\text{Trop} \), rather than SST\(_\text{Atl} \) alone, are supported by both modeling and empirical results (e.g., Latif et al. 2007; Vecchi and Soden 2007a; Swanson 2008; Brender et al. 2010; Zhao et al. 2010; Ramsay and Sobel 2011; Vecchi et al. 2008b, 2011; Villarini et al. 2010, 2011, 2012) and are the basis of skillful seasonal forecasts (Vecchi et al. 2011; Zhao et al. 2010; Villarini and Vecchi 2013). In the model of Villarini and Vecchi (2012a), the positive coefficient on Atlantic SSTs is larger than the negative coefficient on tropical-mean SSTs [Eq. (2)], and a similar difference in the magnitude of the Atlantic and tropical-mean coefficients to the fit of PDI was found by Swanson (2008). This indicates that uniform warming (cooling) of the tropics should lead to an increase (decrease) in PDI. In addition, warming (cooling) of the Atlantic relative to the tropical average will also lead to an increase (decrease) in PDI.

In this study, we examine projected changes in PDI by applying the statistical model of Villarini and Vecchi (2012a) to outputs from 17 GCMs (see Table 1 for a list) to address questions related to future changes in North Atlantic tropical cyclone intensity, using 1986–2005 as our reference period to compute anomalies, and the median of the gamma distribution as reference value. We have recently analyzed these GCMs for possible changes in tropical cyclone activity (Villarini and Vecchi 2012b). We showed that, while both tropical Atlantic and tropical-mean SSTs are projected to increase over the twenty-first century, there is a significant radiatively forced increase in North Atlantic tropical storm frequency only over the first half of the century, which is not driven by \( \text{CO}_2 \) but is likely the result of anthropogenic aerosol changes (with a particular influence of a projected clearing of aerosols over the North Atlantic). This increase, however, does not extend over the entire twenty-first century, for which the sign of the trend is uncertain. Differences in the behavior of PDI and tropical cyclone frequency indicate changes in tropical cyclone intensity and duration at the strongest intensities (Villarini and Vecchi 2012a).

3. Results

Figure 1 shows the time series of PDI anomalies for three representative concentration pathways (RCPs; each RCP is labeled to reflect the radiative forcing change at the end of the twenty-first century, in watts per meter squared). The observations over the period 1949–2008 are within the GCMs ensemble spread. The projected PDI values tend to be larger than the PDI values over the last 130 years. Regardless of the RCP, there is a tendency toward increases in PDI over the twenty-first century. There are statistically significant trends in six
Table 1. Summary of the 17 GCMs used in this study. For all of them, data for the RCP 2.6, RCP 4.5, and RCP 8.5 are available. The same holds true for the $2 \times CO_2$ runs with the exception of MIROC-ESM-CHEM. The final column indicates the models for which the “greenhouse only” historical experiments were available (see Fig. 5). Here, Y indicates available.

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out of the 17 models over the 2006–99 period for RCP 2.6 (five positive and one negative trends). This number increases to nine and 13 for RCP 4.5 and 8.5, respectively, all of which are increasing trends. The magnitude of these increases depends on the RCP, with RCP 2.6 showing smaller increases relative to RCP 8.5. This magnitude increase is coupled with an increase in the ensemble spread (Figs. 1 and 2). The projected mean over 2016–35 is, on average, 20% larger than the corresponding values over 1986–2005 (Fig. 2). Averaged over 2046–65, the multimodel mean PDI values are between 50% and 75% larger than the values for the reference period. At the end of the twenty-first century, the magnitude of the changes shows a positive dependence on the strength of projected greenhouse gas (GHG) forcing.

FIG. 1. Time series of PDI anomalies from 1878 to 2099. PDI projections are based on 17 GCMs under the CMIP5 for three RCPs: (top) RCP 2.6, (middle) RCP 4.5, and (bottom) RCP 8.5. The blue line refers to the observations corrected according to Landsea (1993). The red line represents the median of the model described in Villarini and Vecchi (2012a) fitted to the observations; the orange line represents the median of the reconstructed PDI anomalies based on the statistical model in Villarini and Vecchi (2012a) and using ERSSTv3b time series (Smith et al. 2008) as input to the statistical model. The solid black line represents the average of the 17 medians from the GCMs. The light (dark) gray areas represent the region between the 10th and 90th percentile (between the minimum and maximum) from the 17 medians. The anomalies are computed with respect to the 1986–2005 period for each model and the observations.
With the exception of RCP 2.6, which has a mid-century maximum in GHG forcing, the largest projected increases in PDI are toward the end of the twenty-first century. For RCP 4.5 (approximately a CO₂ doubling at the end of the twenty-first century) the PDI values over 2080–99 are on average 50% larger than the reference period. Meanwhile, the PDI values for RCP 8.5 (approximately a quadrupling of CO₂ at the end of the twenty-first century) are, on average, 100% larger than over 1986–2005, with a large increase in intermodel variability.

Storm duration, frequency, and intensity are used to compute the PDI. Could it be that the increases in PDI are reflecting an increase in tropical cyclone frequency? A recent analysis of the same GCMs (Villarini and Vecchi 2012b) showed that the ensemble-mean North Atlantic tropical cyclone frequency is not projected to change significantly over the entire twenty-first century, regardless of the RCP. In further contrast to the PDI projections, frequency increases that were found were the largest in the first half of the twenty-first century (driven by aerosol changes) and showed no relation to GHG forcing. The increase in PDI, therefore, indicates a projection for an increase in North Atlantic tropical cyclone intensity or the duration over which these storms
Intercomparison Project (CMIP3) (Emanuel et al. 2008; Bender et al. 2010).

Multiple forcing agents (GHG, aerosols, ozone, etc.) are changing in these RCPs. An idealized suite of experiments in which CO$_2$ concentrations are doubled over a 70-yr period isolates the impact of CO$_2$ in the projections (Fig. 3). An increase in CO$_2$ results in an average slight increase in PDI, driven by the overall warming of the tropics (Villarini and Vecchi 2012a), in contrast to a CO$_2$-driven decrease found for tropical storm frequency (Villarini and Vecchi 2012b). However the magnitude of the PDI sensitivity to CO$_2$ in these models is not large enough to explain the increase in PDI for the three RCPs (e.g., compare the response at year 70 of Fig. 3 with 2100 in RCP 8.5 of Fig. 1), indicating that other forcing agents also contribute to the projected intensity increases.

To assess the role of aerosols in the PDI projections, we explore a partial perturbation experiment using a GCM from the CMIP5 suite [Geophysical Fluid Dynamics Laboratory Climate Model, version 3 (GFDL CM3)], in which aerosol precursors in RCP 4.5 are not allowed to change after 2005 and compare that with the full RCP 4.5 projections. This set of experiments indicates that the projected increase in PDI in the projections from GFDL CM3 is driven both by GHG increases and aerosol changes (largely through a projected decrease in Atlantic
The aerosol-driven increase in North Atlantic TC intensity in the GFDL CM3 projections arises both from the tropical-mean warming driven by aerosol optical depth decreases and from warming of the Atlantic relative to the tropics driven by a more rapid reduction of aerosols over the Atlantic than over the global tropics in this RCP scenario. Unfortunately, this experiment is not available for the full CMIP5 model suite; because of the large potential role of aerosols in climate change, future coordinated experiments should include idealized experiments like these to allow an assessment of the relative contributions of aerosols and GHGs to projected climate changes.

An analysis of a couplet of historical CMIP5 experiments over the 1880–2005 period, one using “all forcings” (changing GHGs, aerosols, natural forcing, etc.) and another using past GHG forcing only (in which aerosols, natural forcings, etc. are kept at preindustrial values) indicates that the projected influence of aerosol changes on PDI may have begun in the 1990s (Fig. 5). These historical perturbation experiments are only available for a subset of the CMIP5 models (Table 1). In particular, the impact of GHGs alone leads to an increase in PDI over the twentieth century in these models, while the non-GHG forcing leads to a decrease between the 1960s and 1980s, and a rebound following that. Unfortunately again, experiments isolating the role of aerosols are available from few CMIP5 models at this time; however, the timing of the non-GHG decrease suggests that increasing aerosol loading in the Atlantic was a key countervailing force against a GHG-induced increase of PDI over the twentieth century, but over the recent decades (and in the projections of the twenty-first century—see Fig. 4) GHG and aerosol forcing both act to increase PDI in these models. In particular, the timing of the observed local minimum in PDI over the 1970s and 1980s is well captured by the radiatively forced models (comparing the dashed line with the “all forcing” CMIP5 line in Fig. 5), suggesting that this minimum was due, at least in part, to past changes in radiative forcing—likely anthropogenic aerosols. So the recent (since the mid-1980s) radiatively forced increase in our PDI index in the CMIP5 models is largely a rebound from a radiatively forced decrease over the 1960s and 1970s, likely because of anthropogenic aerosols, and is not representative of the sensitivity of PDI to GHG forcing. The amplitude of the observed changes in PDI is larger than that of the multimodel ensemble; we speculate that this is in part because the PDI is based on a statistical model that by construction will only capture part of the variance, and in part it is an indication that the observed changes included a nonradiative component. However, we cannot exclude the possibility that it may also indicate that this statistical downscaling of GCMs may underestimate the magnitude of forced changes in PDI, either because of problems with the statistical model, the GCMs, or the radiative forcing. Future work should explore these issues.

4. Discussion and conclusions

In this study, we used output from a new suite of coupled climate simulations (CMIP5; Taylor et al. 2012) and a recently developed statistical model (Villarini and Vecchi 2012b). The aerosol-driven increase in North Atlantic TC intensity in the GFDL CM3 projections arises both from the tropical-mean warming driven by aerosol optical depth decreases and from warming of the Atlantic relative to the tropics driven by a more rapid reduction of aerosols over the Atlantic than over the global tropics in this RCP scenario. Unfortunately, this experiment is not available for the full CMIP5 model suite; because of the large potential role of aerosols in climate change, future coordinated experiments should include idealized experiments like these to allow an assessment of the relative contributions of aerosols and GHGs to projected climate changes.

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Vecchi 2012a) to project changes in North Atlantic PDI over the twenty-first century. These analyses are based on 17 GCMs and explore three future radiative forcing scenarios (or RCPs). Comparison of the PDI projections with projections of North Atlantic TC frequency (Villarini and Vecchi 2012b) allows us to interpret the changes in terms of tropical cyclone intensity. Our results suggest that the North Atlantic PDI, driven primarily by changes to tropical cyclone intensity and the duration of TCs at highest intensity, is projected to increase over the current century in all three RCPs. By the end of the twenty-first century, the magnitude of the projected increase depends on the projected GHG forcing. The projected intensification of North Atlantic tropical cyclone is in response to GHG increases and aerosol changes.

The results of this study are based on the statistical model described in Villarini and Vecchi (2012a), in which the dominance of certain physical processes is implicit. In particular, the model assumes that tropical tropospheric warming will follow something close to a “moist adiabat” (warming will be about twice as large in the upper troposphere than at the surface) and that the “weak temperature gradient” (WTG) approximation holds (Sobel et al. 2002; the WTG approximation reflects the tendency of tropospheric temperature anomalies to be relatively spatially homogeneous in the tropics). Therefore, we do not account for the impact of direct radiative heating on free-atmospheric temperatures or other factors that would make tropospheric temperature changes deviate from a moist adiabat (e.g., Emanuel 2010; Emanuel et al. 2013; Vecchi et al. 2013), which would require other relevant predictors that are currently not included in the model. With these caveats in mind, these results point to a substantial increase in North Atlantic tropical cyclone intensity and growing probability of extreme hurricane seasons over this century (Fig. 6).

The CMIP5 coupled GCM experiment suite leads to a projection of increases in North Atlantic PDI over the twenty-first century in response to projected increases in GHGs and changes in atmospheric aerosols (largely reductions in Atlantic aerosol loading). The projections for increased PDI reflect a projection of increase tropical cyclone intensity and duration at the highest intensities, rather than an increase in frequency. These projected changes in PDI are large, indicating substantially increased probability of years as or more active than 2005 (Fig. 6), which may have been the most active year on record. However, these same models do not indicate that we should have seen an increase over the past century—nor do reconstructions of PDI from SST (Fig. 1; Villarini and Vecchi 2012a). The lack of an expectation for increasing PDI over the past century in these GCMs appears to arise in part because of large internal variability (Fig. 1), but also because the slight GHG-driven increase over the past century has been masked by a sharp non-GHG-driven decrease around the 1960s–80s—the timing of which suggests a role for aerosols (Fig. 5), similar to a potential masking of a GHG-induced weakening of oceanic circulation (e.g., Delworth and Dixon 2006). Only in the recent decades has the GHG and non-GHG PDI response in these models been in the same direction (Fig. 5), a constructive influence that is projected to continue over the next few decades (Fig. 4).

These results add to the growing body of work (e.g., Rotstayn and Lohmann 2002; Mann and Emanuel 2006; Evan et al. 2009; Chang et al. 2011; Booth et al. 2012; Villarini and Vecchi 2012b) suggesting that the observed multidecadal variability in the North Atlantic, and its related impacts (e.g., the inactive Atlantic hurricane period between the late 1960s and early 1990s), may include a component driven by changes in atmospheric aerosols (primarily through an increase in the post–World War II era, and a decrease in the 1980s–90s, of aerosol optical depth over the Atlantic). However, the CMIP5 historical experiments only explain a fraction of the recently observed multidecadal swing in PDI (Fig. 1), indicating that factors such as internal variability (e.g., Zhang and Delworth 2005, 2006, 2009; Robson et al. 2012) may also have contributed.

In contrast to projections of surface warming, which have already been observed and attributed in part to increasing GHGs (Solomon et al. 2007), for PDI we are...
in an uncomfortable position where the GCMs are projecting potentially dramatic and societally relevant changes, while at the same time indicating no detectable changes should be present in the record. Therefore, tests of these projections must be indirect and are intimately tied to our confidence in the fidelity of the GCMs and the projected radiative forcing. In particular, because of the role of aerosol changes in the historical simulations and projections of PDI, and because there are currently substantial uncertainties in the role of aerosols in past climate variations (e.g., Booth et al. 2012; Zhang et al. 2013), efforts should continue to improve our understanding and modeling capability for the role of aerosols in regional and global climate change. More generally, the mechanisms behind patterns of SST must be better understood (e.g., Leloup and Clement 2009; Clement et al. 2010; Xie et al. 2010), as should the character of past changes in regional SST (e.g., Vecchi and Soden 2007b; Vecchi et al. 2008a; Deser et al. 2010), to develop confident projections and assessment of past causes for changes in Atlantic hurricane intensity.

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**REFERENCES**


—, and —, 2013: Multiseason lead forecast of the North Atlantic power dissipation index (PDI) and accumulated cyclogenesis energy (ACE). J. Climate, in press.


