Chapter 18

North Atlantic Hurricane Activity: Past, Present and Future

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We review past, present and future North Atlantic hurricane activity based on analysis of observational records and models projections. When adjusted for likely missed tropical cyclones, the observational record does not show any significant increase or decrease of North Atlantic hurricane frequency. Downscaling results for most available CMIP5 models show a decrease or little change in overall frequency of tropical storms and hurricanes, although in the Atlantic basin, previous studies by other investigators report a wider range of change (+/−60%). Some model projections of late 21st century hurricane activity indicate an increase in frequency of the strongest storms (category 4–5 hurricanes). The projected increase is substantial (+100% per century) in the CMIP3 ensemble model downscaling, but much smaller (+40%) and only marginally significant in the CMIP5 ensemble model downscaling. Rainfall rates in the inner core of the hurricanes are projected to increase with potentially a substantial damage impact. The largest source of uncertainty in predicting changes in Atlantic tropical storms activity over the first half of the 21st century arises from the internal variability of the climate system. Nonetheless, some of these natural fluctuations appear to be predictable beyond seasonal time scale. We review recent predictability assessment results based on two CMIP5 models. Initializing these models with observational estimates leads to encouraging results in predicting multi-year variations in North Atlantic hurricane frequency. However the short record and the persistent character of the time series limits the ability to confidently predict North Atlantic hurricane activity for now. Remaining model biases, despite the tremendous improvement over the recent decades, and the changing observational system make it an ongoing challenge to simulate past hurricane activity and project or predict its future behavior.

1. Introduction

A growing scientific effort has been devoted recently for detecting and attributing changes in hurricane activity. Indeed, a potential increase of North Atlantic tropical cyclones (TCs), which includes tropical storms and hurricanes, in response to changing climate conditions could have an important impact on society, particularly if the most intense hurricanes become more frequent, coupled with ongoing sea level rise. A number of studies have discussed the character of and causes behind past changes in North Atlantic TC frequency (*e.g.*, Solow and Moore, 2002; Mann and Emanuel, 2006; Chang and Guo, 2007; Landsea, 2007; Mann *et al.*, 2007; Holland and Webster, 2007; Vecchi and Knutson, 2008; Landsea *et al.*, 2010; Knutson *et al.*, 2010; Villarini *et al.*, 2011b) and in its future evolution (Knutson *et al.*, 2010 and references therein). Having a reliable data record of past hurricane activity, along with a quantitative assessment of its uncertainty is essential for assessing any long-term change in hurricane activity.

Besides the projections of hurricane activity over the coming century, there is a large interest in hurricane climate prediction at shorter time scales, from seasonal to decadal. Reliable seasonal forecasts have become feasible thanks to the tremendous technological improvement over the last decades along with improved understanding of the global climate system and in particular the climate factors that influence hurricane activity. Seasonal prediction efforts are being undertaken at a number of institutions, with a variety of techniques being applied, each exhibiting retrospective skill (Saunders and Lea, 2005; Vitart and coauthors, 2007; Klotzbach, 2007; Wang *et al.*, 2009; Camargo and Barnston, 2009; LaRow *et al.*, 2010). It would be a useful exercise, beyond the scope of the present study, to quantitatively compare the retrospective skills of these various systems across common periods, and to assess the relationship between retrospective skill and real-time skill for seasonal hurricane prediction, and the extent to which a multi-system approach could outperform individual systems. While a number of methods have been developed over the years for seasonal predictions of Atlantic TCs using high-resolution hurricane models (Camargo *et al.*, 2007; Zhao *et al.*, 2010), the use of statistical models combined with downscaled dynamical models proved to be very successful. Despite being less computationally demanding, the methods seem to generally reproduce the results of high-resolution dynamical models (*e.g.* Villarini *et al.*, 2011b). The predictors used for the statistical model can also provide useful information to explore hurricane activity uncertainty. The extent to which such forecasts can be extended beyond the seasonal time scale has been recently investigated and is discussed in this paper, with the assumption that initializing dynamical models with observations could lead to skill in predicting natural variability.

While warm local sea surface temperatures (SSTs) favor the formation and intensification of Atlantic TCs, it is not entirely clear how increasing global SSTs will influence TC activity. Emanuel (2007) showed that the power dissipation of Atlantic storms increased by about 60% since the 1970s and that the average duration and maximum speed also increased. Landfalling storms are only a fraction of the total number of storms. Category 4 and 5 storms account for only about 6% of US landfalls but caused 48% of all hurricane damage between 1900 and 2005 (Blake *et al.*, 2007; Pielke *et al.*, 2008). It is therefore essential to determine how these potentially very destructive hurricanes are projected to evolve as climate warms and sea level rise continues. This historical apparent increase in Atlantic hurricane activity has been linked to observed changes in SST averaged over the Atlantic main development region (MDR) (*e.g.*, Mann and Emanuel, 2006; Emanuel, 2007; Holland and Webster, 2007; Mann *et al.*, 2007). The potential for hurricane formation is enhanced by low values of wind shear in the troposphere. In the tropical Atlantic, warmer SSTs tend to increase wind shear, leading to fewer storms overall. It has been suggested that the observed increase in TCs could also be the result not of global warming *per se* but of the warming of the Atlantic relative to the other tropical ocean basins, or “relative SSTs” (Vecchi and Soden, 2007; Vecchi *et al.*, 2008; Swanson, 2008). This distinction between absolute and relative SST has important implications for projections of future hurricane activity since model projections indicate a substantial warming of the tropical SSTs globally in response to increased greenhouse gases concentrations, but relatively small changes in Atlantic relative SSTs (Vecchi *et al.*, 2008).

The continuous advance of climate models and the public release of a large amount of climate data through the Coupled Model Intercomparion Projects that recently produced its fifth (CMIP5) assessment has allowed us to revisit the Atlantic TC projections that were produced with previous (CMIP3) models (*e.g.*, Bender *et al.*, 2010). We present in this chapter recent advances in assessing the change of North Atlantic hurricane frequency that was observed over the 20th century (Sec. 2) and distinguish between fluctuations that appear to be natural and those resulting from changes in external forcing (Sec. 3). In Sec. 4, we review the projected changes in Atlantic hurricane activity given by the most recent climate model studies and we present in Sec. 5 the uncertainties associated with these projections. Recent results about multi-year predictions of hurricane variability are described in Sec. 6 before the concluding remarks in Sec. 7.

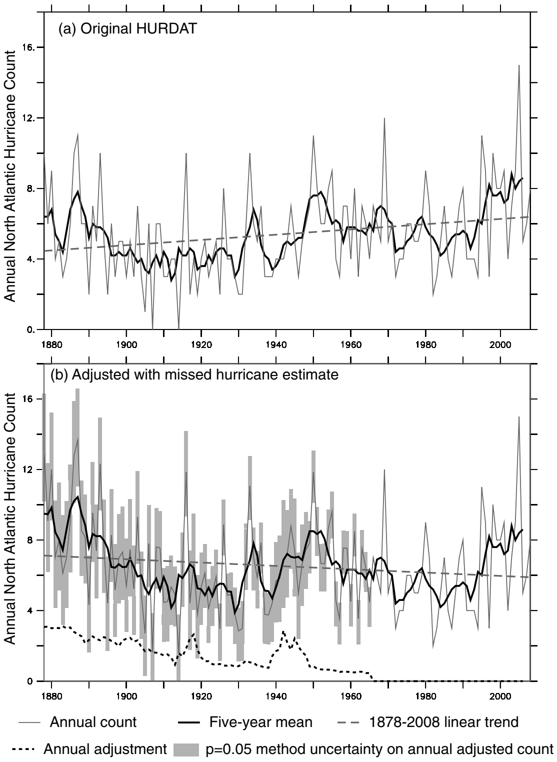

Fig. 1. From (Vecchi and Knutson, 2011) "© Copyright [15 March 2011] AMS": Time series of Atlantic basin hurricane counts over the period 1878–2008 from (a) the unadjusted HURDAT and (b) after the adjustment for estimated missed hurricanes and the magnitude of the hurricane count adjustments. Plots show the annual (light lines) and 10-yr running mean (dark lines) counts; (b) gray shading indicates the 95% method uncertainty on the adjustment. Dashed lines depict the linear least squares trends computed over the period 1878–2008.

2. Observed Hurricane Activity and Record Uncertainty

The historical record of hurricane activity in the Atlantic dates back to the late 19th century and has been more widespread than in any other basin owing to the aircraft reconnaissance that started in the late 1940s. A widely used reconstructed record, the Hurricane Database (HURDAT) has been since provided by the National Oceanic and Atmospheric Administration (NOAA; Jarvinen *et al.*, 1984; MacAdie *et al.*, 2009). It provides a historical record of Atlantic-wide tropical storm and hurricane counts, tracks, and intensities from 1851 to the present. As shown in Fig. 1a, this original record shows a significant upward trend in the annual numbers of hurricanes since the late 1800s, suggesting a substantial increase of hurricane activity over the last century, consistent with the analysis of the 20th historical record by (Holland and Webster, 2007).

However, the methodology and distribution of tropical storm counts observations have considerably changed since the late 19th century along with the technology and recording practices that have been continuously evolving with time (Landsea *et al.*, 2010). Therefore, the secular increase in the observed record could partly reflect our increased observational capabilities. Recent analyses have attempted to adjust the HURDAT database to account for missed tropical storms or hurricanes (Vecchi and Knutson, 2008, 2011; Villarini *et al.*, 2011a), particularly during the pre-satellite era (Fig. 1b). For example, the above studies showed that after adjustment, the updated estimate of Atlantic hurricane counts does not show any significant trend (Fig. 1b). Therefore, although global mean temperatures show a significant warming trend since the late 19$^{\text{th}}$ century, after accounting for known changes to the observing network there is no significant increasing century-scale trend in Atlantic tropical storm or hurricane frequency. It is hence premature to conclude from present observations that Atlantic hurricane frequency has changed (increase or decrease) due to increased atmospheric CO_2 concentrations. Detecting such a change, were it to happen in the future, will require a reliable record of past and future hurricane activity. This is complicated by the fact that long-term changes in hurricane activity are also spatially heterogeneous, partly reflecting a real non-homogeneity and partly because of changes in ship tracks density and location over time. Closer examination (Vecchi and Knutson, 2008, 2011) indicates that areas with increased storm frequency in the raw/unadjusted data are far from US landfall regions (i.e., in the open Atlantic), with decreases present in the western Atlantic. The historical record also includes many storms of relatively brief duration (<2 days) in more recent years (Landsea *et al.*, 2010). Neither the longer-lived storms nor hurricanes that hit the US coast show any significant increase in frequency since 1878.

3. Internal and Forced Components of Hurricane Variability

In addition to the trend that was discussed in the previous section, Fig. 1a shows clear multidecadal variability in the Atlantic hurricane frequency that remains pronounced in the adjusted time series (Fig. 1b). Multiple interpretations of these multi-decadal changes are possible. Mann and Emanuel (2006) attributed the decadal variability in TCs to the impact of anthropogenic forcing on Atlantic SSTs, and anthropogenic aerosol forcing was suggested as the origin of the cooling observed between 1950 and 1970. Decadal fluctuations in hurricane activity have also been related to the basin-wide Atlantic Multidecadal Variability (AMV or AMO, Goldenberg *et al.*, 2001; Zhang and Delworth, 2006), which is thought to be primarily driven by the natural fluctuations of the Atlantic Meridional Overturning Circulation (MOC, Knight *et al.*, 2005; Zhang *et al.*, 2012). The AMV, defined as a basin-averaged SST index, is also influenced by external forcing (*e.g.* greenhouse gases and aerosols), adding difficulty to the problem of attributing the AMV-related climate impacts to internal or forced variability. Few studies have attempted to distinguish in the AMV between the component attributable to external forcing and that due to natural variability (*e.g.* Ting *et al.*, 2009; DelSole *et al.*, 2011; Terray, 2012).

A recent analysis by Camargo *et al.* (2013) explored the relative importance of externally forced and internal SST variability on tropical Atlantic cyclone potential intensity. They showed that the late twentieth century increase in North Atlantic potential intensity (*e.g.* Kossin and Camargo, 2009), while closely related to the tropical Atlantic SST increase, included a considerable influence of internal variability and hence could be attributed purely to anthropogenic warming (Fig. 2). Their study highlighted the importance of remote SST on hurricane activity, which had been previously identified by Vecchi and Soden (2007); Swanson (2008). Using sensitivity experiments to isolate the role of the Atlantic MDR and the other oceans, they showed that when non-local SST effects are taken into account, the influence of global mean SST changes on potential intensity are smaller than those forced by Atlantic SST only (Fig. 2). The remote influence of Indian and tropical Pacific Ocean and to a smaller extent of extratropical North Atlantic reduces the local SST forcing in potential intensity for both forced changes and natural fluctuations. The remote SST influence tends to reduce the

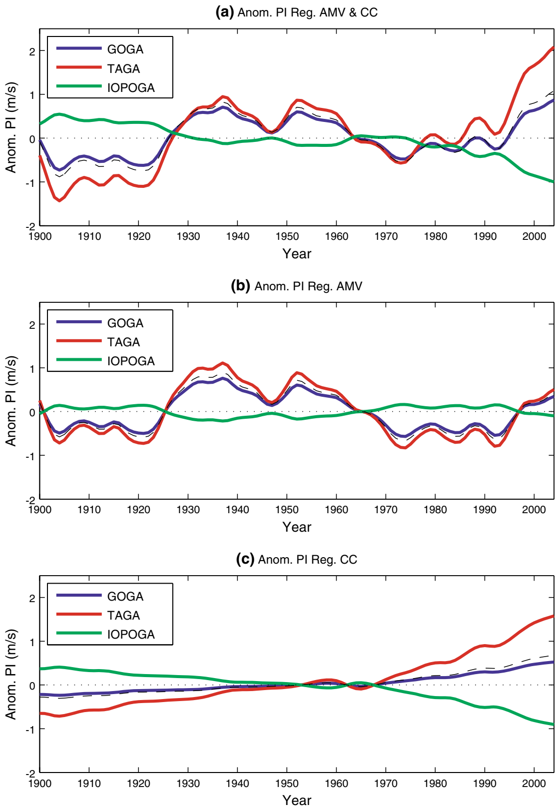

Fig. 2. From Camargo *et al.*, 2013 "© Copyright [March 2013] Springer": Regression of August–September–October (ASO) potential intensity (PI) MDR anomalies onto the sum of AMV and Climate Change (CC) indices (a), onto the AMV index (b), and onto the CC index (C). This decomposition aims at separating the effect of forced variability from that due to internal variability associated with AMV following the method described in Ting *et al.*, 2009. The three colored lines correspond to three different sensitivity experiments in which the global atmospheric model is forced using SST anomalies prescribed over the global ocean (GOGA), over tropical Atlantic ocean only (TAGA) and over the Indian and tropical Pacific Ocean (IOPOGA). The thin black dashed line is the sum of TAGA and IOPOGA to check the linearity of the experiments.

potential intensity relative to the impact of tropical Atlantic SST alone, through changes in the upper level atmospheric temperatures (Vecchi *et al.*, 2008; Camargo *et al.*, 2013). Indeed, the non-local SSTs tend to warm the tropical Atlantic upper troposphere, which increases the atmospheric stability in the tropics, reducing the potential intensity. This is consistent with the idea of relative SST and its relationship with hurricane activity (Vecchi and Soden, 2007; Ramsey and Sobel, 2011). From these studies, it appears that the recent increase in Atlantic potential intensity between 1990 and 2005 is due to both internal and forced variability (Fig. 2).

4. Projected Changes of Hurricane Activity

While warm local SSTs favor the formation and intensification of Atlantic tropical storms, it is not entirely clear how increasing global SSTs will influence TC activity because of the large number of other key features that impact hurricane formation and development. For instance, a lack of vertical wind shear between the surface and upper-level winds will tend to favor hurricane formation. Depending on the nature of the circulation changes, the more favorable conditions associated with warmer SSTs can be offset by a higher magnitude vertical wind shear. As mentioned in Sec. 1, Atlantic hurricane activity has been linked to changes in SST averaged over the Atlantic MDR relative to changes that occur over the whole tropical ocean. In particular, it has been suggested that the increase in tropical storm counts since about 1980 could be the result of the warming of the Atlantic relative to the other tropical ocean basins, i.e. an increase of relative SST (Vecchi and Soden, 2007; Vecchi *et al.*, 2008; Swanson, 2008).

This distinction between local absolute SST and relative SST has implications for projections of future hurricane activity since model projections indicate a warming of the tropical SSTs globally (and hence in the tropical Atlantic) in response to increased greenhouse gases concentrations, but relatively small changes in relative SSTs. As shown by Vecchi *et al.*, 2008, using relative SST to project hurricane changes over the 21st century indicates a much smaller

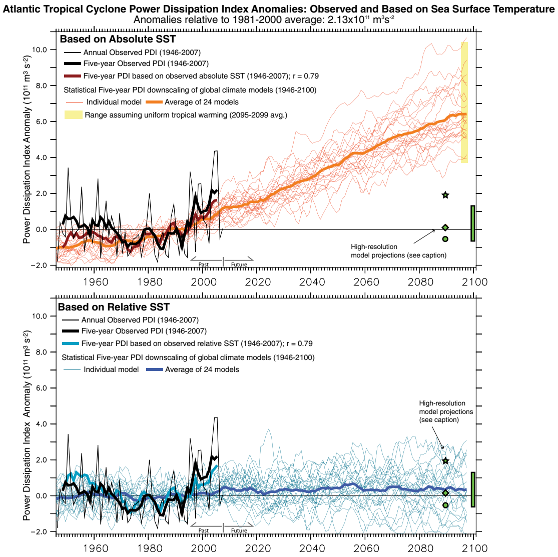

Fig. 3. From (Vecchi *et al.*, 2008) "© Copyright [31 October 2008] Science': Observed (1946–2007) and simulated (1946–2100) changes in PDI anomalies. The observed PDI anomalies (relative to the 1981–2000 average) are regressed onto the absolute (upper panel) and relative (lower panel) SST. These regression models are used to build estimates of PDI from output of global climate models for historical and future conditions.

projected change in Atlantic PDI over the coming century than suggested by using a statistical model based on MDR SST alone (Fig. 3). A recent statistical analysis by Villarini *et al.* (2011b) indicates that both local MDR SSTs and tropical-mean SSTs modulate TCs activity with similar weights but opposite signs, supporting the notion that relative SST is a robust indicator of Atlantic hurricane activity changes in response to climate change (*e.g.* Latif *et al.*, 2007; Vecchi and Soden, 2007; Swanson, 2008; Knutson *et al.*, 2008; Bender *et al.*, 2010; Zhao *et al.*, 2010; Ramsey and Sobel, 2011; Villarini and Vecchi, 2012) .

A number of current model projections indicate a potential for decrease in Atlantic hurricane frequency over the 21st century (Bender *et al.*, 2010; Sugi and Yoshimura, 2012; Knutson *et al.*, 2013). Besides assessing the changes in overall hurricane frequency, it is important to understand, and if possible make accurate projections of the behavior of the strongest landfalling hurricanes because historically they have caused the largest damage and thus have the greatest potential impact on society (Emanuel, 2011). Based on the Coupled Model Intercomparison Project 3 (CMIP3) multi-models ensemble, (Bender *et al.*, 2010) projected a significant (100%) increase of basin-wide category 4–5 Atlantic hurricane frequency by the end of the 21st century. These results were recently revisited by (Knutson *et al.*, 2013) using the Coupled Model Intercomparison Project 5 (CMIP5) models and the associated RCP4.5 climate change emission scenarios. For the CMIP5 projections, a distinction between the early and late part of the 21st century was made to account for the possible non-linearity of the changes in hurricane frequency (Villarini and Vecchi, 2012). In both CMIP3 and CMIP5 ensembles, [Knutson *et al.* (2013)] found a reduction in the frequency of TCs in a warmer climate when all storm categories are combined and an increase in the frequency of the strongest storms (Fig. 4). A robust projected increase in hurricane rainfall rates was also found as the climate gets warmer and the atmosphere holds more water vapor. The projected changes in precipitation appear to scale better with the increase in Atlantic temperature rather than with the decrease in hurricane frequency (Fig. 5).

The increase of the strongest storms was however smaller (+40% by the end of the 21st century) for the CMIP5 multi-model ensemble than for CMIP3 and only marginally significant. For the early 21st century, the projected increase is larger (+45% in 30 yr) but again is only marginally significant. The differences between CMIP3 and CMIP5 ensembles could also be the result of different forcing (IPCC A1B scenario vs. RCP4.5) or a different model response to the same forcing, as will be discussed in the next section. To explore the spread of the results among models, Knutson *et al.* (2013) additionally downscaled ten of the individual

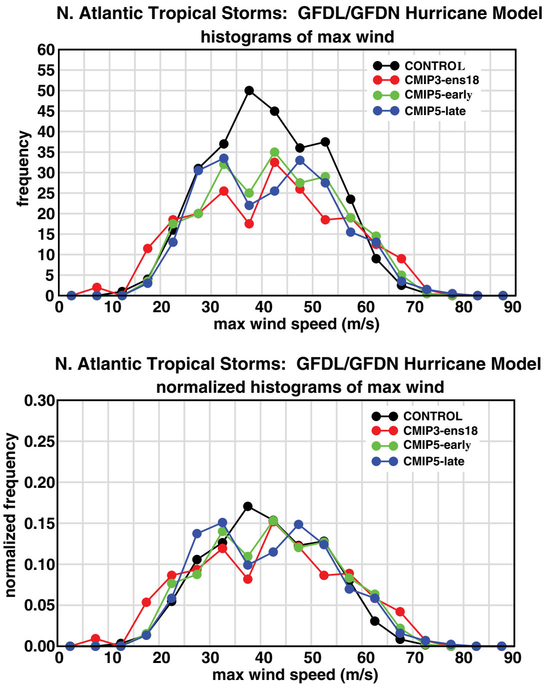

Fig. 4. From (Knutson *et al.*, 2013) "© Copyright [2013] AMS": Upper panel: Frequency histograms for lifetime maximum surface wind speeds projected by the GFDL hurricane model downscaling experiments based on the CMIP3/A1B scenarios and the more recent CMIP5/representative concentration pathway (RCP) 4.5 ensemble mean climate change experiments relative to a control run. A distinction between early and late 21st century projections is made for the CMIP5 experiments as detailed in the text. Lower panel: same as upper panel for the normalized frequency.

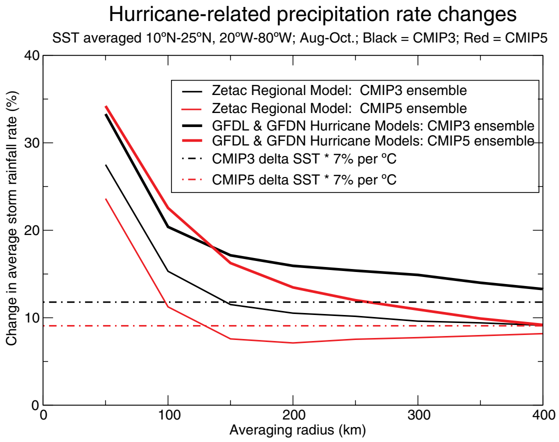

Fig. 5. From (Knutson *et al.*, 2013) "© Copyright [2013] AMS": Change (in %) between the control to warm climate in average hurricane rainfall rate for various averaging radii about the storm center (in km) for the CMIP3/A1B (black) and CMIP5/RCP4.5 (red) late 21st century multi-model ensemble climate changes, based on the Zetac regional model (thin solid lines) or the GFDL/GFDN hurricane model ensemble (thick solid lines). The dashed lines illustrate idealized water vapor content scalings, obtained by multiplying the average SST change in the region 10–25°N, 20–80°W by 7% per degree Celsius.

CMIP3 models using the GFDL hurricane model and found a significant increase of the strongest storms (category 4–5) in three of the ten downscaled models, based on 13-yr samples.

A decrease in the number of US landfalling storms was also projected for the late 21st century but these changes were not statistically significant (Knutson *et al.*, 2013). Villarini and Vecchi (2013) projected, using a statistical model, an increase in Atlantic PDI in the CMIP5 climate models, which they attributed to an intensification of Atlantic TCs in response to both greenhouse gases and aerosols (Fig. 6). An increase in the mean lifetime maximum intensity of hurricanes was also found in the CMIP3 and CMIP5 experiments analyzed by Knutson *et al.* (2013). Due to their experimental design (five-day integrations of storm cases), Knutson *et al.* (2013) were however not able to clearly address the issue of PDI changes in their higher resolution model.

5. Uncertainty in Decadal-to-Centennial Scale Projections of Atlantic Hurricane Frequency

Climate model projections provide the best estimate of likely upcoming changes in hurricane activity, but as in any forecasts these projections are associated with large uncertainty. While the analysis by Knutson *et al.* (2013) shows relatively robust projections of decreasing Atlantic tropical storm frequency over the 21st century in the CMIP3 and CMIP5 ensemble mean projections, their results differ from

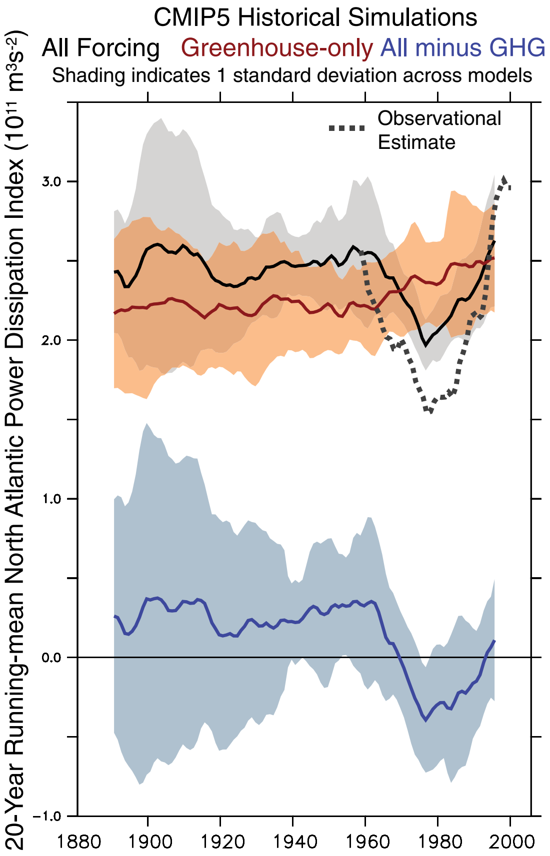

Fig. 6. From (Villarini and Vecchi, 2013) "© Copyright [May 2013] AMS": PDI evolution in response to external forcing (black) in the CMIP5 ensemble mean of 13 climate models. The impact on PDI of greenhouse forcing (in red) and non-greenhouse forcing (in blue) is distinguished. Shading indicates one inter-model standard deviation. Non-greenhouse forcing includes natural (*e.g.* solar forcing and volcanoes) and anthropogenic (ozone, aerosols) forcing.

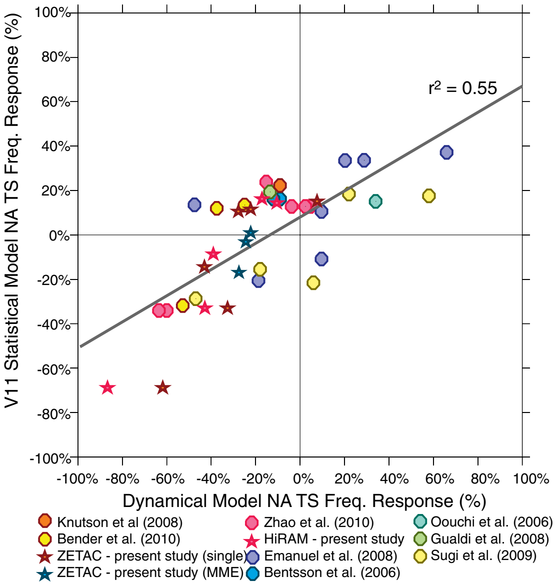

Fig. 7. From (Knutson *et al.*, 2013) "© Copyright [2013] AMS": Comparison of published dynamical model projections of Atlantic hurricane frequency (x-axis) with projections based on relative SST using the statistical downscaling model defined in Villarini *et al.* (2010, 2011b). Blue stars correspond to the CMIP3, CMIP5-Early and CMIP5-Late multi-model ensemble results.

previous studies by other investigators. Comparing the results of Knutson *et al.*, 2013 with previously published results (Fig. 7) indicates a lack of robustness in the sign of the projected change in Atlantic tropical storm frequency given that a number of other model studies indicate an increased frequency in a warmer climate (Sugi *et al.*, 2002; Oouchi *et al.*, 2006; Chauvin *et al.*, 2006; Emanuel *et al.*, 2008; Sugi *et al.*, 2009; Murakami *et al.*, 2012). Despite these discrepancies in the projected change in tropical storm frequency, models are more consistent if their tropical storm projections are viewed in terms of the projected change in relative SST. Indeed models that project an increase in TC frequency in a warmer climate are generally forced with (or simulate) a SST in the Atlantic that exceeds the tropical-mean warming (Fig. 7, Villarini and Vecchi, 2012). Relating the changes in tropical storm frequency to changes in relative SST thus helps us understand and interpret the differences in model projections. It also suggests that a better constraint on Atlantic relative SSTs could improve the confidence in Atlantic tropical storm and hurricane frequency projections.

Further, even though climate models have improved greatly in recent years, they still contain large biases that limit their reliability. Emanuel *et al.* (2013) stressed that historical simulations with current climate models fail to reproduce the observed cooling trend near the tropopause over the Atlantic, and they suggested that this could lead to an underestimation of future TC increase. One major source of model errors comes from the representation of tropical convection, which is itself linked to the simulation of clouds that rely on complex processes (Randall *et al.*, 2007). The simulation of hurricane activity is also tightly linked to that of El Niño Southern Oscillation (ENSO), adding it as a source of uncertainty for the projections of future hurricane activity. Indeed, ENSO is unevenly represented among climate models and because of the models spread, there is no consensus on its future evolution (Guilyardi *et al.*, 2009; Vecchi and Wittenberg, 2010; Guilyardi *et al.*, 2012) and therefore on the subsequent future hurricane changes due to ENSO.

Currently the resolution of climate models is usually not sufficient to simulate the key features of atmospheric circulation that impact hurricane formation and development, projections as in (Knutson *et al.*, 2013) presented in Sec. 4 rely on downscaling techniques. Knutson *et al.* (2013) explored the dependence of the hurricane projections on the downscaling model, using two different downscaling models: an 18-km grid regional model (Zetac) and a 50-km grid global model (HiRAM C180) with similar large-scale climate projections from global climate models as boundary conditions. While the projection of fewer Atlantic tropical storms was overall robust between the two downscaling experiments, little consistency was found when looking at individual CMIP3 models.

Vecchi *et al.* (2011) showed that the forcing could also have a strong impact on the downscaled circulation with biased trends in the reanalysis (*e.g.* NCEP) imprinting on the simulation of historical trends in storm counts in the Zetac model. This indicates that further work is needed to assess the role of reanalysis uncertainty in historical simulations and assessments of TC activity.

The downscaling experimental design can limit the applicability of a study for landfalling storm statistics. For example, in Knutson *et al.* (2013) the downscaling framework used (i.e., an operational hurricane prediction system) was limited to five-day runs since that is how the model is used operationally. For the study, the time of maximum intensity of each storm was identified in the parent regional atmospheric model (*e.g.* the Zetac model) and then the starting point for the five day experiment was determined by backing up three days from that time of maximum intensity. Since the hurricane model was integrated forward for a maximum of five days, the simulations were generally too short for most of the case-study storms to reach the US coast. In future studies, a focus on landfalling systems for climate impacts applications, as well as increased computational resources, should help address this limitation.

Given the numerous sources of uncertainty, it is important to determine which one might dominate on the time scale of interest, to put more effort into reducing it. Villarini and Vecchi (2012), following the methodology developed by Hawkins and Sutton (2009), have partitioned the sources of uncertainty in projections of North Atlantic hurricane frequency into three main components: the forcing uncertainty that arises from imperfect knowledge of future radiative forcing, the response uncertainty arising from imperfect knowledge of how the climate system will respond to changes in radiative forcing, and the internal variability uncertainty arising from chaotic variations in the climate system that are not driven by radiative forcing. Interestingly, they showed that even though tropical Atlantic and tropical mean SSTs are both predictors of tropical storm activity in the statistical model, the sources of uncertainties for projected tropical Atlantic SST and tropical mean SST are very different from the uncertainty of projecting changes in relative SST and TCs (Fig. 8).

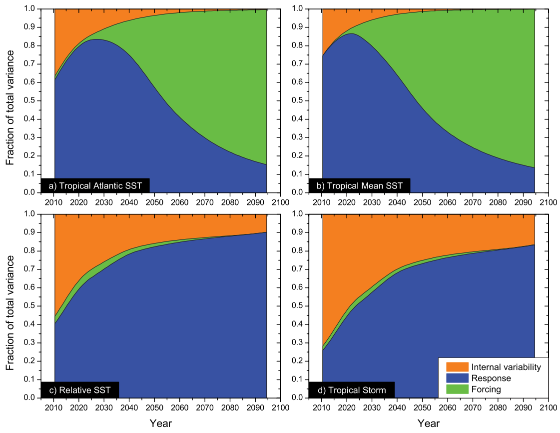

Fig. 8. From (Villarini and Vecchi, 2012) "© Copyright [2012] Nature": Fractional contribution to uncertainties in CMIP5 projections of Atlantic tropical storm frequency and its predictors as defined in the statistical-dynamical model of (Villarini *et al.*, 2010). The decomposition follows the method defined by (Hawkins and Sutton, 2009).

For tropical Atlantic and tropical mean SSTs, the response uncertainty dominates until the mid-21st century, after which the climate forcing becomes the dominant source of uncertainty. In contrast, internal variability is the largest source of uncertainty in projections of hurricane frequency during the first half of the 21st century with an important contribution of the response uncertainty as well, which becomes dominant at the end of the century. The uncertainty of forcing (i.e. future greenhouse gas emissions and other radiative forcing) does not play a large role for hurricane frequency whereas it does for projections of tropical Atlantic SST. This again shows that a better constraint on future changes in Atlantic SST, and in particular relative SST, could help reduce the uncertainty in future projection of Atlantic hurricane frequency.

6. Multi-year Predictions of Hurricane Activity

The large internal variability of hurricane activity is a large source of uncertainty in future projections, as described in the previous section, and it complicates the assessment of whether an observed change within a relatively short record is due to anthropogenic forcing or natural variability. In an attempt to quantify or predict the part that is caused by internal climate variability, recent coordinated experiments have been performed as part of CMIP5. In these experiments, besides imposing historical and future projected time-varying forcings as boundary conditions, the models used for the predictions were initialized with estimates of the observed state of the climate system (Taylor *et al.*, 2012). The purpose of these experiments was to determine where initialization could increase skill by either predicting some of the internal variability or improving the forced response or both. While for SST, most of the skill on multi-year timescales arises from predicting the warming trend associated with radiative forcing changes (van Oldenborgh *et al.*, 2011), Smith *et al.* (2010) suggested that initialization can increase the skill in multi-year hurricane forecasts. This is consistent with and motivated by a number of studies, which suggested that internal variations of the climate system could play a large role in changes of hurricane frequency on decadal timescales (*e.g.* Goldenberg and Shapiro, 1996; Zhang and Delworth, 2006, 2009; Knight *et al.*, 2006; Latif *et al.*, 2007; Dunstone *et al.*, 2011; Villarini *et al.*, 2010; Villarini and Vecchi, 2012).

Vecchi *et al.* (2013) investigated the predictability of North Atlantic hurricane frequency in two climate prediction systems based on the GFDL and UKMetOffice coupled models using a statistical-dynamical model based on tropical Atlantic SST and relative SST as predictors (Vecchi *et al.*, 2011). In this way, statistical-dynamical predictions could be made without a direct count of the exact number of storms produced by the model. The retrospective 5-yr mean and 9-yr mean predictions from these two models are encouraging with the best results

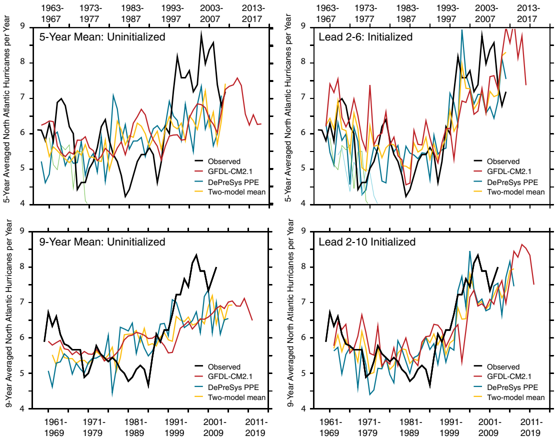

Fig. 9. From (Vecchi *et al.*, 2013) "© Copyright [August 2013] AMS": Retrospective and future forecasts of 5-yr mean and 9-yr mean hurricane frequency in uninitialized (left) and initialized (right) decadal prediction experiments. Black line shows the observed counts from the NOAA HURDAT database that includes the adjustement for observing inhomogeneity prior 1966 described in (Vecchi and Knutson, 2011). Red lines correspond to forecasts from the GFDL-CM2.1 system, blue lines show results from the UKMetOffice-DePreSys-PPE system, and yellow lines correspond to the two-system ensemble-mean.

for the two-model mean (Figs. 9 and 10). The predicted time series follow quite closely the observed variations for several years. The correlations show a nominal improvement in the initialized experiments for both 5-yr and 9-yr mean predictions. However, the nominal improvement in the lead 2-to10-yr forecast arises only in the first part of the decade, suggesting potential multi-year forecast skill rather than decadal skill.

The improved accuracy in the initialized predictions was mainly attributed to a reduction of the conditional bias in SST that is large in the uninitialized predictions (Vecchi *et al.*, 2013). The impact of initialization on forecasts of the Atlantic MDR conditions appears key to the higher skill in the initialized forecasts. Though encouraging, these results need to be viewed with caution. Indeed the observational dataset is too short to confidently assess whether the additional correlation skill added by initializing with observations is statistically significant compared to the forced experiments as shown by the large confidence intervals in Fig. 10. Furthermore, the observed time series of North Atlantic hurricane frequency (Fig. 1) is characterized by an abrupt rise in 1995 leading to a positive trend over the 1961–2011 period. Vecchi *et al.* (2013) found that both the UKMetOffice and GFDL models show an increase in hurricane frequency in the mid-90s, leading to high correlations with observations. However they showed that these high correlations do not come from predicting the dynamical evolution of the climate system that leads to the mid-90s shift in hurricane frequency, but from "recognizing" that a climate shift has occurred around 1995 and persisting that shift.

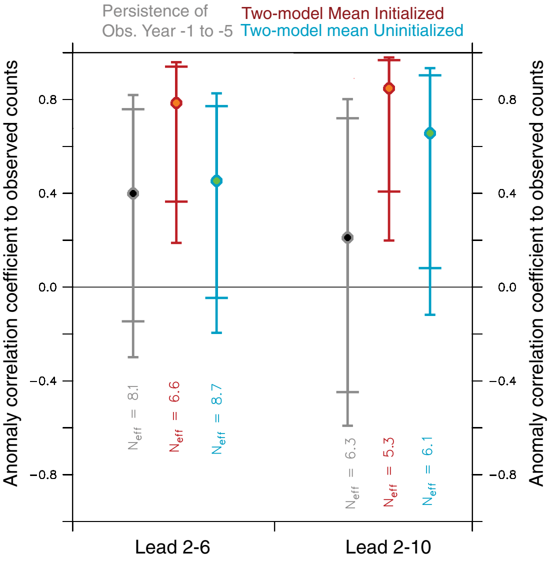

Fig. 10. (Adapted from (Vecchi *et al.*, 2013) "© Copyright [August 2013] AMS": Anomaly correlation of retrospective multi-year forecasts of North Atlantic hurricane frequency, for forecast leads of 2–6 years and 2–10 years. The values shown are averages of two prediction systems based on the GFDL and the UKMetOffice models. The sample correlation estimate is shown by a circle; the bars show the two-sided 90% and 95% uncertainty. Red bars correspond to the initialized predictions, blue bars to the uninitialized ones and gray bars indicate the correlation from a persistence forecast.

Identifying the source of skill in retrospective predictions is key to assessing the likely success of future forecasts. The analysis of Vecchi *et al.* (2013) suggests a limited chance of predicting a similar positive or negative shift in hurricane frequency, were it to happen, using the current predictions systems. Identifying the origin of the observed upward shift in hurricane frequency in 1995 and assessing whether the modeled mechanisms are consistent with those in the real world are keys to interpreting any apparent skill in the retrospective forecasts. There is also a need to better understand the physical sources of predictability of Atlantic hurricane activity, whether remote as suggested by Dunstone *et al.* (2011) and Camargo *et al.* (2013) or local (Vecchi *et al.*, 2013). There are indications that changes in atmospheric aerosols could have influenced hurricane activity over the second half of the 20th century, with a decrease in Atlantic aerosol driving an increase in Atlantic hurricane activity (Mann and Emanuel, 2006; Evan *et al.*, 2009; Villarini and Vecchi, 2012). However, the discontinuities in the observing system for both hurricane counts and the observed ocean conditions used for the initialized decadal predictions make it challenging to attribute changes in hurricane activity to specific causes. There is a coincidence between the global implementation of Argo drifting floats in 2003 and the increase in hurricane activity predicted by the GFDL model (Fig. 9), suggesting an artifact of changes in the observing system. Vecchi *et al.* (2013) found a much reduced increase in hurricane activity over the next decade when the prediction experiments were repeated withholding Argo data, suggesting that enhanced observational sampling after 2003 may have led to a substantial change in the lead-dependent climatology. Additional methods to minimize the impact of observing system changes must be explored to improved future predictions of hurricane activity.

7. Conclusion

We reviewed in this chapter recent work on assessing past, present and future changes in North Atlantic hurricane activity. Although comprehensive observations of TCs have been collected in the Atlantic for more than a century, the original NOAA database almost certainly has important biases such as missing or miscategorized storms. Consequently, the dataset shows a (likely spurious) increase in the number of storms over the 20th century that could be misinterpreted as a response to anthropogenic warming. An estimated adjustment to the HURDAT database by (Vecchi and Knutson, 2008, 2011), has led to a revised estimate of past tropical storm and hurricane numbers and to the associated long-term trends. The updated record shows no significant trend, similar to U.S. landfalling hurricane counts, which also show no significant long-term trend, even without any adjustments applied. Our confidence in any climate change detection and attribution statements, or even in future projections, requires a sustained effort to observe the climate system, including tropical storms, along with a careful assessment of the available climate records. Recent changes have been documented in the observed record of Atlantic hurricane activity including an increase in potential intensity between about 1990 and 2005 (Kossin and Camargo, 2009). While such changes could be interpreted as the climatic impact of anthropogenic forcing on Atlantic hurricane activity, the attribution of these changes to climate forcing agents is complicated by the fact that decadal to multi-decadal changes in hurricane activity are closely linked to those of North Atlantic SST which presumably include contributions from anthropogenic forcing, natural forcing, and internal climate variability (Ting *et al.*, 2009; Terray, 2012). Model experiments have suggested that the late twentieth century increase in North Atlantic potential intensity includes a substantial contribution from internal variability and hence cannot be attributed purely to anthropogenic forcing Camargo *et al.* (2013). A number of studies also highlighted the importance of remote SST, showing that relative SST was a more robust indicator of hurricane changes than local MDR SST (Vecchi *et al.*, 2008; Ramsey and Sobel, 2011). From these studies, it appears that the recent increase in potential intensity is likely due to both internal and forced variability.

Statistical and dynamical models that reproduce quite well past hurricane activity have been used to project future hurricane activity. At present, we do not know with confidence even the sign of the expected changes in North Atlantic hurricane frequency over the coming century. However, the most likely response to increased greenhouse gases, according to current model projections, is a reduction in the overall frequency of North Atlantic tropical storms and hurricanes and an increase in the frequency of the most intense hurricanes, which means fewer but stronger storms in the tropical North Atlantic in a warmer climate (Bender *et al.*, 2010; Knutson *et al.*, 2013). Models project robustly that tropical storms in a warmer climate will be associated with higher rainfall rates than those in the present climate, in particular in the hurricane inner core where the projected increase exceeds what would be expected from a simple Clausius-Clapeyron atmospheric water vapor response.

Very intense hurricanes are relatively rare but are potentially very dangerous (Mendelsohn *et al.*, 2012; Peduzzi *et al.*, 2012). Pielke *et al.* (2008) stressed that although category 4–5 hurricanes account for only about 15% of US landfalling TCs, the damage they cause is considerable and disproportionate. Bender *et al.* (2010) estimated that by 2100 the overall destructive potential of hurricanes could increase by over 30% because of long-term climate warming leading to a greater frequency of category 4 and 5 hurricanes in the Atlantic. Higher cyclone wind speeds, along with increased sea level, would tend to increase the probability of storm surges. However, the net change in storm surge threat will depend on other factors as well, such as storm frequency changes and changes in preferred tracks, which are even less well-constrained.

Future hurricane activity will likely also depend on regional details of SST changes, which can differ substantially between the different climate model projections (Emanuel *et al.*, 2008; Villarini and Vecchi, 2012). The observed past TC changes and the model projections of hurricane activity are not spatially uniform (Vecchi and Soden, 2007; Vecchi and Knutson, 2008, 2011; Zhao *et al.*, 2009) and the spatial structure of these changes needs to be considered in relating future TC projections to impacts. Increasing the confidence in these projected regional details remains a challenge.

On the basis of current global climate model projections and our downscaling models, the forced response and internal variability uncertainties appear as dominant limitations in our ability to confidently project North Atlantic hurricane activity over the 21st century. Aerosol forcing and the climate response to aerosols also remain major sources of uncertainty. A better understanding of the climate forcings and the dynamical processes that will control changes in hurricane predictors like tropical Atlantic SST, over the 21st century, are key to reduce these uncertainties. A further source of uncertainty that cannot be eliminated, however, is the uncertainty that arises from the chaotic behavior of the atmosphere, with the limited predictability of weather patterns that can affect hurricane activity and vice versa.

Predicting hurricane frequency on multi-year timescales, and hence beyond the seasonal forecasts, is an emerging field of research. Recent studies suggest that coupled models that account for changes in both the initial state and external forcing can potentially lead to skillful multi-year predictions of Atlantic hurricane frequency (Smith *et al.*, 2010; Vecchi *et al.*, 2013). This improvement due to initialization should, however, be interpreted with caution given the relatively small effective number of degrees of freedom that results from the limited observed record and temporal persistence in the time series. Although models and observational techniques have improved and expanded greatly in recent years, there are still many challenges to face. It appears likely that additional improvements in dynamical models will improve TC representation and predictions. Landfalling hurricanes have not been discussed in detail in this chapter. While these are of even greater societal importance, they tend to be associated with larger uncertainties in terms of model projections and thus represent an additional long-term challenge.

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