Draft Final Report on Project 07121-1801:
Effect of Climate Variability and Change in Hurricane Activity in the North Atlantic

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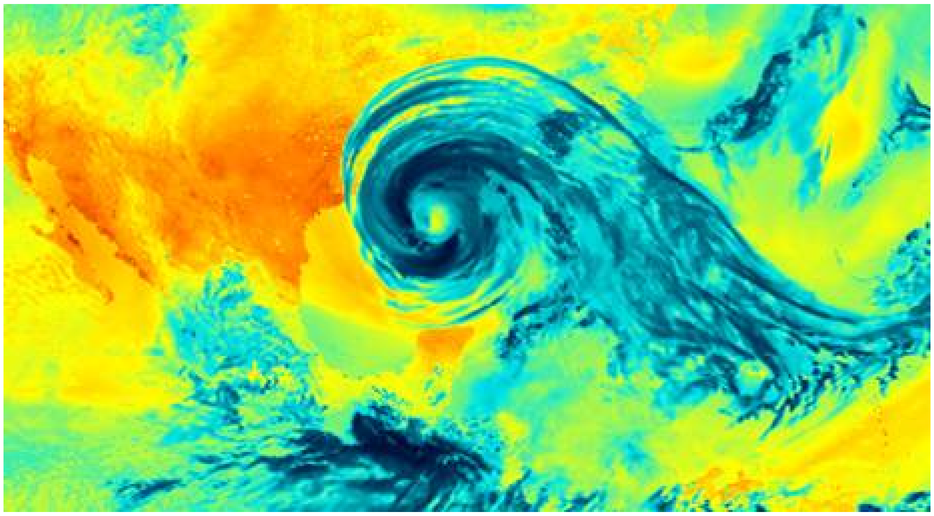

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Contents

Abstract

RPSEA research award 07121-1801 (hereafter 1801 project) has funded an extremely successful project on the effect of climate variability and change in hurricane activity in the North Atlantic. This report summarizes the major results of the project together with estimates of confidence and highlights areas ready for future research.

According to three recent assessments, hurricane activity, particularly intensity, is likely to increase in the future. If true, this raises the possibility that new coastal and offshore facilities are being under-designed; that older facilities may need hardening in order to maintain presently accepted risk levels; and, that evacuation costs may change in the future. The 1801 project has provided credible predictions of changes in hurricane activity in the North Atlantic over the next 50 years by developing and applying a combination of advanced dynamical and statistical modeling techniques with particular focus on the Gulf of Mexico. These predictions have been complemented by new approaches to assessing their degree of uncertainty.

Recent increases in computational capacity have enabled dynamical assessments in unprecedented detail. The benefits of utilizing such enhanced model resolution are demonstrated together with an assessment of sensitivity of tropical cyclone activity to critical details of the experimental approach. Results show North Atlantic hurricanes will experience an accelerated increase in numbers from 1-3 percent per decade near the present to 4-10 percent per decade leading up to 2050; the region of maximum storm activity and formation will move equatorward over the same time period; and there will be a modest increase of mean intensity, but a more marked increase in the frequency and intensity of the most intense hurricanes. Consistent results between statistical and dynamical assessments further increase confidence in these predictions and results are shown to be robust to details of our experimental approach.

Changes in storm activity on sub-basin scales including the Gulf of Mexico are less certain due to the low numbers of storms and therefore small sample size. Motivation is provided for a future research focus on developing statistical modeling specific to the Gulf of Mexico to generate large numbers of forecasts and increased confidence in future changes.

Additional work was undertaken to assess changes in expected storm damage to offshore facilities. In this aim a hurricane damage index was developed to translate hurricane parameters directly into quantitative damage assessments. In applying the index to storms in the dynamical model forecasts damage assessments have been produced over the next 50 years. These show that although storms are projected to be more intense, changes in size and translation speed counteract this.

Introduction

Globally averaged intensity of tropical cyclones will shift towards stronger storms under predicted climate change scenarios, with intensity increases of 2–11% by 2100 according to an assessment by a World Meteorological Organization Expert Team on Climate Change Impacts on Tropical Cyclones (Knutson et al, 2010). They also state that existing modeling studies consistently predict decreases in the globally averaged frequency of tropical cyclones, by 6–34%, yet substantial increases in the frequency of the most intense cyclones. The synthesis reports of IPCC (2007) and CCSP (2008) are in general agreement with these assessments. Predicted changes for individual basins, however, show large variations between different modeling studies and there is disagreement on whether numbers of storms in individual basins will increase or decrease (e.g. Knutson et al 2007, 2010 and Bengtsson et al 2007).

North Atlantic hurricane activity averaged over the past 15 years has been well above than the longer term historical average (e.g. Holland and Webster 2007, Vecchi and Knutson 2008). Over the past 15 years hurricane activity within the Gulf has also been above the longer-term average. Indeed, Cooper and Stear (2006) point out that recent storms like Ivan and Katrina appear to fall far above the historical hazard curve in the Gulf. Should this elevated hurricane activity in the Gulf continue or increase further it will have far reaching impacts on the offshore energy industry in the Gulf of Mexico. Impacts may include:

- Higher design criteria for new construction which is especially important in deepwater where a 10% increase in wave height can increase construction cost on the order of $50 million;
- Increased damage to infrastructure such as platforms, pipelines, shore bases, and refineries located near the coast. Experience from Rita, Ivan, and Katrina showed that severe hurricanes can substantially reduce Gulf production of crude and refined products for months resulting in increased energy costs that can amount to billions of dollars for consumers;
- Increased capital expenditures to harden existing infrastructure. There are over 3000 active offshore structures in the Gulf and tens of thousands of miles of pipelines so the potential costs to strengthen this infrastructure enough to maintain historical risk levels could amount to billions of dollars of additional investment;
- Increased costs and risks for personnel evacuations. For the overall industry, these costs have sometimes reached $500 million during the most severe hurricane seasons.

Clearly there is a strong business need for the energy industry to better understand the likelihood that future hurricane activity in the Gulf might increase. With sufficient warning, the industry could mitigate at least some of the future costs. Towards this end, a consortium including the Department of Energy and 19 energy companies have funded the National Center for Atmospheric Research (NCAR) to produce a range of predictions of hurricane activity over the next 50 years for the Gulf of Mexico, together with estimates of uncertainty. Our approach is to use a powerful combination of the latest dynamical modeling and novel statistical methods.

Dynamical models of the Earth’s climate system represent the full processes of the climate system, including both representation of climate variability such as El Nino Southern Oscillation and the North Atlantic Oscillation and response to external climate forcings such as solar variability and changes in atmospheric composition. However, these models are too coarse to include information on critical hurricane parameters. Our dynamical modeling approach is to add detailed hurricanes to the climate model by embedding a weather model within the global climate model in a process known as dynamical downscaling. We anticipate significant benefits to hurricane simulation as hurricane dynamics become better resolved on finer grids. A representation of smaller scale physical and dynamical processes results in the emergence of important structural details such as spiral rainbands, eye-wall thunderstorms, and other hurricane processes that may include; the birth of hurricanes from individual thunderstorm clusters; extra-tropical transition; and anticipated improvement in the upscale impact of hurricanes back on the large-scale environment. Further, hurricane upscale impacts on the large-scale environment are currently a major source of uncertainty for future climate predictions. In addition to generating forecasts of future tropical cyclone activity through dynamical downscaling, a thorough assessment of the sensitivity of tropical cyclone activity to critical details of the experimental approach is undertaken.

A second method of downscaling is developed to complement the results of dynamical downscaling. Known as statistical downscaling, this technique uses known relationships between the large-scale, slowly varying environment and tropical cyclones to infer tropical cyclone activity from the global climate model data (e.g. Camargo *et al.,* 2007). These relationships include the influence of climate variability such as El Nino Southern Oscillation and climate forcings such as change in atmospheric composition on tropical cyclone activity through their signal in the large-scale environmental variables. A further step is to directly assess impacts on Gulf of Mexico facilities using relationships that statistically combine hurricane parameters, such as intensity, size and translational speed, with historical damage data.

This report is structured following the technical tasks as defined in the project proposal. Under each task is a summary of the major findings and level of confidence in the results. Significant additional work has been conducted well beyond the scope of the original tasks and is summarized here. This additional work comprises a thorough assessment of uncertainty in future changes in tropical cyclone activity and an assessment of future storm losses to the industry. Finally, conclusions are drawn together with a discussion of future research directions.

Task 1: Model Setup and Initial Testing

Existing Nested Regional Climate Model (NRCM) datasets at the beginning of the project consisted of simulations on a tropical channel domain using a horizontal grid spacing of 36 km. This channel domain ran for 6 years from 1 January 2000 to 1 January 2006 and initialized once at the start of the simulation based on large-scale conditions from NCEP/NCAR global reanalysis data at 2.5° lat/lon grid spacing and thereafter driven at the northern and southern lateral boundaries by the six-hourly reanalysis dataset and at the lower boundary by monthly observed sea surface temperature data at 0.5° lat/lon grid spacing interpolated to six-hourly. This model configuration produced a reasonable temporal and spatial distribution of tropical cyclones globally but had a tendency to overproduce the total number of tropical cyclones.

Within the parent channel domain are multiple nested domains at 12 km and 4 km grid spacing for select periods and sub-regions allowing for an initial investigation of the impact of model resolution on tropical cyclone activity. Of particular relevance to this project is a nested domain at 12 km grid spacing covering the region of the tropical North Atlantic (see Fig. 9 in Done et al. 2010). For the period 1 May 2005 through 1 December 2005 this 12km domain produced a good simulation of both the number and spatial distribution of tropical cyclones with 29 storms compared to 27 in the observations (not shown). This necessary initial testing phase allowed us to move ahead with the 50 year forecasts with a modeling system that was able to reproduce global tropical cyclone activity. The specific outputs for task 1 have been completed and plots of tropical cyclone parameters from the channel domain simulations are available.

Cyclone Detection and Tracking

As part of task 1 a new objective tracking algorithm was developed that incorporates detection attributes used in other studies and information on the vertical structure of the warm core. A storm is detected when the following attributes have existed for at least 48 hours: local minimum in sea level pressure; relative vorticity > 5×10^{-5} s^{-1}; maximum wind speed > $17 ms^{-1}$ in the vicinity of the pressure minimum; and a warm temperature anomaly aloft compared to the immediate surroundings. The cyclone phase space developed by Hart (2003) is then used to differentiate between tropical, subtropical and extra-tropical cyclones. The cyclone is then tracked by a search of these conditions in the vicinity at each archive step, and it ceases to exist when the conditions are no longer present. This tracking algorithm is used to extract storm data from all model simulations described in this report.

Task 2: Intermediate Testing

A comparison of multi-year trends in wind-shear over the Tropical North Atlantic has been completed between existing global climate model simulations for the 50-year period 1957-2007 and NRCM simulations for the 10-year period 1995-2005. Multi-year trends in mixed-layer ocean temperatures have also been extracted from the global climate model simulations and compared with available observations. Deep ocean conditions in the Gulf of Mexico are predicted to warm at an accelerated rate over the next century, to reach $+2.5^{o}C$ by 2100, significant at the 99% level. Available oceanic heat energy for tropical cyclones is predicted to increase 5-fold, also significant at the 99% level. Future predictions also show a substantial warming of the mixed layer in the Gulf of Mexico. The results were provided at the first 1801 project report and are available on request.

Task 3: 50 Year Forecast

Experimental Design

Dynamical Downscaling: Zooming in on Future Hurricanes

The NCAR global Community Climate System Model (CCSM, Collins et al. 2006) provides the global climate predictions for the study. This is a full earth system model, including atmosphere, ocean, cryosphere, biosphere, and land surface. The NCAR Nested Regional Climate Model (NRCM), based on the NCAR Weather Research and Forecasting model (Skamarock et al. 2008), is embedded within the CCSM to generate high resolution climate information.

Global climate data were generated using CCSM under the A2 ‘business-as-usual’ scenario based on moderate economic growth for the period covering 1950-2100. These data were then used to drive the NRCM over the domains shown in Fig. 1 for three periods: a decade of current climate conditions referred to hereafter as ‘base climate’, and two future decades of

2020-2030 and 2045-2055. Ideally, the NRCM would run for the entire period 1950-2100 but computational constraints requires a time slice approach of one current and two future decades only. The NRCM is run at two horizontal grid spacings; 36- and 12-km. The model setup is such that information flows one-way down from the coarse global climate data to the 36 km domain and then to the 12 km domain. A further set of simulations at 4km for individual hurricanes will occur during 2011 in continuing NCAR research. The 36- and 12-km domains are much larger than the Gulf of Mexico, our region of interest, to ensure the majority of atmospheric processes that impact the region are handled by the higher resolution model rather than the coarser climate model (e.g. easterly waves). Importantly, the NRCM-generated climate is not nudged to be similar to the climate of the driving model (CCSM) so as to allow the beneficial upscale impacts of smaller scale processes such as individual thunderstorm clusters on the regional climate.

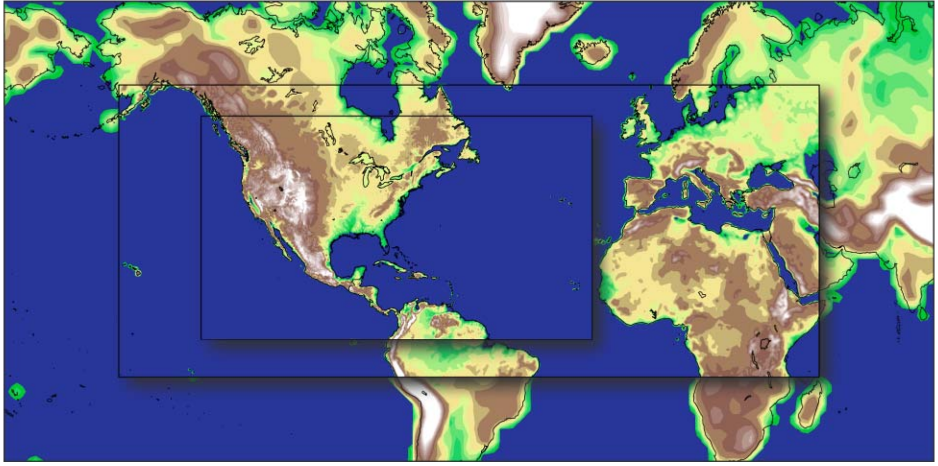


Figure 1: NRCM model domains at 36 km grid spacing (large black box) and 12 km grid spacing (small black box). Model terrain height (shaded) is shown at the different model resolutions and extends beyond the 36 km domain to indicate the resolution of the driving global climate model.

Dynamical Modeling Issues

Initial testing of the modeling system found a significant climate bias in the regional climate generated by the NRCM when it was directly coupled to the unmodified CCSM. This included a bias in the large-scale flow at upper-levels over the tropical North Atlantic, which resulted in high vertical wind shear, as shown in Fig. 2. This shear of well in excess of 30 ms^{-1} effectively stops any simulation of tropical cyclone development and maintenance in this region. Sensitivity studies (not shown) revealed the bias was transferred to the NRCM from CCSM, partly due to dynamical propagation from the east and west boundaries. But the major underlying cause arose from a well-known tendency for global climate models to generate anomalously warm eastern North Pacific ocean temperatures that results in permanent El-Nino-like conditions, which have been shown to increase the vertical shear over the tropical Atlantic (Gray 1984).

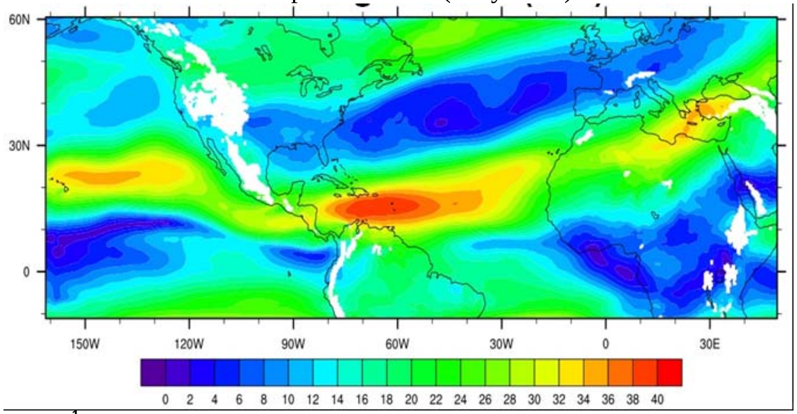


Figure 2: Vertical wind shear (ms^{-1}) averaged over Aug-Sept-Oct 1996 from the NRCM 36 km domain showing high shear covering much of the tropical North Atlantic.

A method that combines the CCSM simulation with NCEP-NCAR reanalysis (Kalnay et al 1996) data was designed to remove this climate bias from the CCSM fields. Six-hourly CCSM data for the entire simulation (1950-2100) were broken down into an average annual cycle plus a perturbation term:

$$CCSM = \overline{CCSM} + CCSM' \qquad 1.$$

The average annual cycle is defined over a 20-year period from 1975-1994. This length was chosen to smooth out any influence of El-Nino. The choice of smoothing period is not important for this investigation into trends in tropical cyclone characteristics as shown later in this report. Equation 1 is applied to the zonal and meridional wind, geopotential height, temperature, relative humidity, land and sea surface temperature and mean sea level pressure. Similarly, the 6-hourly NCEP-NCAR reanalysis data are broken down into an average annual cycle plus a perturbation term:

$$NNRP = \overline{NNRP} + NNRP' \qquad 2.$$

The revised climate data, $CCSM_R$, are then constructed by replacing $\overline{CCSM}$ in Eq. 1 with $\overline{NNRP}$ in Eq. 2:

$$CCSM_R = \overline{NNRP} + CCSM' \qquad 3.$$

The revised CCSM simulation for the entire simulation period (1950-2100) thus has a base climate provided by NCEP-NCAR reanalysis data from the period 1975-1994 and the day-to-day weather, climate variability and climate change signal from the global climate model. This correction resulted in improved definition of current climate and when used to drive the NRCM through the horizontal and surface boundary conditions resulted in substantially improved simulation of tropical cyclone activity.

Statistical Downscaling: Multiple Fast Assessments

Confidence in tropical cyclone variability and trends obtained through dynamical downscaling is limited by the relatively short period and small number of storms that can be simulated; a small sample size does not permit statistical significance. Sample size, and therefore confidence, can be increased substantially by complementing the dynamical results with statistical assessments. Statistical downscaling uses relationships between the large-scale and slowly varying environment and tropical cyclone activity to infer tropical cyclone activity directly from climate model data. These statistical assessments are extremely quick to run and can therefore be applied to multiple climate datasets to explore the range of possibilities of future changes in tropical cyclone activity.

Emanuel and Nolan (2004, see also Emanuel et al 2006) developed the Genesis Potential (GP) index, a statistical downscaling tool for assessing frequency of tropical cyclones, formulated as:

$$GP \quad = \quad \left|10^5 \eta\right|^{3/2} \left(\frac{RH}{50}\right)^3 \left(\frac{V_{pot}}{70}\right)^3 \left(1 + 0.1 V_{shear}\right)^{-2} \qquad 4.$$

where η is the absolute vorticity (s^{-1}) at 850 hPa, RH is the relative humidity (%) at 700 hPa, V_{pot} is the maximum potential intensity (ms^{-1}) and V_{shear} is the vertical wind shear (ms^{-1}) between 850 and 200 hPa. The maximum potential intensity (Emanuel, 1995) is determined from the vertical structure of temperature and moisture, sea level pressure and sea surface temperature following the method used by Camargo et al (2007).

In this study GP is applied to the same global climate dataset that has been dynamical downscaled with the NRCM to generate a complimentary assessment of tropical cyclone activity.

Results: Dynamical Assessments

The impact of climate variability and change on tropical cyclone activity is assessed here using two NRCM model resolutions. The impact of model resolution on the structure of simulated hurricanes is shown in Fig. 3. At 36-km the simulated hurricane has a simple circular structure whereas at 12-km sub-system scale structure emerges in the form of eye-wall thunderstorms and spiral rain bands. These features have associated signatures in the surface wind fields thereby improving impact assessments. Other studies have shown resolution also impacts genesis mechanisms, eye-wall replacement cycles, rapid intensification and upscale impact of the hurricane back on its environment.

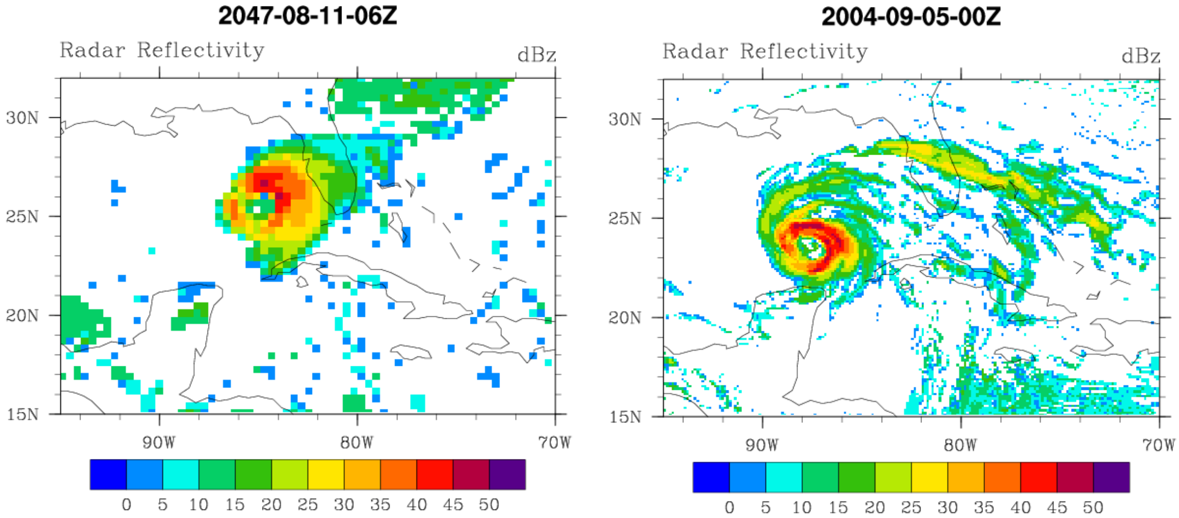


Figure 3: Snapshots of example NRCM tropical cyclones in the Gulf of Mexico generated on (left) the 36 km grid and (right) the 12 km grid, shown in model derived radar reflectivity (dBz).

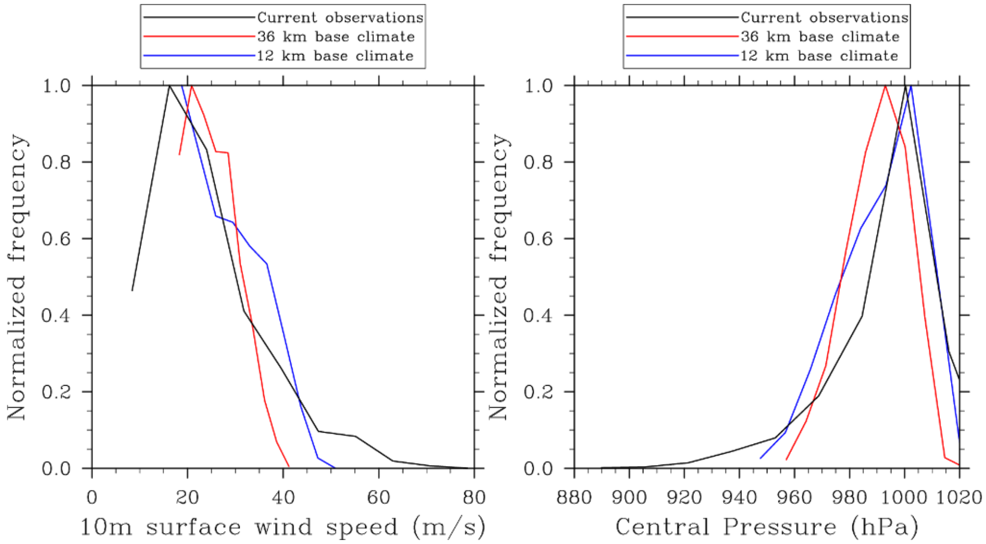


Figure 4: Frequency distributions of tropical cyclone intensity normalized by maximum frequency shown in (left) wind speed (ms^{-1}) at 10m above the surface and (right) central pressure (hPa) for all tropical cyclone track data points in the period 1995-2005 for (black line) observations, (red line) 36 km domain and (blue line) 12 km domain.

A comparison of tropical cyclone intensity distributions between storms on the 36- and 12-km domains and observations, shown in Fig.4, shows that NRCM storms do not capture the most intense storms observed. This result is common to all dynamical model-based studies and is due to insufficient model resolution to resolve the dynamics of the inner core of a tropical cyclone (e.g. Knutson et al 2008, Davis et al 2010). Fig. 4 also shows stronger storms on the 12- than the 36-km grid. An analysis of the differences in the wind pressure relationships between storms on the 36- and 12-km domains, shown in Fig. 5, shows for a given central pressure the 12 km domain is able to capture stronger winds (that are also closer to the observed wind-pressure relationship, not shown) due to the ability of higher resolution to represent sharper pressure gradients from the environment to the storm center.

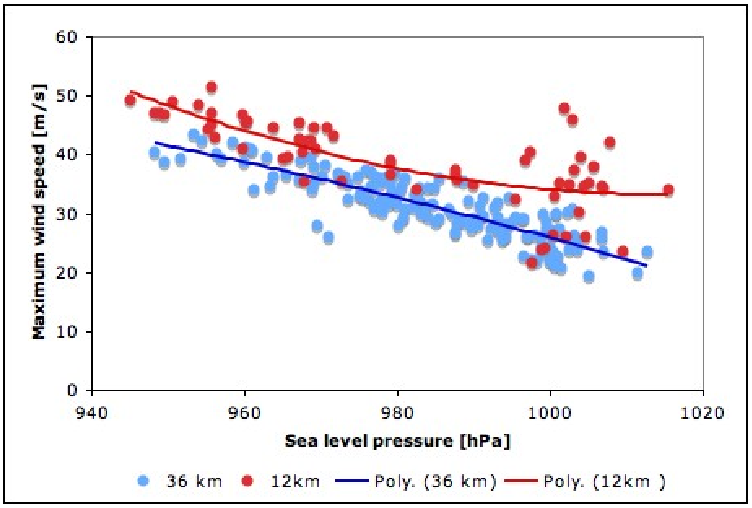


Figure 5: Scatter plot of minimum surface pressure (hPa) and maximum wind speed (ms^{-1}) at the time of storm lifetime maximum intensity for (blue) 36km domain, and (red) 12km domain. Red and blue lines are quadratic fits to the data.

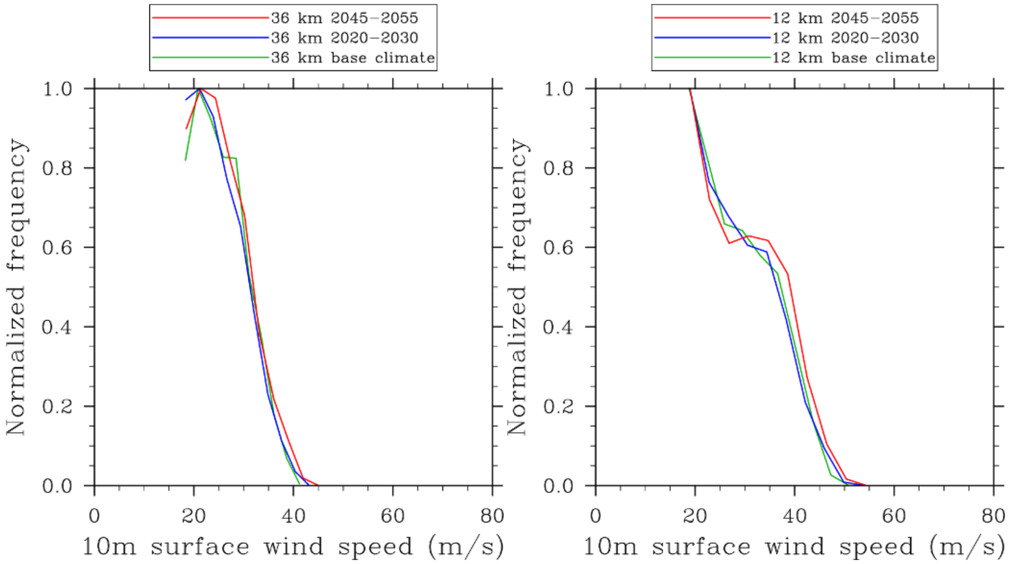


Figure 6: Frequency distributions of tropical cyclone intensity normalized by maximum frequency shown for (left) 36 km domain and (right) 12 km domain for (green line) base climate, (blue line) 2020-2030 and (red line) 2045-2055.

The intensity climate change signal is shown in Fig. 6 (the reason for the bump in the intensity distribution of the 12-km domain storms in the middle intensity range is currently being investigated). Storms on both the 36- and 12-km domains experience a modest yet statistically significant (at 90%) increase of average intensity of approximately 2 ms^{-1} and a more marked increase in the number and intensity of the most intense hurricanes that can be resolved by the model. Application of extreme value statistics under this project (described in detail later in this report) has shown that the relatively small intensity increases for the storm intensities resolved here lead to marked increases of over 50% in the number of intense hurricanes in the category 4 and 5 range. This is in agreement with other modeling studies and theory.

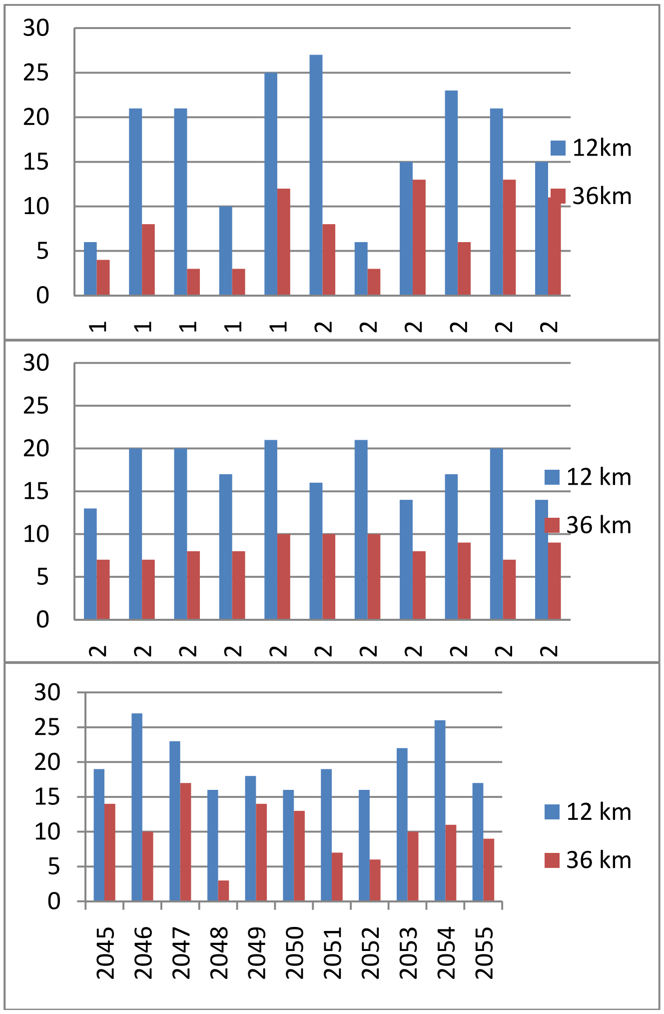


Figure 7: Annual frequency of NRCM tropical cyclones generated on (red) the 36 km domain and (blue) the 12 km domain for (top) base climate, (middle) 2020-2030, and (bottom) 2045-2055.

Annual tropical cyclone frequency, shown in Fig. 7, shows that the 12 km domain generates more storms than the 36 km domain every year. This is an expected result of us maintaining constant detection and tracking criteria for both resolutions. Given that the increased wind speeds for a given pressure on the 12 km domain (Fig. 5) and lower central pressure for the strongest storms, a tracking algorithm with a constant wind speed criteria will naturally detect more storms. Similar tropical cyclone frequencies between the 36- and 12-km domains could be achieved simply by tuning the tracking criteria for each domain, but we choose not to do so here to allow a clean comparison of the climate change signal between the 36- and 12-km domains and remove possible contamination of the signal by the use of different tracking criteria.

The NRCM simulations for the base climate period produced an average of 7.6 storms annually on the 36-km domain and 17.3 storms annually on the 12 km domain storms. The observed annual average is 14.3 storms. Again a better comparison between modeled and observed annual frequency could be obtained by tuning the detection and tracking criteria, but we choose not to do so here to allow for clean comparisons. As shown later, provided consistent criteria are chosen, the projected future changes are not affected by the explicit choice of tracking approach.

A comparison with the observed annual frequencies for the base climate period is not shown since even for a perfect modeling system we do not expect interannual correlation between model and observed storms. The CCSM climate that is used as boundary conditions was started in 1950 and is fully free running with the only external forcing being from solar radiation and known perturbations (such as volcanoes), no attempt is made to force it to follow the shorter-term variability in current climate. Previous studies have shown that this approach produces a mean and variable global climate close to that which is observed (e.g. Meehl et al 2007), but it does not, and cannot be expected to precisely follow any observed short-term variability such as that may have contributed to the high level of tropical cyclone activity in 2005.

In the next 50 years the NRCM projects a marked increase in tropical cyclone frequency, with annual numbers increasing from 7.6 for the base climate period to 8.5 in 2020-2030 and 10.4 in 2045-2055 for the 36 domain and for the 12km domain increasing from 17.3 for base climate to 17.6 in 2020-2030 and 19.9 in 2045-2055. The model shows accelerating increase in hurricane activity going from 0.6 to 3.4% per decade near the present to 4 -10% per decade by the middle of the 21st century. These results are different to those of other studies, which have tended towards predicting small changes and if anything a decrease in overall Atlantic tropical cyclone frequency over coming decades (Knutson et al, 2008; Bengtsson et al 2007).

Figure 8: Tropical cyclone genesis points (red) and tracks (blue) for all NRCM tropical cyclones generated on the (left column) 36 km domain and on the (right column) 12 km domain for (top row) base climate, (middle row) 2020-2030, and (bottom row) 2045-2055. The numbers in the bottom left of each panel indicate the average annual tropical cyclone frequency.

Both the 36- and 12-km model domains produce sensible geographic distributions of tropical cyclone genesis and track for all three time slices, as shown in Fig. 8. Further, the NRCM produces storms in the Gulf of Mexico sufficient to proceed with our investigation into changes in Gulf storms. Figure 9 shows tracks and genesis locations of all storms on the 12-km domains that entered the Northern Gulf of Mexico. Taking all three time slices together, 15% of storms entering the Northern Gulf formed out in the deep tropical North Atlantic, compared to 25% in the observations. It is also notable that this percentage increases in time, but the numbers of these storms is too small to assess confidence in this result.

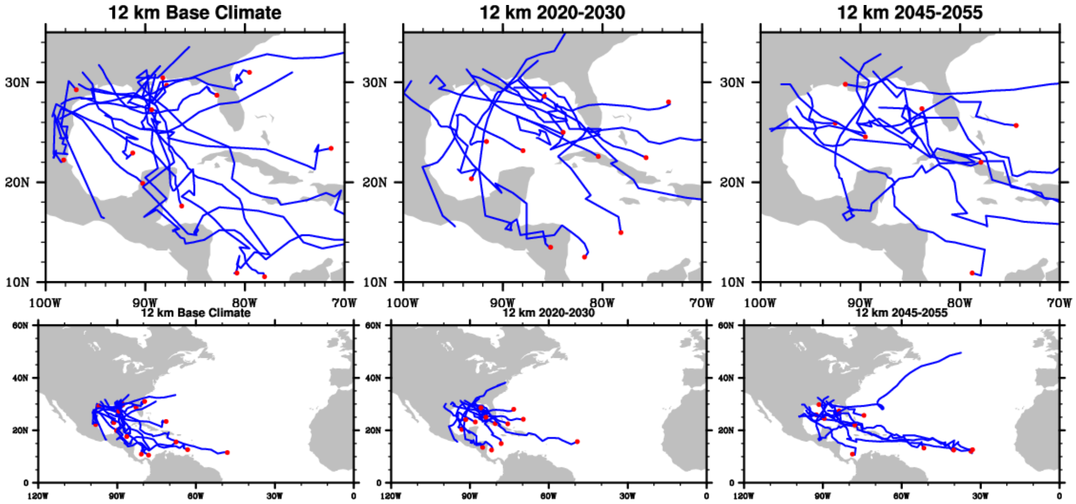


Figure 9: Tropical cyclone tracks (blue) and genesis locations (red) for all NRCM 12-km domain storms that entered the northern Gulf of Mexico for (left column) base climate, (middle column) 2020-2030 and (right column) 2045-2055. Top row shows a zoomed in view of the Gulf and the bottom row shows the entire North Atlantic basin.

The future climate predictions exhibit a consistent change in track density (Fig. 10), from a maximum in the mid-Atlantic in current climate, to double maxima with a new one developing in lower latitudes by 2020-2030, then a single, low-latitude maximum in 2045-2055. This is consistent between both domains and also with the observed changes over the past 30 years. As noted by Kimberlain and Elsner (1998), 1995 saw a marked changeover from a period with low proportions of equatorial development to enhanced equatorial development that has continued to the present (Holland and Webster 2007). Holland and

Webster also showed that the equatorward jump was associated with a sharp increase in the proportion of major hurricanes (Cat 3-5), the infamous “Cape Verde Storms”. Figure 10 shows a consistent decrease in track density in the Gulf of Mexico. This is consistent with the increase in Cape Verde developments (since a higher proportion of storms can move poleward before reaching the Gulf).

Figure 10: Future change in tropical cyclone track density (colors) and genesis density (contours, positive is solid and negative is dashed) for all NRCM tropical cyclones generated on (left column) the 36 km domain and (right column) the 12 km domain. The change from base climate is (top row) to 2020-2030 and (bottom row) to 2045-2055. The densities represent the number of 6-h occurrences within overlapping 5° Marsden squares, normalized to a maximum value of 1.

Results: Statistical Assessments

Emanuel and Nolan (2004) have shown that the GP in Eq. 4 performs well in explaining hemispheric seasonal variations in tropical cyclones. Our initial investigations using observed tropical cyclone data and reanalysis data for an historical period showed GP performed less well on the scale of the North Atlantic basin (not shown). A more detailed investigation revealed strong relationships between basin total tropical cyclone frequency and summertime average GP over the tropical eastern North Atlantic. GP in the tropical eastern North Atlantic is found to explain 62% of the variance in total basin tropical cyclone frequency after the effects of El Nino are removed. This is shown in Fig. 11; periods of high GP (red areas) coincide with periods of increased storm frequency in the 1960s and since 1995.

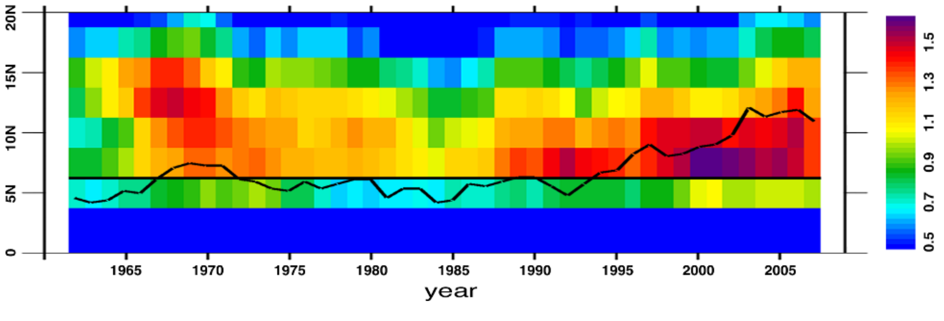


Figure 11: GP plotted as an average over 2.5° latitude zonal bands from 60-15°W, as indicated on the left vertical axis, and smoothed using a 5-year running mean. The superimposed black line is a 5-year running mean of the observed number of tropical cyclones. The black horizontal reference line indicates 10 storms per year.

GP over the tropical eastern North Atlantic is therefore used as a predictor to estimate the number of storms that will develop in the basin. Figure 12 shows predicted storms using GP on the same global climate model data used to drive the NRCM for the period 1970-2100. This statistical assessment predicts an increase in the annual number of storms from current climate by approximately 1 storm by the 2050s and by another 3 storms during the last half of the 21st century. The statistical and dynamical assessments are similar in that they both indicate an increase in tropical cyclone frequency of 1 to 3 storms by the mid 21st century. This increases our confidence in the result of increasing storm frequency. Although these results are based on statistical downscaling of one climate dataset, this technique can be applied to other climate datasets to quickly generate a range of possible future scenarios of storm activity.

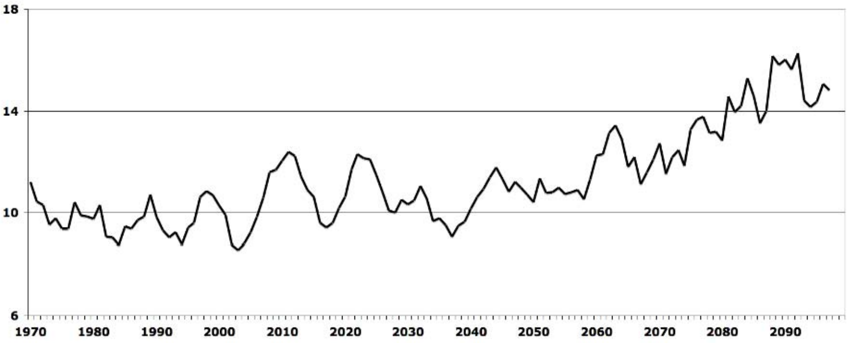


Figure 12: Annual tropical cyclone frequency for the North Atlantic basin predicted using GP on climate data generated by CCSM under A2 emissions scenario. The data have been smoothed using a 5-year running mean.

A breakdown of the GP components (not shown) reveals that taking components of GP on their own can explain tropical cyclone variability better than total GP. We find that potential intensity alone explains 89% of the variance and a combination of potential intensity with shear explains 90%. This shows that GP components in their own right are better predictors than GP. Current research is building on this initial analysis to create a better predictor for the North Atlantic basin.

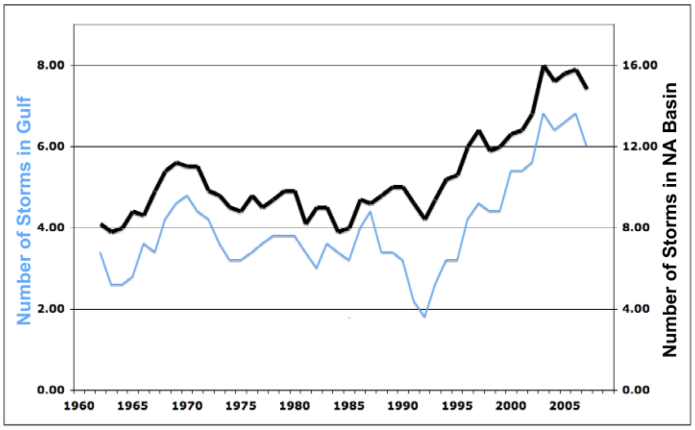


Figure 13: Annual tropical cyclone frequency for (black line) the North Atlantic basin and (blue line) the Gulf of Mexico from 1960 to 2008. Data have been smoothed using a 5-year running mean.

The observational tropical cyclone record since the dawn of the satellite era in the early 1960s shows a strong link between the total number of storms in the North Atlantic basin and the number of storms in the Gulf of Mexico, as shown in Fig. 13. This suggests there exists a relationship between Gulf Storms and large-scale climate variables that could be used to develop a statistical predictor for Gulf of Mexico storms. This will be a focus for future research.

Additional Task: 25-km Global Climate Simulation

In this task, it was anticipated that a series of global climate simulations at 25 km spatial resolution would be available for analysis and comparison with the NRCM simulations. This task was dependent on an external group achieving a stable global model simulation on a 25 km grid but this has not yet been possible. As a result this task has been put on hold.

Additional Completed Work

Significant additional work has been completed that has extended far beyond what was originally proposed. Through a comprehensive assessment of sensitivities of our modeling approaches this work has increased our understanding of where are confidence lies and areas where we are less certain. In addition, an assessment of storm damage has been conducted through the development and application of a hurricane damage index specific to offshore facilities. The additional work completed is summarized here, and some areas have recently been expanded upon into significant research areas.

Sensitivity Studies

A number of sensitivity studies are performed here to determine whether the signal of increasing storms in the future is robust to details of our modeling approach; thereby increasing confidence in our assessments.

Sensitivity to the Tracking Algorithm

The number of storms in the model may be sensitive to details of the detection and tracking algorithm. To examine this sensitivity, two additional model storm datasets are generated by varying thresholds in the tracking algorithm. Specifically, the intensity and duration criteria are perturbed within the resolution of the observed North Atlantic tropical cyclone dataset: that is ±5 knots (~2.5 ms^{-1}) and ±6 hours from the standard criteria of 17 ms^{-1} and 2 days.

The impact on annual storm frequency and interannual variability is shown in Fig. 14. As expected, the cyclone dataset generated under lenient criteria has more storms than the dataset generated under strict criteria. It is interesting to note that some years show larger differences than others and more work is needed to understand this result. The important result here is that the time series track one another closely showing that the interannual variability is robust to details of the tracking criteria. To test the robustness of the climate change signal we need to look at the impact of tracking criteria on the longer timescales. Figure 15 shows that the 11-yr mean simulated tropical cyclone frequency increases in the future for each of the three tropical cyclone datasets.

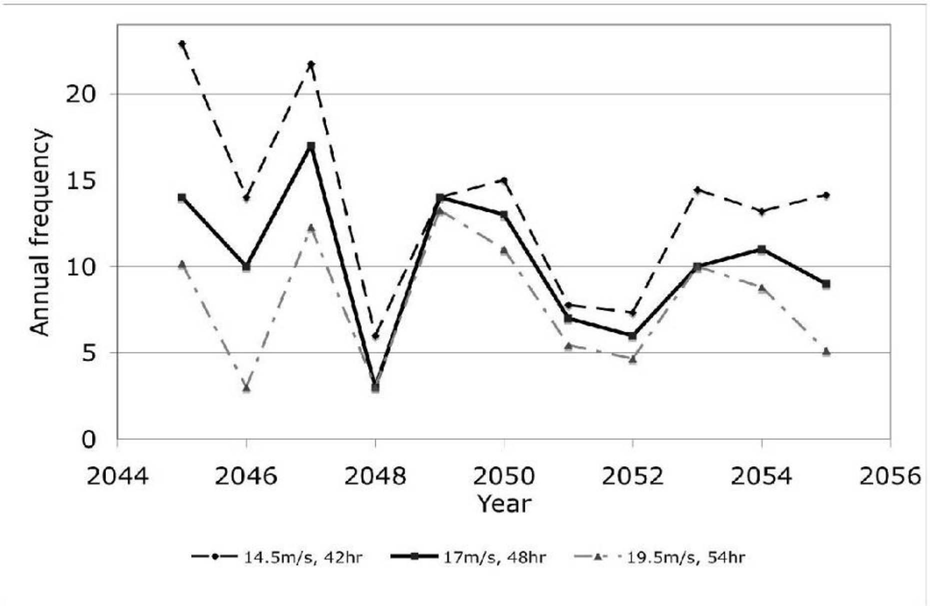


Figure 14: Time series of annual tropical cyclone frequency from the 36 km domain for the period 2045-2055 for three different tropical cyclone tracking criteria combinations.

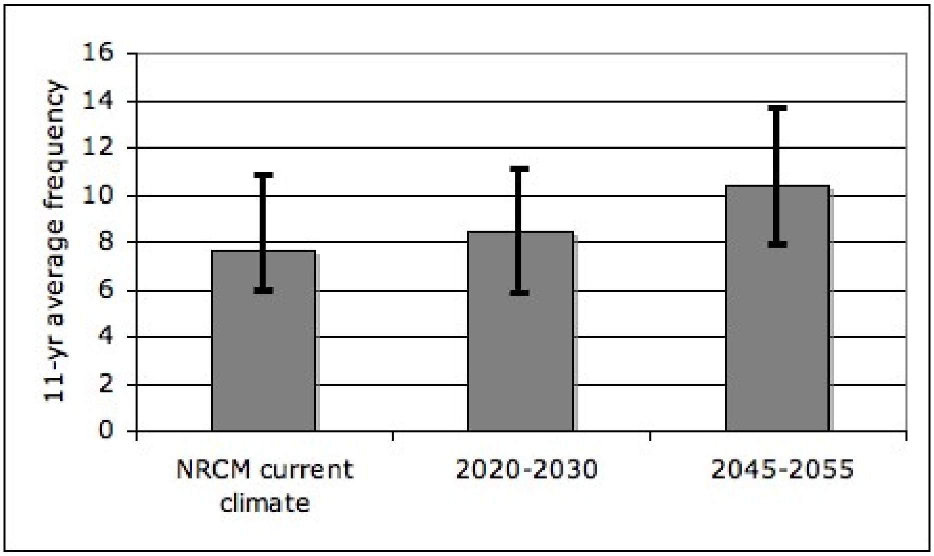


Figure 15: Simulated 11-year average annual tropical cyclone frequency from the 36 km domain using the standard tracking criteria of 17m/s and 2 day duration (gray bars) and the range determined using two tracking criteria combinations representing lenient (14.5m/s and 42 hours duration) and strict (19.5m/s and 54 hours duration) extremes (black lines).

This analysis suggests that both the simulated interannual variability and climate change signal are largely independent of details of the tracking algorithm. We therefore have confidence in performing subsequent analysis on any of the simulated tropical cyclone datasets and we chose to use the dataset derived using the standard 17 ms^{-1}, 2-day tracking criteria for consistency with existing analysis.

Sensitivity to Initial Condition

Dynamical model simulations can be sensitive to small perturbations in the initial state due to non-linear dynamic and thermodynamic relations and multi-scale feedbacks that govern the climate system. This puts a predictability limit on details of weather to about 2 weeks. An open question remains as to the sensitivity of the statistics of tropical cyclones to small perturbations in the initial state.

Simulations on the 36 km domain were composed of 3 continuous runs of 11 years each: 11 years of base climate and two future time slices of 2020-2030 and 2045-2055. Simulations on the 12 km domain; however, were run slightly differently to fit efficiently onto available supercomputing resources. Simulations on the 12km domain were composed of 33 discrete annual runs of 7 months each initialized on 1st May each year for the same years of base climate, 2020-2030 and 2045-2055.

The difference between continuous decadal versus discrete annual simulations is effectively a different initial condition on the 1st May each year. Its impact on the 12 km domain is examined here through comparisons between a 3 year continuous simulation from 1st Jan 2045 to 1st Jan 2048 and three discrete annual runs each starting on 1st May for the three years 2045, 2046 and 2047. Figure 16 presents an overview of the simulations used in this sensitivity study.

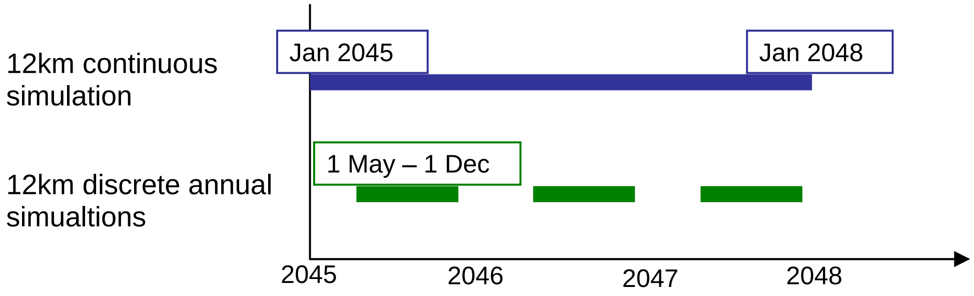


Figure 16: Timeline of continuous and discrete annual simulations used to examine sensitivity to the initial condition.

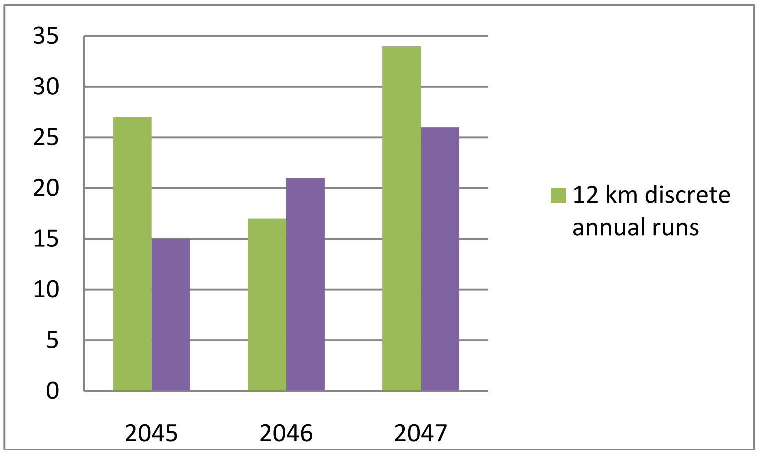


Figure 17: Annual tropical cyclone frequency for the continuous and discrete simulations.

Figure 17 shows large differences in annual frequency and interannual variability between the continuous and discrete simulations. This suggests that the initial condition is important for tropical cyclone statistics on annual and interannual timescales.

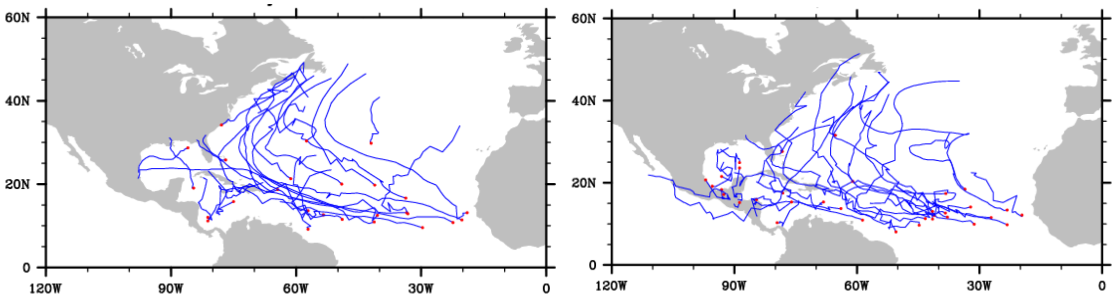


Figure 18: Tropical cyclone tracks (blue) and genesis locations (red) for (left) the continuous simulation and (right) the discrete annual simulation for the year 2047.

A comparison of genesis locations and storm tracks between the continuous and discrete simulations for the year 2047 are shown in Fig. 18. As expected, there is no one-to-one correlation in individual genesis locations suggesting an important role for stochastic processes in determining the specific genesis locations of individual hurricanes. On the other hand the preferred region of genesis in the deep tropical North Atlantic suggests an important role of the predictable large-scale and slowly varying environment in determining preferred regions of storm formation within the basin. There are also indications that there are preferred times of storm formation within the hurricane season (not shown). Owing to the small numbers of storms in any given year it is not possible to determine the sensitivity to the initial condition for Gulf of Mexico without running a larger number of simulations.

In showing that the preferred regions within the basin and preferred times within the season of storm formation are not sensitive to the initial condition this sensitivity study increases confidence in our assessments of the climate change signal in tropical cyclone activity and changes in preferred regions of tropical cyclone activity within the North Atlantic basin. In addition, other studies suggest that the impact of the initial condition on weather statistics decreases on longer timescales, particularly for regional model domains such as the 36-km and 12-km domains used here. It is therefore likely that the impact of initial condition on decadal timescales will be small compared to the climate signal due to climate variability and change.

Sensitivity to Base Period

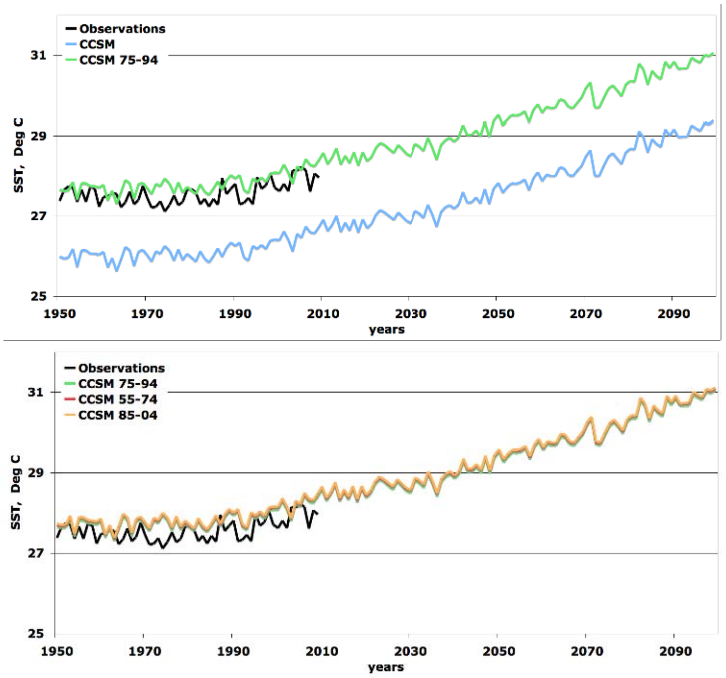


Figure 19: Time series of Aug-Sept-Oct average Sea Surface Temperature (SST) over the tropical eastern North Atlantic for (black line) observations from 1950 to 2008 and (colored lines) CCSM data from 1950 to 2100. Top panel shows raw CCSM data (blue line) and bias corrected CCSM data (green line) using the base period 1975-1994. Bottom panel shows observations (black line) and CCSM data bias corrected using three different base periods: 1975-1994; 1955-1974; and, 1985-2004. The three lines lie on top of each other and are indistinguishable.

It was necessary to remove a marked bias in the raw CCSM climate simulations to provide NRCM with suitable boundary conditions for the regional climate simulations (details provided in the Dynamical Modeling Issues section). The bias correction procedure involves replacing a base climate in CCSM with a base climate from NCEP-NCAR reanalysis data. Owing to multi-decadal variability in the reanalysis data there may be sensitivity of the corrected climate to the choice of the base period. The top panel of Fig. 19 shows time series of Aug-Sept-Oct average Sea Surface Temperature (SST) over the tropical eastern North Atlantic. The bias towards low temperatures in raw CCSM data is clear when compared to the observed time series. The bias correction removes this low bias and brings the CCSM time series up to values within the range of the observed time series. The bottom panel of Fig. 19 shows that the bias corrected values are not sensitive to the choice of time period. The SST variations for bias corrections based on 1975-1994, 1955-1974 and 1985-2004 are indistinguishable from one and other. Moreover, the fact that the climate bias of CCSM remains constant over the period of the historical record brings enhanced confidence that a changing bias in the future will not contaminate future predictions.

Impacts Assessment

Decision support tools enable a quantitative specification of industry impacts based on model predictions. For the case of tropical cyclones, such tools can be typically applied to weather forecast simulations to provide real-time impact assessments for short-term planning, and also to climate forecasts to provide impact assessments for the coming decades to aid long-term planning.

Additional work has developed and applied a downscaling tool of direct relevance to the offshore energy industry in the Gulf of Mexico. This tool, the Willis Hurricane Index (WHI), combines hurricane intensity, size and translation speed to estimate the potential damage to off-shore facilities in the Gulf of Mexico (Owens and Holland, 2009). The WHI thus combines parameters into a single index that provides a proxy for waves, currents, storm surge and structural fatigue from high winds.

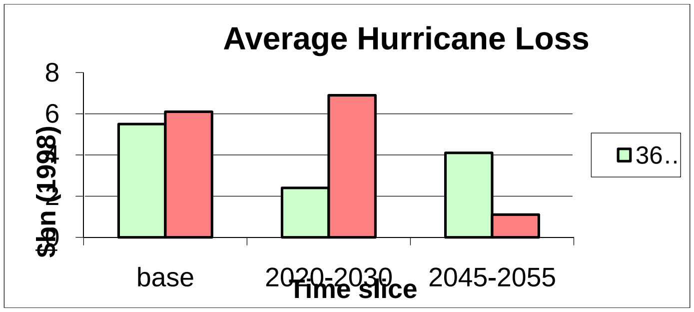
The original formulation has been modified slightly into a form suitable for use on the storms generated on the NRCM 36- and 12-km domains:

$$\begin{aligned} &WHI = \left(\frac{v_m}{34}\right)^3 + 5\left(\frac{R_{\max}}{30}\right) + 5\left(\frac{v_t}{15}\right)^{-2} \\ &For\, v_m > 34, \\ &If\ v_t < 7, v_t = 7, \end{aligned} \qquad 5.$$

where the first term represents the amount of energy dissipated at the surface by the maximum winds (v_m in kts), the second term is the radial extent of the surface wind field based on the radius of maximum winds (R_{max} in nautical miles); and the third term is the translational speed of the hurricane (v_t in kts). The use of nautical units was for compatibility with existing hurricane archives. As an aside, it is notable that hurricane intensity is the minor contributor to offshore facility damage (provided the wind speeds are above hurricane force). Hurricane size explains nearly twice the variance in losses than intensity, and translation speed explains nearly three times the variance. This has implications for the way vulnerability assessments for current and future stock are made.

Applying the WHI to our dynamical assessments of future hurricane activity provides an assessment of likely changes in hurricane damage in 1998 dollars. The underlying assumption is that there will be no significant change in the engineering design of offshore facilities over the climate prediction time scale. For tropical cyclones on the 36 km domain the expected average hurricane damage halves from \$5.7b to \$2.5b from base climate to the 2020s then increases to \$4.3b around the mid 21st century, as shown in Fig. 20. For tropical cyclones on the 12-km domain; however, the average hurricane damage remains constant through the 2020s and then decreases in the mid 21st Century. The maximum losses for a single hurricane, also shown in Fig. 20, show similar differences between the 36- and 12-km domains. A breakdown of the WHI components, shown in Table 1, shows that damage decreases for storms on the 12-km domain largely due to the increase in cyclone translation speed.

The low numbers of damaging storms and the lack of resolution of true hurricane intensity means these numbers need to be treated with caution. However, the more accurate depiction of hurricane dynamics on the 12km domain will allow more accurate estimates of damage and the increased total sample size will increase our confidence in the results.



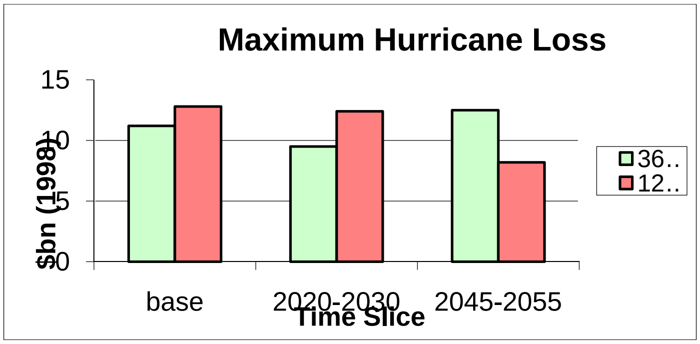


Figure 20: (top) Average loss (billions of 1998USD) per hurricane for storms on the 36- and 12-km domains, and (bottom) maximum loss due to a single hurricane, for the three time slices.

Parameter	1995-2005	2020-2030	2045-2055
# Cyclones	15/16	10/13	20/11
# 6-hourly data points	96/108	50/75	78/33
Average Intensity (kt) Maximum Intensity (kt)	50/55 72/87	49/63 67/91	25/50 73/88
Average Rmax (nm)	44/49	24/31	31/34
Average Trans. Speed (kt)	***10/12***	***12/15***	***11/19***
Average Intensity Term Average Size Term Average Speed Term	3.7/5.4 7.3/8.2 14.4/12.5	3.4/7.6 4.0/5.2 11.9/14.1	3.7/4.1 5.2/5.7 13.9/8.9
Average Hurricane WHI Max Hurricane WHI	24.4/25.3 41.5/44.8	19.3/26.6 38.2/44.0	22.1/17.3 44.1/35.6

Table 1: Breakdown of the Willis Hurricane Index components for the 36/12 km domains.

Additional Pilot Work Completed

The work under the 1801 project led to a small pilot examination of the potential application of Extreme Value Theory (EVT) statistics to assessing hurricanes and other weather extremes. This has now evolved into a strong international consortium, with funding from the National Science Foundation and the insurance/re-insurance industry, aimed at pursuing the concepts fully.

To illustrate the underlying problem we consider hurricane activity in the North Atlantic. For historical data we utilize the historical archive of North Atlantic tropical cyclones held in the IBTrACS data base (Knapp et al 2010). Only data since 1945 are used to minimize the influence of data errors (Landsea 1993) and the intensity data were adjusted to account for documented biases prior to 1980 (Landsea 1993, Holland 2008). Modeled storm data are taken from the NRCM 36-km domain. The modeled intensity distribution has a much sharper decrease than the observed intensity distribution (shown earlier in Fig. 4) and a truncation at around 45 ms^{-1}. The model predicts a steady shift towards more intense storms over the next 50 years (shown earlier in Fig. 6), but this gives no information on the potential changes to hurricanes of intensity >45 ms^{-1}.

Reverse Weibull statistics are used to assess the changes in the intense cyclones not resolved by the NRCM. This is done by applying the changes in mean and standard deviation of tropical cyclone intensity distributions predicted by the NRCM to the observed intensity distribution. The result is that the relatively small predicted changes in the resolved distribution will result in a much greater potential change in the more intense systems (Fig. 22). For example, Cat 5 hurricanes are predicted to increase by 60% from a base climate period of 1980-1994 and by 30% from a base climate period of 1995-2008. These results are similar to Bender et al (2010) who used a high resolution hurricane model initialized with simulated storms from a coarser resolution regional climate model to estimate the likely intensity changes. Bender et al found an increase in Cat 4-5 hurricanes of 78% over current climate, which is higher than our estimate of 20-30%, depending on the base climate period chosen. Part of this arises from the likelihood that the EVT approach will produce a conservative estimate of likely changes to the extremes, since the changes to both the mean and variance are also limited by the NRCM model resolution on the 36-km domain.

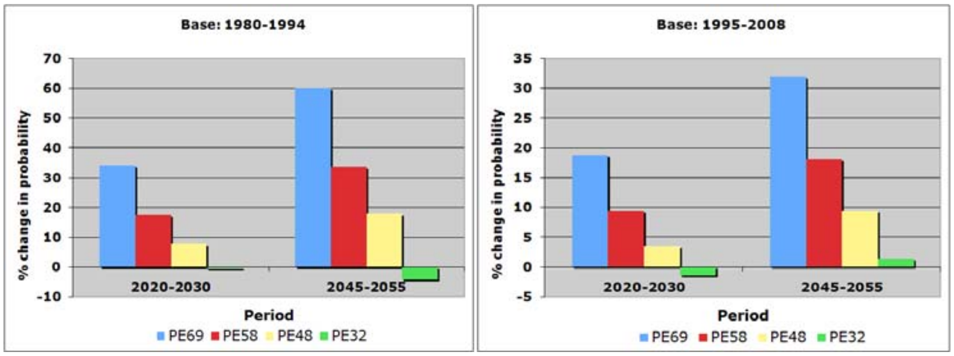


Figure 22: Estimated future changes to all hurricanes (PE32), Cat 3-5 (PE48), Cat 4-5 (PE58) and Cat5 (PE 69) using a base climate of: left) 1980-1994 and right) 1995-2008.

This example demonstrates the potential for application of extreme value approaches to downscaling changes in hurricanes. The goal of the continuing study is to develop the concept further, first by application to storms on the NRCM 12-km domain and then to utilize more sophisticated approaches, based at least in part on more extensive use of the EVT, and to extend it to direct assessment of business and societal impacts from the extremes.

Concluding Discussion

The extremely successful 1801 project has assessed future changes in hurricane activity in the North Atlantic over the next 50 years. Our approach was to use a powerful combination of the latest dynamical modeling and novel statistical methods to identify consistencies in future changes.

Dynamical assessments predicted tropical cyclone intensity to increase, with average increases of ~2 ms^{-1} towards 2050, but with larger increases in the strongest storms. This result was consistent between the 36- and 12-km model domains. An additional pilot project to assess changes in the most extreme hurricanes using combined statistical-dynamical modeling showed that the frequency of the most intense hurricanes (categories 4 and 5) are predicted to increase by 20-30%.

Tropical cyclone frequency is predicted to increase at an accelerating rate during the next 50 years, from a rate of ~1-3% per decade at present to ~4-10% per decade towards 2050. This increase was consistent between the 36- and 12-km NRCM domains. The results of a statistical downscaling technique, developed to make multiple fast predictions of tropical cyclone frequency over the North Atlantic from coarse resolution climate, are in agreement with the dynamical model results in that tropical cyclone frequency will increase between 1 to 3 storms by the mid 21st century. The powerful combination of somewhat independent techniques further increases our level of confidence in this assessment.

The observed equatorward shift in cyclone activity over the past decade is predicted to continue, significant at the 99% level, with the region of maximum frequency shifting equatorward by 10-15^{o} latitude by 2050. This result is consistent between dynamical and statistical assessments

Sensitivity studies to critical details of the dynamical model setup including resolution, storm detection and tracking criteria and initial condition have increased our understanding of where our confidence lies and areas where we are less certain. Specifically, increasing model resolution resulted in more storms, an increase in average storm intensity (closer to the observed intensities) as expected, yet importantly these studies showed the climate change signal in storm intensity, frequency and location is robust to model resolution and storm detection and tracking criteria. The sensitivity studies also highlighted preferred locations and timings of storm activity within the basin and within the hurricane season that are generally insensitive to details of the model thereby further increasing our confidence in the climate change signal.

Changes in storm activity within the Gulf of Mexico are less certain due to the low numbers of storms and therefore small sample size. Motivation is provided for a future research focus on developing statistical modeling specific to the Gulf of Mexico to generate large numbers of forecasts thereby increasing confidence in future changes.

Additional work focused on the development and application of a hurricane damage index specific to offshore facilities that translates hurricane parameters directly into quantitative damage assessments. In applying the index to storms in the dynamical model forecasts damage assessments have been produced over the next 50 years. These show that although storms are projected to be more intense, and therefore more damaging, changes in size and translation speed counteract this. Again, confidence in these damage assessments is low due to the low numbers of Gulf storms. Increasing our confidence in damage assessments is a high priority for future research. First, the index will be tested on independent data for any Gulf storms that may occur during the 2011 and a second step will be to explore impact assessments on Gulf of Mexico facilities using relationships that statistically combine large-scale climate variables with historical damage data.

The 1801 project represents an ambitious prediction and analysis program to better quantify the frequency, duration, and intensity of tropical cyclones and the resulting damage under climate variability and change. We invite community involvement in helping to further analyze the several hundred terabytes of model output from existing and in process model simulations that are available to the research community through an NCAR data portal.

Research Directions

Our focus is on improving predictions of future hurricane activity and increasing our understanding of the range of possibilities using a powerful combination of independent dynamical and statistical techniques. Areas ready for investigation with anticipated high return include:

Assessing the Impact of Atmosphere-Ocean Interaction

A limitation to the simulations conducted thus far under Project 1801 is that the NRCM is not two-way coupled to a full ocean model. The NRCM model therefore responds to the temperature of the sea surface but is not able to feed back onto the ocean via cloud-radiation interaction, winds, and rainfall. Capitalizing on current work to two-way couple the NRCM to a full ocean model will enable exploration of the impact of such coupled interaction on hurricane variability and trends with focus on the Gulf of Mexico. Examination of the coarser model simulations indicate that the deep-ocean thermal structure in the Gulf of Mexico will warm markedly in coming decades, with potential changes of up to 2.5^{o}C at 70 m depth by then end of the 21st century. This has a considerable impact on the Tropical Cyclone Heat Potential, an indicator of the amount of energy available for cyclone intensification, which is projected to increase by a factor of five over the same period. High-resolution, coupled NRCM simulations will be conducted to assess this impact. Furthermore, future variability, and potential future changes in, the loop current have implications for a number of gulf operations including the potential for impact on hurricane climatology.

Statistical Downscaling of Gulf Storms

Confidence in hurricane variability and trends in the Gulf produced under Project 1801 is limited by the relatively small number of storms. This can be helped by developing statistical downscaling techniques specific to the Gulf. Relationships between the large-scale environment and Gulf storms will be explored and used for improved predictions of Gulf storm activity and for improved specification of the level of uncertainty in the results. Going a step further, in combination with the use of coupled air-sea simulations, the potential for regional changes in hurricane climatology within the Gulf of Mexico will be assessed. Of particular interest is whether the regions of major impact may change from the eastern to western Gulf.

Statistical-Dynamical Assessments of the Most Intense Hurricanes

The application of Extreme Value Theory to enable an exploration of hurricanes at the tail of the intensity distribution and associated changes will be further explored. Project 1801 has demonstrated that the use of Extreme Value Theory combined with physically based arguments, results in a powerful combination to translate the truncated information output from regional climate models to the full observed hurricane intensity range. Further expansion of this work by developing a comprehensive and defensible statistical approach to assessing the impact of climate variability and change on the full range of hurricane intensities is desired.

Impact Assessments and Decision Tools

The major benefit arising from improved assessments of future hurricane climatology lies in the capacity to mitigate future impacts. Direct assessment of hurricanes impacts on offshore energy facilities has been demonstrated to have skill when applied to both short term forecasts and NRCM simulations of current climate. This work has opened the possibility of use of this technique for a wider range of applications, including specific facilities, and onshore facilities. Also of interest is its use to assess the potential impacts of, e.g., east-west changes in hurricane frequency across the Gulf, and the benefits of future engineering advances.

Acknowledgements

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References

Bender, M.A., T.R. Knutson, R.E. Tuleya, J.J. Sirutis, G.A. Vecchi, S.T. Garner, and I.M. Held, 2010: Modeled Impact of Anthropogenic Warming on the Frequency of Intense Atlantic Hurricanes. *Science,* **22**, 454-458.

Bengtsson, L., K. I. Hodges, M. Esch, N. Keenlyside, L. Kornblueh, J.-J. Luo, & T. Yamagata, 2007: How may tropical cyclones change in a warmer climate. *Tellus*, **59A,** 539-561.

Camargo, S. J., A.H. Sobel, A.G. Barnston, and K.A. Emanuel, 2007: Tropical cyclone genesis potential index in climate models, *Tellus*, **59A**, 428-443.

CCSP, 2008: *Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands.* A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. [Karl, T. R., Meehl, G. A., Miller, C. D., Hassol, S. J., Waple, A. M., Murray W. L. (eds.)]. Department of Commerce, NOAA's National Climatic Data Center, Washington, D.C., USA, 164 pp.

Collins, W.D., C.M. Bitz, M.L. Blackmon, G.B. Bonan, C.S. Bretherton, J.A. Carton, P. Chang, S.C. Doney, J.J. Hack, T.B. Henderson, J.T. Kiehl, W.G. Large, D.S. McKenna, B.D. Santer, and R.D. Smith, 2006: The Community Climate System Model Version 3 (CCSM3). *J. Climate,* **19***,* 2122–2143.

Cooper, C. and J. Stear, 2006: Hurricane Climate in the Gulf of Mexico. *Proc. 2006 Offshore Technology Conference*, 18418.

Davis, C., Wang, W., Cavallo, S., Done, J., Dudhia, J., Fredrick, S., Michalakes, J., Caldwell, G., Engel, T., Ghosh, S., and Torn, R. 2010: High-resolution Hurricane Forecasts. *Computing in Science and Engineering* CISESI-2010-03-0023.

Done, J. M., Holland, G. J., and P.J. Webster, 2010: The role of wave energy accumulation in tropical cyclogenesis over the tropical North Atlantic.*Clim. Dyn*.**36**. DOI: 10.1007/s00382-010-0880-5

Emanuel, K. A. 1995. Sensitivity of tropical cyclones to surface exchange coefficients and a revised steady-state model incorporating eye dynamics. *J. Atmos. Sci.* **52**, 3969–3976.

Emanuel, K. A. and Nolan, D. S. 2004. Tropical cyclone activity and global climate. In: *Proc. of 26th Conference on Hurricanes and Tropical Meteorology*, pp. 240–241, American Meteorological Society, Miami, FL.

Emanuel, K.A., S. Ravela, E. Vivant, and C. Risi 2006: A statistical-deterministic approach to hurricane risk assessment, *Bull. Amer. Meteor*. *Soc*., **19**, 299-314.

Gray, W.M., 1984: Atlantic Seasonal Hurricane Frequency. Part I: El Niño and 30 mb Quasi-Biennial Oscillation Influences. *Mon. Wea. Rev.*, **112**, 1649–1668.

Hart, R.E., 2003: A cyclone phase space derived from thermal wind and thermal asymmetry. *Mon. Wea, Rev*., **131**, 585-616.

Holland, G., 2008: A Revised Hurricane Pressure–Wind Model. *Mon. Wea. Rev.*, ***136***, 3432–3445.

Holland, G. J., and P.J. Webster, 2007: Heightened tropical cyclone activity in the North Atlantic: natural variability or climate trend? *Phil. Trans. R. Soc. A*, doi:10.1098/rsta.2007.2083.

Holland, G.J., J. Done, C. Bruyere, C. Cooper and A. Suzuki, 2010: Model Investigations of the Effects of Climate Variability and Change on Future Gulf of Mexico Tropical Cyclone Activity. *Proc. 2010 Offshore Technology Conference*, 20690.

IPCC, 2007: Climate Change 2007: *The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Kalnay, E. *et al*., 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Am. Meteorol. Soc.* **77**, 437–477.

Kimberlain, T.B., and J.B. Elsner, 1998: The 1995 and 1996 North Atlantic Hurricane Seasons: A Return of the Tropical-Only Hurricane. *J. Climate*, **11**, 2062–2069.

Knapp, K.R., M.C. Kruk, D.H. Levinson, H.J. Diamond, C.J. Neumann, 2010: The International Best Track Archive for Climate Stewardship (IBTrACS). *Bull. Amer. Meteor. Soc.,* ***91****,* 363-376.

Knutson, T. R., J.J. Sirutis, S.T. Garner, I.M. Held, and R.E Tuleya, 2007: Simulation of the recent multidecadal increase of Atlantic hurricane activity using an 18-km-grid regional model. *Bull. Am. Meteorol. Soc.* **88**, 1549–1565.

Knutson, T., J.J. Sirutis, S.T. Garner, G. Vecchi, I.M. Held, 2008: Simulated reduction in Atlantic hurricane frequency under twenty-first-century warming conditions, *Nature Geoscience*, **479**.

Knutson, T., J. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J.P. Kossin, A.K. Srivastava, and S. Masato, 2010: Tropical cyclones and climate change. *Nat. Geosci.* **3**, 157.

Landsea, C.W., 1993: A climatology of intense (or major) Atlantic hurricanes. *Mon. Wea. Rev.,* **121,** 1703–1713.

Meehl, G. A. *et al*. 2007: The WCRP CMIP3 multimodel dataset: A new era in climate change research. *Bull. Am. Meteorol. Soc.* **88**, 1383–1394.

Owens, B. and G.J. Holland, 2009: *The Willis Hurricane Index.* 2nd International Summit on Hurricanes and Climate Change, Corfu, Greece, May 31 - June 4 2009.

Skamarock, W., J. Klemp, J. Dudhia, D. Gill, D. Barker, W. Wang and J. Powers, 2008: A Description of the Advanced Research WRF Version 3. *NCAR Technical Note 475.* 113 pp.

Vecchi, G. A., and T. R. Knutson, 2008: On estimates of historical North Atlantic tropical cyclone activity. *J. Clim.*, **21**, 3580-3600.