# OTC 20690

# Model Investigations of the Effects of Climate Variability and Change on Future Gulf of Mexico Tropical Cyclone Activity

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## Abstract

According to three recent assessments, global warming will likely cause increased hurricane activity[1] in the future. If true, this raises the possibility that new coastal and offshore facilities are being under-designed, and that older facilities may need hardening in order to maintain presently accepted risk levels. As these three assessments readily admit, many uncertainties remain concerning the accuracy of their forecast. The study summarized in this paper has sought to narrow the uncertainties by using several methods. A set of relatively high resolution regional climate simulations are being made with the NCAR Nested Regional Climate Model (NRCM) embedded in the global Community Climate System Model (CCSM). These are being combined with statistical and statistical-dynamical downscaling techniques to provide an assessment of changes in North Atlantic hurricane activity out to 2050. Comparisons with the historical record show that the model can reasonably duplicate both the observed frequency and severity of hurricanes in the North Atlantic as well as in the Gulf of Mexico.

This initial analysis suggests that under the business as usual IPCC A2 scenario North Atlantic tropical cyclones will experience an accelerated increase in numbers from 3.4% per decade near the present to 10% per decade leading up to 2050; the region of maximum storm frequency and formation will move equatorward over the same time period; and there will be a modest increase of mean intensity of ~2 $ms^{-1}$, but a more marked increase in the frequency and intensity (~3.5 $ms^{-1}$) of the most intense hurricanes that can be resolved by the model (Cat 3). All of these changes are statistically significant at the 95% level or greater.For the Gulf of Mexico, the results are more ambiguous in part because of the limited number of storms in each decadal time slice which is exacerbated by a strong multi-decadal natural climate variability. These are preliminary results from a more comprehensive prediction and analysis program that is in progress. We invite community involvement in helping to analyze the several hundred terabytes of model output from existing and in-process model simulations that are being archived.

## Introduction

Recent synthesis reports (IPCC 2007, CCSP 2008) concluded that global warming will likely result in increased hurricane activity[1] in the North Atlantic. Their conclusion is based on

- Modeling and observational evidence that shows near-surface ocean temperatures have increased due to global warming, and are very likely to increase in the future (Meehl et al. 2007, Gillett et al. 2008). It is also well established from theoretical and observational considerations that hurricane activity tends to increase with warming ocean temperatures (Henderson-Sellers et al. . 1998, Emanuel 2007, Elsner et al. 2008);
- An increase in the observed hurricane power associated with the near-surface sea temperature in the hurricane generation region of the North Atlantic (Emanuel 2005);
- Numerical model results which have almost universally found an increase in intensity and rainfall, but there are substantial differences on whether the numbers of storms will increase or decrease (Knutson and Tuleya 2004, Knutson et al. 2007, Bengtsson et al. 2007).

There has been a marked increase in tropical cyclone activity in the historical data set for the North Atlantic, although it is unclear how much of this increase is caused by improved observations, multi-decadal variability in the natural climate, and climate change (Holland and Webster 2008, Vecchi and Knutson 2008). Cooper and Stear (2006) point out that recent storms

[1]The term "activity" includes one or both of hurricane intensity or occurrence frequency.

like Ivan and Katrina appear to fall far above the historical hazard curve in the Gulf although almost certainly some of this is due to uncertainty in the historical observations especially those prior to 1950.

If indeed global warming will increase hurricane activity in the Gulf this could, depending on the amount of increase, have far reaching impacts on a multitude of human activities. Of course the devastating impact of Katrina on New Orleans and the surrounding region is the most obvious recent example of how an intense hurricane can severely affect people and infrastructure. For the offshore energy industry, some of the more noteworthy impacts could be:

- Higher design criteria for new construction which is especially important in deep water 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 causing increases in energy costs to consumers that can amount to billions of dollars;
- 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 some of the future costs. Towards this end, a consortium including the Department of Energy and 20 energy companies have funded the National Center for Atmospheric Research (NCAR) to conduct a study using the most advanced numerical models presently available. While such models are far from perfect, there is really no alternative to forecasting future events.

Dynamical models of the Earth's climate system attempt to represent the full processes of the climate system comprised of atmosphere, ocean, land-surface and sea-ice components. For hurricane activity, however, it is well known that the coarse resolution of global models cannot adequately resolve the hurricane core and maximum intensity, nor can they resolve all of the processes leading to genesis and thus overall frequency. For example, Davis et al.(2008) have shown that horizontal resolutions approaching 1 km are required to accurately simulate the full range of hurricane intensities and testing conducted under this study has shown that simulated hurricane frequency decreases with coarser resolution, all other things being equal.

Given the above limitations we have taken a multitiered approach by combining four complementary methods. The first, known as dynamical downscaling, combines the benefits of a high resolution weather model and global climate simulation capacity by embedding the weather model within the global model over regions of interest (e.g. Knutson et al, 2007). The second method, known as statistical downscaling, exploits known relationships between the large-scale climate provided by the global model and tropical cyclones to extract climatological cyclone information (e.g. Camargo *et al.*, 2007). Third is the statistical-dynamical approach adopted by Emanuel (2008). And the last approach recognizes that even the best of current regional climate modeling resolution cannot resolve cat 4 or 5 hurricanes well. To compensate we apply extreme value analysis developed by Holland (2009) to the model intensity distributions to assess potential changes at the extremes.

In this report, we describe the experimental design and present initial results from the dynamical, and some of the statistical downscaling approaches. The next section provides a discussion of the experimental design and downscaling methodology; a selection of results is then presented; and the final section provides conclusions and discusses some implications of the findings.

## Experimental Design

The NCAR global Community Climate System Model (CCSM, Collins et al. 2003) provides the global climate predictions for the study. This is a full earth system model, including atmosphere, ocean, cryosphere, biosphere, and land surface. CCSM is coupled to the NCAR Weather Research and Forecasting model (Skamarock et al. 2002) to make up the Nested Regional Climate Model (NRCM), which is the basis of this study. All models are maintained at NCAR but have been developed by a large consortium of academic, private industry and government groups from around the world. CCSM is one of the leading models used by the IPCC and the Weather Research and Forecasting model is currently used by over 13,000 scientists and in more than 50 forecast centers. Thus, the NRCM benefits from an enormous level of experience and expertise in both global climate and high-impact weather modeling.

Three CCSM simulations have been made covering 1950-2060, each under different IPCC emissions scenarios: two versions of the A2 'business-as-usual' scenario based on moderate economic growth, and one version of the A1B scenario based on some curtailment of emissions. Here, one of the A2 emissions scenarios is used as the baseline climate to drive the NRCM for three time-slices of 1995-2005, 2020-2030 and 2045-2055 for the domains shown in Fig. 1. No nudging of the NRCM to CCSM data is applied in the interior of the domain. The NRCM is free to generate its own weather and climate constrained only by atmospheric data at the lateral boundaries and sea surface temperatures at the lower boundary. The outer domain was chosen to ensure that features, such as easterly waves, of importance to tropical cyclone development were adequately simulated. This domain is run at 36 km horizontal resolution with 51 levels in the vertical and full inclusion of all greenhouse gas changes and their associated radiative effects. A detailed analysis of one simulation from this domain is presented in this paper. In addition, we are conducting high-resolution, 12-km, simulations over the intermediate domain in Fig. 1 and short-period 4 km simulations over the two smaller domains (red triangles).

**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 that severely impacted cyclone climatologies. The problem is illustrated by comparing the analysis and model results in the example in Fig. 2 (top and middle). Note the anomalous band of extreme shear in the NRCM simulation extending from the eastern Pacific Ocean through the Caribbean and towards Africa. 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. A major underlying cause arose from a well-known tendency for global climate models to generate anomalously warm eastern oceanic temperatures. In the eastern North Pacific this results in permanent El-Nino-like conditions, which have been shown to increase the vertical shear over the tropical Atlantic (Gray 1984).

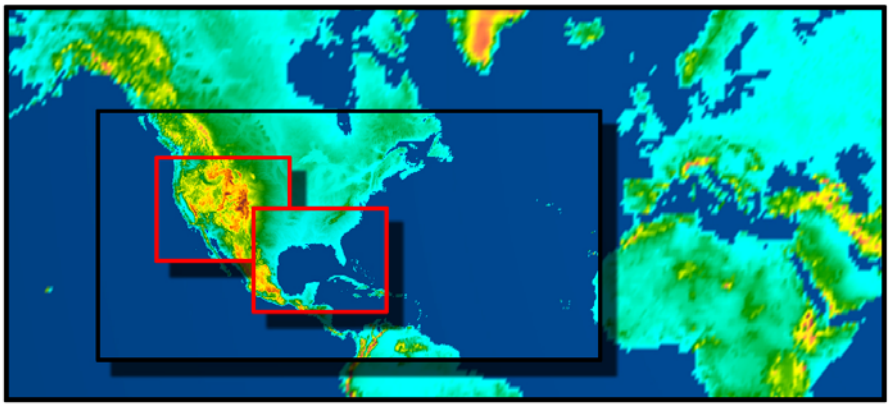

***Fig.* 1: NRCM model domain at 36 km grid spacing. Also shown are smaller domains at 12 km grid spacing (black rectangle) and 4 km grid spacing (red rectangles).**

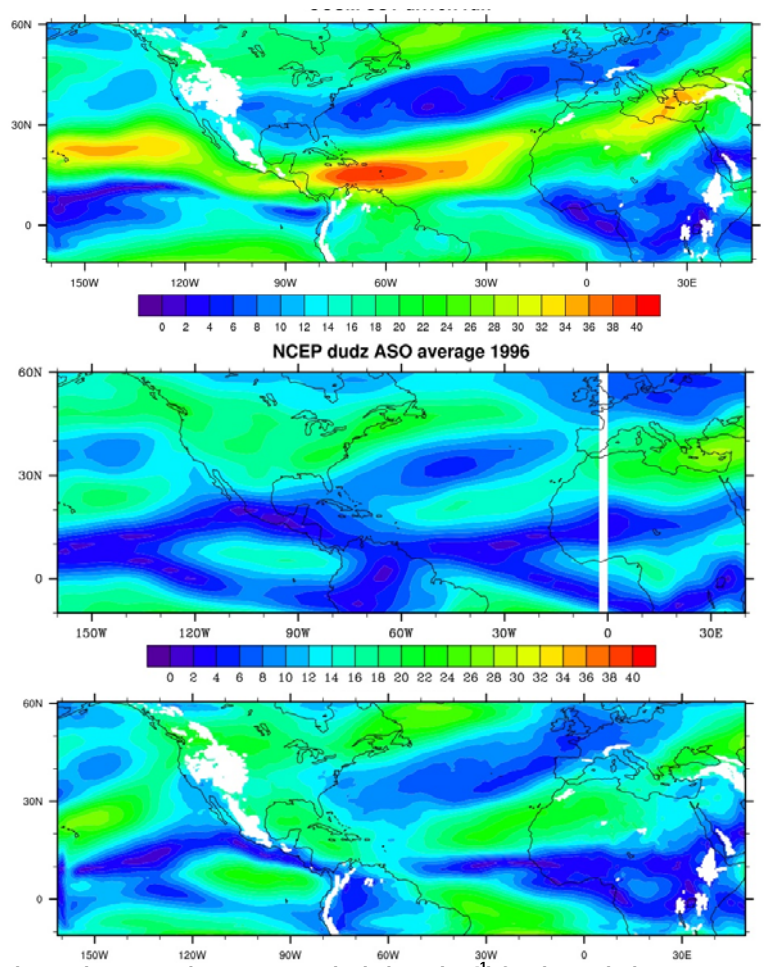


**Fig. 2: Three-month average vertical shear ($ms^{-1}$) for the period August-October 1996 for: (top) NRCM driven by raw CCSM output; (middle) NCEP-NCAR reanalysis data; and (bottom) NRCM driven by revised CCSM output.**

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 (1950-2060) were broken down into an average annual cycle plus a perturbation term:

$$CCSM = \overline{CCSM} + CCSM' \tag{1}$$

The average annual cycle is defined over a 20-year from 1975-1994. This length was chosen to smooth out any influence of El-Nino but may not be sufficient to smooth out any influence of multi-decadal modes. The choice of smoothing period is not important for this investigation into trends in tropical cyclone characteristics. Eq. 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:

$$NNRP = \overline{NNRP} + NNRP' \tag{2}$$

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

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

The revised boundary conditions for the entire simulation period (1950-2060) thus has a base climate provided by NCEP-NCAR reanalysis data from the period 1975-1994 and the weather and climate change signal provided by the raw CCSM data. Applying this to the NRCM resulted in a substantially improved definition of current climate as shown in the bottom panel of Fig. 2. A good approximation to tropical cyclone statistics for the current climate also was achieved, as described below in results.

**Statistical Downscaling.**

We are utilizing a variety of statistical and statistical-dynamic downscaling methods in support of the analysis of future hurricane changes. Here we report on one of direct application to the offshore energy industry in the Gulf of Mexico, the Willis Hurricane Index (WHI). This index combines hurricane intensity, size and translation speed to explicitly estimate the potential damage to offshore facilities in the Gulf of Mexico (Owens and Holland, 2009). The original formulation has been slightly modified to a form suitable for use on the NRCM time-slice data:

$$\begin{aligned} &WHI = \left(\frac{v_m}{34}\right)^3 + 5\left(\frac{R_{\max}}{30}\right) + 5\left(\frac{v_t}{15}\right)^{-2} \\ &For\ v_t < 25\ and\ v_m > 34, \\ &If\ v_t < 7, v_t = 7, \end{aligned} \tag{4}$$

where the first term represents the amount of energy dissipated at the surface by the maximum winds ($v_m$ in kt), the second term is the radial extent and character 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 kt). The use of nautical units was for compatibility with existing hurricane archives. The WHI thus combines parameters into a single index that provides a proxy for waves, currents, storm surge and structural fatigue from high winds. 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 from 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.

WHI offshore damage values were obtained from the Willis Energy Loss Data (an assessment of insurance losses from specific hurricanes by Willis Re) for the Gulf of Mexico inflated by CEPCI (Arnold and Chiltern 1963) to 1998 values. Applying the WHI to climate model predictions provides a convenient direct 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.

Throughout the paper statistical significance is measured by the 1-sided T-test.

## Results

**Sea Surface Temperatures.**

Before moving to the tropical cyclone statistics, it is instructive to first examine the changes in ocean temperatures for both SST and deep layer conditions. SST changes for the main tropical cyclone season of August to October are shown in Fig. 3 for the A2 (business as usual) and A1B (modest reduction in greenhouse gas emissions) CCSM simulation. The A2a scenario

(similar to the A2, but assuming a much more heterogeneous economic and energy use increase) was similar to the A2 and therefore not shown. We also present the entire tropical band to enable us to put the Atlantic increases in perspective.

Predicted tropical SST increases are consistent with other climate modeling studies (e.g. Meehl et al.2007). SSTs increase by between 0.5 and 2°C over the North Atlantic (top panels of Fig. 3), with the largest increase in the eastern equatorial region and along a band extending westward into the Gulf of Mexico. Relative SST, defined as the difference from the global tropical mean, has been suggested as an alternative mechanism to local SST for interpreting tropical cyclone changes (Vecchi and Soden 2007). We therefore include the relative SST changes obtained from subtracting the tropical mean (±20° Latitude, +1.2°C) in the bottom panels of Fig. 3. This shows that the warm band extending from the eastern equatorial Atlantic to the Gulf of Mexico is also anomalously warm relative to the global tropics. The ~0.5°C relative SST change maximum in the eastern Atlantic is not exceeded in area or magnitude anywhere else in the tropical belt.

Both IPCC scenarios result in similar oceanic changes in the North Atlantic. The most noticeable difference is that the A1b SST maximum has moved slightly eastward to butt up against the African coast.

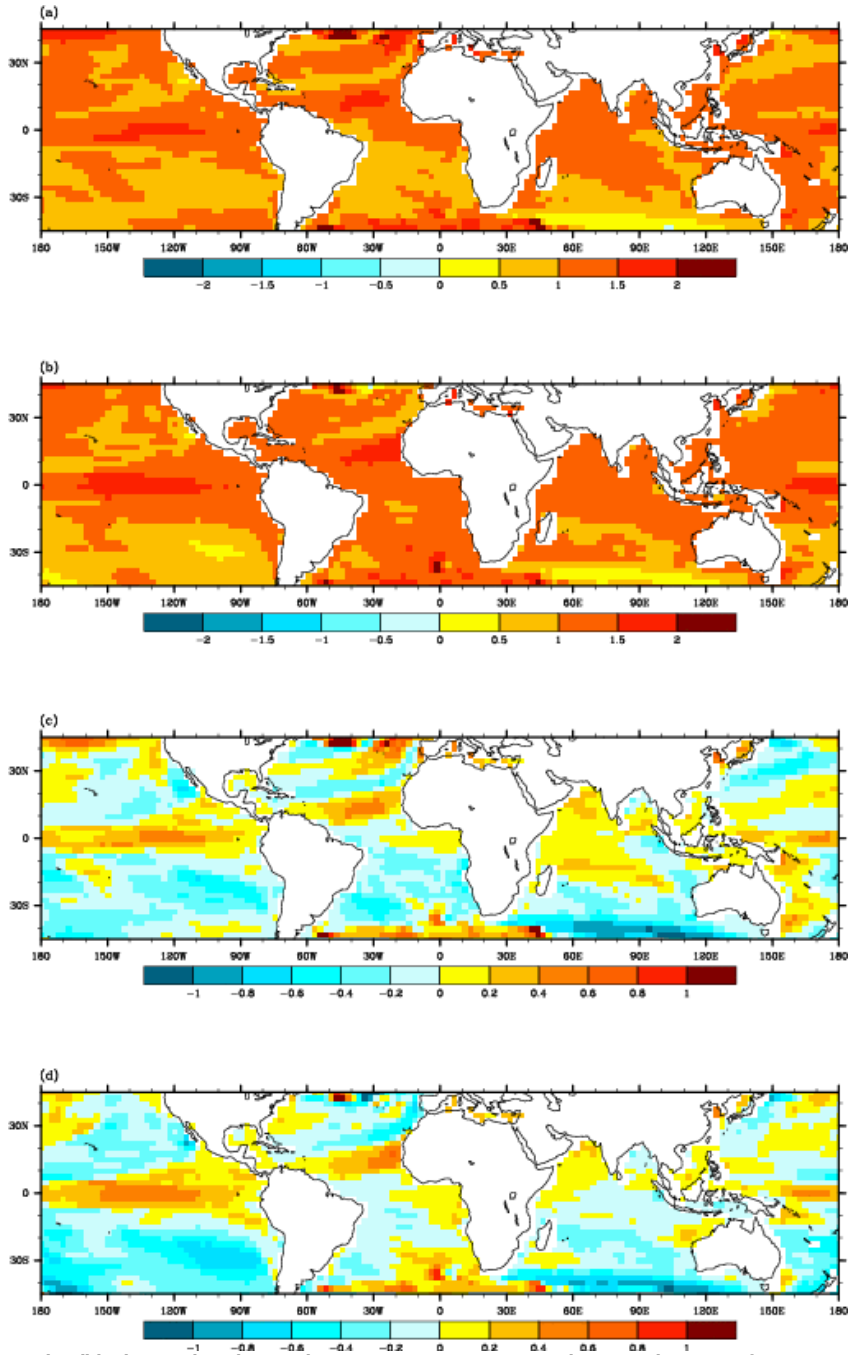


**Fig. 3: Panel a (b) shows the change in 11-year mean summer (Aug-Oct) sea surface temperature from 1995-2005 to 2045-2055 for the IPCC A2 (A1b) scenario. Panel c (d) shows the change in relative sea surface temperatures compared to the global tropical mean for ±20° latitude for IPCC A2 (A1b). Note that different scales are used in the top and bottom panels.**

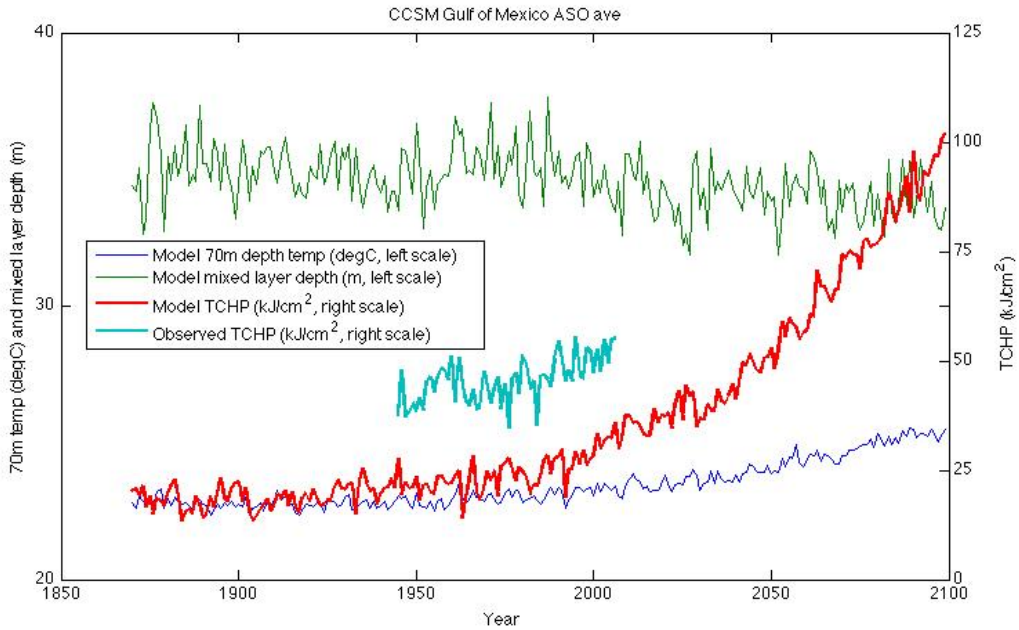


**Fig. 4: Time-series of upper ocean thermal properties averaged over summer (August-October) for the Gulf of Mexico showing: TCHP from the CCSM (kJcm$^{-2}$, red); TCHP from observations (kJcm$^{-2}$, green); temperature at 70m from the CCSM (°C, blue); mixed-layer depth from the CCSM (m, black).**

**Deep Ocean Conditions in the Gulf of Mexico.**

A number of interesting changes in the upper ocean thermal structure for the Gulf of Mexico are predicted (Fig. 4). These are derived from an extended CCSM simulation from 1870 to 2100 under the A2 scenario. The mixed layer depth (as defined by Large et al.1995) changes only slightly over the entire period. The noticeable variations are a distinct interannual fluctuation, a small multidecadal oscillation, and a small decrease between 1980 and 2000; the latter decrease is significant at the 99 % level. The ocean temperatures at 70 m depth remained relatively constant up to the 1980s and then steadily increased through to the end of the simulation. Compared to the mean before 1980, the decade from 2045-2055 was 1.3$^{o}$C warmer at 70 m and this increased to 2.5$^{o}$C for 2090-2100, both significant at the 99% level. The Tropical Cyclone Heat Potential (TCHP, Leipper and Valgenau 1972), an indicator of the amount of energy available for cyclone intensification, increased only slightly up to 1980, but then turns exponentially upwards to increase by a factor of 5 through the end of the century. This is significant at the 99% level.

Care needs to be taken with these initial results from a single climate model simulation. The ocean model used also is of relatively course resolution and not capable of simulating important Gulf features such as the Loop Current. This may be one explanation for the strong negative bias from present observed climate also shown in Fig. 4 (these simulation data have not been bias corrected following Eq. 3, due to the lack of basin-wide observations). Nevertheless, the remarkable increase in both 70 m ocean temperatures and the integrated TCHP is hard to explain purely from model bias or error. We are examining this further.

**Tropical Cyclone Frequency.**

Tropical cyclone tracks from the 36 km NRCM simulation are shown in Fig. 5 together with observed tracks from the NOAA IBTrACS archive. For the model analysis we use an objective tracking algorithm 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 > 5x10$^{-5}$ s$^{-1}$; maximum wind speed > 17ms$^{-1}$ in the vicinity of the pressure minimum; and a warm temperature anomaly aloft compared to the immediate surroundings with a vertical structure consistent with the cyclone phase space developed by Hart (2003). 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.

The 36 km NRCM simulations for the current climate period of 1995-2005 produced an average of 7.6 storms annually compared to the observed 14.3 storms per year. There are several reasons for this lower number. First, the CCSM climate that is used as boundary conditions 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 the model 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 cannot be expected to precisely follow any observed short-term variability that may have contributed to the high level of tropical cyclone activity of 1995 or 2005. Second, the base climate from which the bias correction perturbations were defined was determined by the 1975-1994 period, which was one of low cyclone activity. Third, we have established that lower-resolution models produce fewer storms than climatology in current climate (Suzuki et

al.2008), which can be attributed to a lack of simulation of important small-scale characteristics. We also caution that the actual number and distribution of storms in the model simulation are highly dependent on the detection and tracking method used and how it is tuned. We have not tuned the algorithm to higher detection to fit the low-resolution simulations and intend to use the same criteria across all model resolutions.

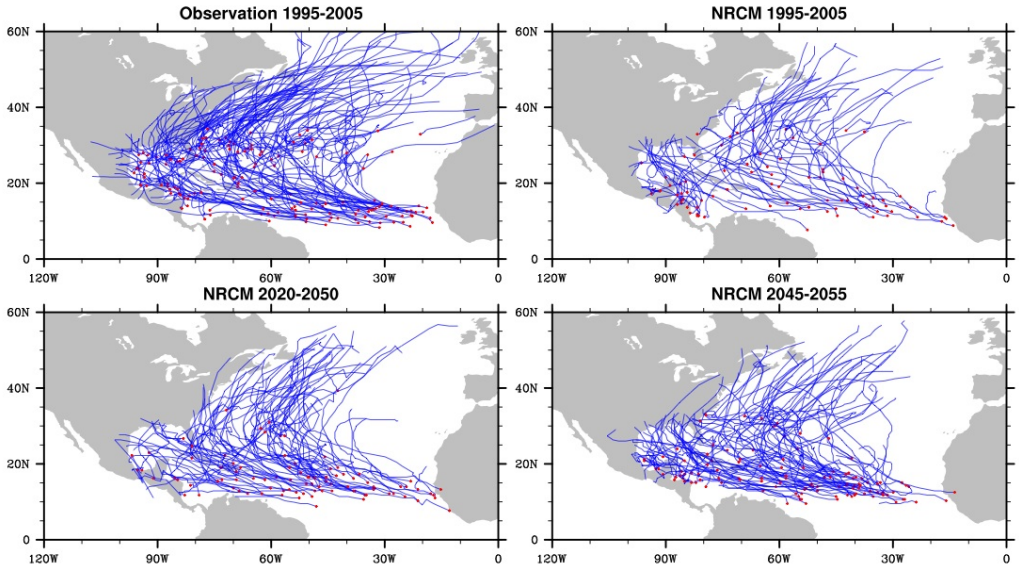


***Fig. 5: Tropical cyclone genesis points (red) and tracks (blue) for all North Atlantic basin cyclones from: IBTrACS data 1995-2005(top left); NRCM 1995-2005(top right); NRCM 2020-2030(bottom left); and NRCM 2045-2055 (bottom right). Note that the NRCM tracks typically stop soon after coastal crossing, whereas the IBTrACS continue over land for long distances.***

None of these reasons for the under-prediction of current cyclone frequency precludes using the NRCM results in a "relative sense". In other words, it seems reasonable to compare the NRCM hurricane activity in future decades to the NRCM historical period to get a relative sense of how future global warming might affect hurricane activity. This is standard practice in climate modeling assessments of future climate.

By comparison, the modeled tropical cyclone formation and impacted areas for current climate are quite close to the observed climatology (Fig. 6). The main difference is the occurrence of a simulation minimum in storm frequency over Florida and Cuba with a small secondary maximum in the western Caribbean. The period 1995-2005 was noted for its high proportion of storms forming at low latitude (Kimberlain and Elsner 1998) and the NRCM captured this aspect. Also captured well was the proportion of tropical cyclones in the Gulf of Mexico and the eastern coastal regions.

In the next 50 years the NRCM projects a marked increase in tropical cyclone frequency, with annual numbers increasing from 7.6 in 1995-2005 to 8.5 in 2020-2030 and 10.4 in 2045-2055. Said another way, the model shows an accelerating increase in hurricane frequency going from 3.4% per decade near the present to 10% per decade by the middle of the 21$^{st}$ century. Scaling the model to account for the bias in frequency brings a predicted average annual number of ~20 cyclones around 2050. This is consistent with the modeled actual and relative increase in ocean temperatures in the eastern Atlantic (Fig. 5).

These results are different to those of other studies which have tended to predict small changes and if anything a decrease in overall Atlantic tropical cyclone frequency over coming decades (Knutson et al, 2008; Bengtsson et al. 2007). We return to this difference in the discussion section.

The future climate predictions exhibit a consistent change in track density (Fig. 6), 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 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 2008). 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".

The modeled distribution of locations where storms reached maximum intensity agrees closely with observations for current climate (Fig. 7). Over the next 40-50 years the current maximum in the Gulf of Mexico migrates to lie off the Florida coast. It then migrates back to form a bimodal distribution with maxima in the Gulf of Mexico and western Caribbean.

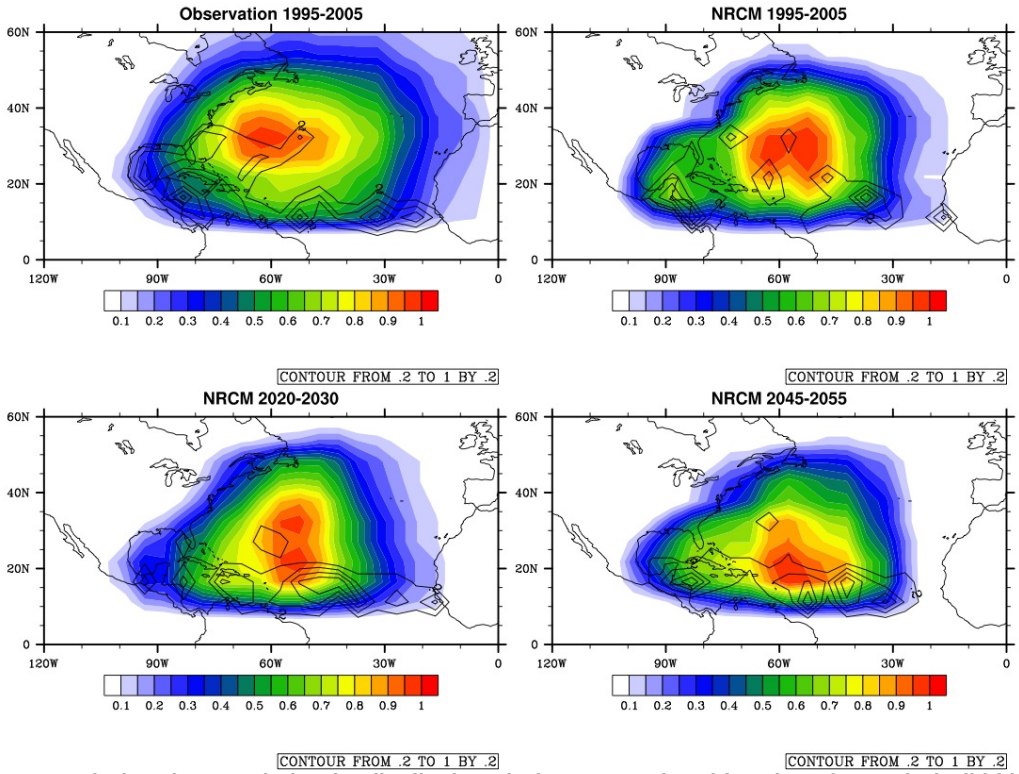


**Fig. 6: Tropical cyclone track density distributions (color contours) and location of genesis (solid black contours): observed 1995-2005 (top left), NRCM 1995-2005 (top right), NRCM 2020-2030 (bottom left), and NRCM 2045-2055 (bottom right). The densities represent number of 6-h occurrences within overlapping 5° Marsden squares, normalized to a maximum value of 1.**

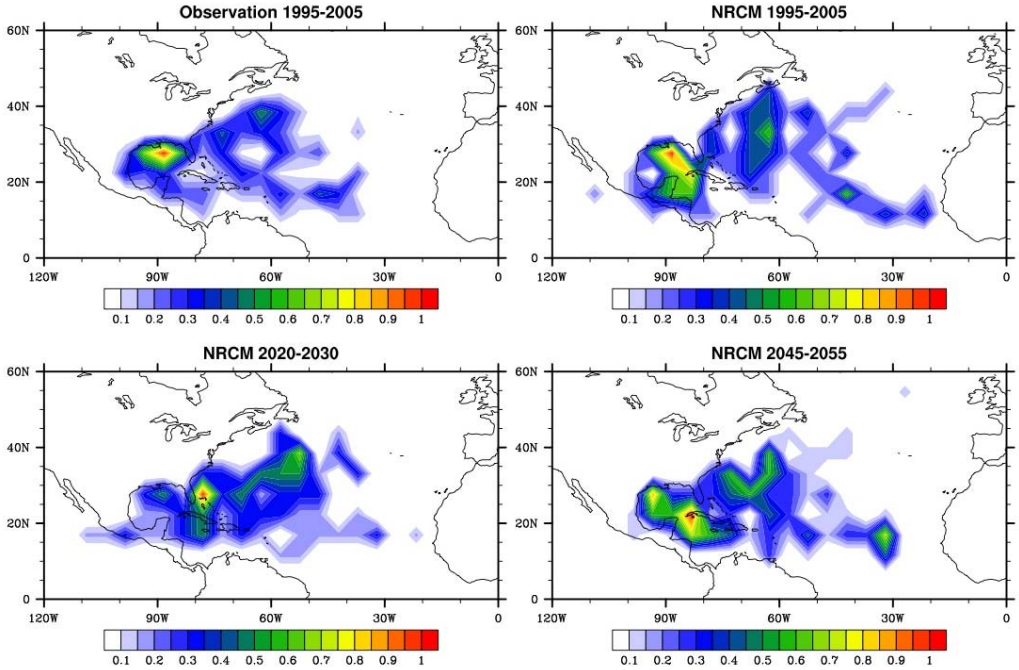


**Fig. 7: As Fig. 6 except for density of locations of maximum intensity (only the point of maximum intensity for each storm is counted).**

**Tropical Cyclone Intensity.**

PDFs of simulated and observed tropical cyclone intensity are presented in Fig. 8 for the maximum intensity achieved by each cyclone and in Fig. 9 for all 6-hour cyclone maximum wind observations. The left panels of both figures demonstrate the well known lack of capacity to simulate intense cyclones in lower-resolution models (e.g. Davis et al. 2009, Knutson et al. 2008). Note also the related tendency to over-predict moderate intensity systems (which occurs because intense cyclones are constrained to the mid-intensity zone in the model). However, there is reason to believe that the changes to this truncated distribution are indicative of changes in the extreme end also (Holland 2009), with the major difference being that the

extreme hurricane changes will have greater amplitude. The right panels of Figs. 8 and 9 indicate very little change in moderate and weaker tropical cyclones, but there is a consistent increasing trend in intense systems both in number and in maximum intensity.

Averaged over the three time slices, mean intensity for all cyclones increases from ~30 $ms^{-1}$ (1995-2005) to ~32 $ms^{-1}$ (2020-2030), and ~32 $ms^{-1}$ (2045-2055), and the total change is statistically significant at the 95% level. This trend is consistent with predictions by theoretical models of tropical cyclone intensity (Emanuel 1987, Henderson-Sellers et al. 1998) and it could be considered to be relatively unimportant, especially given that it is below the 2.5 $ms^{-1}$ resolution of the current observational data base. However, Holland (2009) has shown by application of extreme-value theory that even small changes such as these are reflected in marked increases in the very intense end of the distribution. Relating to the current observed distribution, Holland found that a 2 $ms^{-1}$ change in the mean should result in a 70% increase in the frequency of Cat 5 hurricanes.

The right panels of Figs. 8 and 9 also indicate a trend towards a broadening of the PDF to more intense systems, with the absolute maximum increasing from ~40 to ~42 and ~43 $ms^{-1}$over the three decades studied. In other words, a ~2 $ms^{-1}$ increase in the mean is associated with a ~3.5 $ms^{-1}$ increase at the extreme end of the model resolved PDF. We suggest that a substantially larger increase can be expected in the more intense cyclones that are not resolved. This increase is consistent with other indicators, such as: the overall increase in SST over the tropical Atlantic, both in absolute terms and relative to the overall tropical mean changes (Fig. 3); the tendency towards more cyclone developments at lower latitudes and decreasing developments more poleward, and the related increase in tropical cyclone development in the eastern, equatorial Atlantic. Indeed, this process may have already commenced; the equatorward shift in tropical cyclone development after 1995 (Kimberlain and Elsner 1998) has been associated with a marked increase in major hurricanes (Holland and Webster 2008) and a >300% increase in the frequency of Cat 5 hurricanes (Holland 2009). A recent study by Bender et al. (2010) using a hurricane forecast model embedded into climate models also has found a substantial increase in the number and proportion of Atlantic Cat 4-5 hurricanes, despite a projected decrease in the overall number of storms.

Combining our results and previous studies, leads to a conclusion that in the North Atlantic a marked increase in hurricane frequency at the Cat 3-5 level may occur and that there is little chance of there being no increase, or a decrease in the proportion of intense hurricanes over the next 50 years. This aspect is subject to detailed further investigation, which will be reported elsewhere.

## Gulf of Mexico Changes

***Tropical Cyclone Frequency.***

The tracks of all simulated cyclones moving through the Gulf of Mexico offshore facilities region (defined as north of 26°N and within the longitude band 100° W - 87°W) are shown in Fig. 10. The numbers varied between 15, 10 and 20 for the three decadal time-slices (Table 1) with an apparent strong multidecadal oscillation imposed on a moderate trend consistent with that for the basin as a whole. This occurred by the initial secondary maximum in track density over the Gulf weakening (Fig. 6) and being replaced in 2045-2050 by a band extending from the newly developed low-latitude track density maximum. Interestingly, translation speed and size also exhibited strong decadal oscillations superimposed on trends (Table 1). These aspects will be investigated in subsequent studies.

***Tropical Cyclone Intensity.***

No substantial overall change is predicted for mean intensity of tropical cyclones in the Gulf of Mexico over the next 40-50 years (Table1). There is evidence of a multi-decadal oscillation in maximum intensity of ~2 $ms^{-1}$, which is consistent with the migration of the location where most storms reach maximum intensity, out of and back into the Gulf of Mexico (Fig. 7). A similar, but stronger, multidecadal oscillation is predicted for storm size, and there was an overall trend towards smaller storms over the full period.

PDFs of tropical cyclone intensity are shown in Fig. 11 for those storms that directly affected the region of offshore energy facilities in the Gulf of Mexico. These show that the intensity of the strongest hurricanes may decrease by 2-3 $ms^{-1}$ to 2025 and then recover to 2050. These changes are not statistically significant due to the small number of data points.

***Hurricane Damage Index.***

We applied the Willis Hurricane Index (WHI, Eq. 4) to all cyclones in the NRCM simulations that moved through the region of offshore facilities in the northern Gulf of Mexico to provide a first-order assessment of likely changes in net damage to these facilities. Note that this applies only to current offshore facility stock and does not account for future improvements. The WHI results are summarized in Table 1 together with the contributions from each component in Eq. 4. The expected average hurricane damage halves from $5.7b to $2.5b from present the 2020-2030 decade. It then increases to $4.3b, but there is a net decrease of ~$1.4b over the entire period. And each of the constituent terms produced a similar result. The opposite occurs for the most damaging storm, which increases by $1.6b. However, the low number of damaging storms and the lack of resolution of true hurricane intensity means these numbers need to be treated with caution. They could easily change sign based on one storm.

***Table 1: Summary of the WHI and component terms for the Gulf of Mexico over the three time-slices 1995-2005, 2020-2030 and 2045-2055.***

| Parameter | 1995-2005 | 2020-2030 | 2045-2055 |
|---|---|---|---|
| # Cyclones | 15 | 10 | 20 |
| # 6-hourly data points | 96 | 50 | 78 |
| Average Intensity ($ms^{-1}$/kt)<br>Maximum Intensity ($ms^{-1}$/kt) | 26/50<br>37/72 | 25/49<br>34/67 | 25/49<br>37/73 |
| Average Rmax (km/nm) | 81/44 | 45/24 | 58/31 |
| Average Trans. Speed ($ms^{-1}$/kt | 5/10 | 6/12 | 6/11 |
| Average Eq. 4 Term1<br>Average Eq. 4 Term2<br>Average Eq. 4 Term3 | 3.7<br>7.3<br>14.4 | 3.4<br>4.0<br>11.9 | 3.7<br>5.2<br>13.9 |
| Average Hurricane WHI | 24.4 | 19.3 | 22.1 |
| Ave Hurricane Damage | $5.7b | $2.5b | $4.3b |

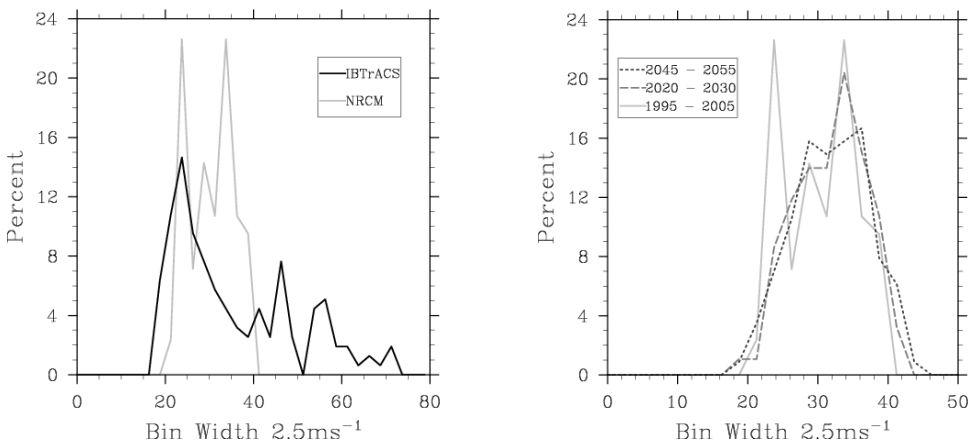


**Fig. 8: Distributions of maximum cyclone wind at 10m above the surface attained throughout the lifetime of each cyclone in the North Atlantic basin ($ms^{-1}$) for: (left) the period 1995-2005 in IBTrACS data (black) and NRCM (grey); and, (right) NRCM data for the three time slices.**

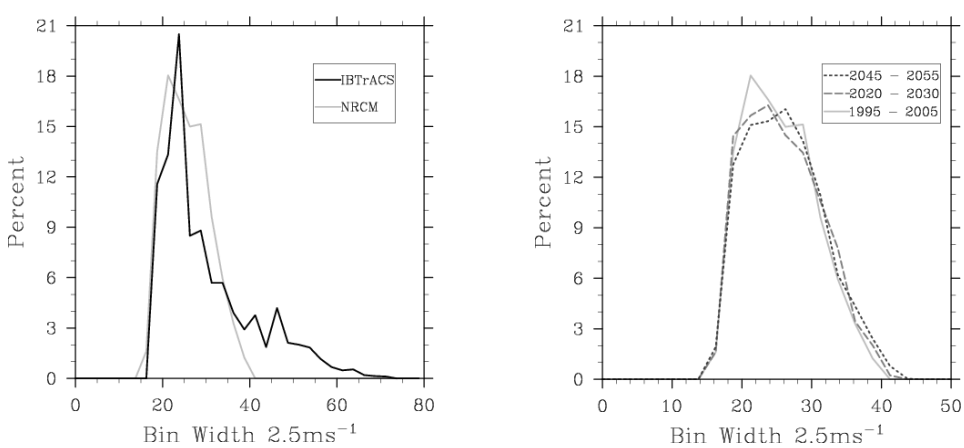


**Fig. 9: Distributions of maximum winds at 10m above the surface at 6-h intervals for all cyclones in the North Atlantic basin ($ms^{-1}$) for: (left) the period 1995-2005 in IBTrACS data (black) and NRCM (grey); and, (right) NRCM data for the three time slices.**

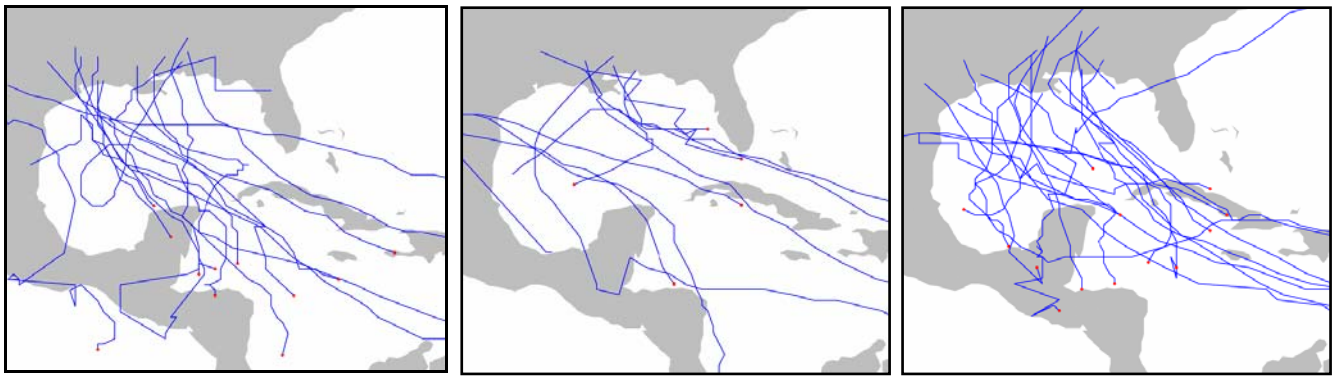

**Fig. 10: Model cyclone genesis points (red) and tracks (blue) for all cyclones that passed through the Gulf of Mexico offshore facilities region, defined as north of 26°N and within the longitude band 100°W - 87°W for the periods 1995-2005 (left), 2020-2030 (middle) and 2045-2055 (right).**

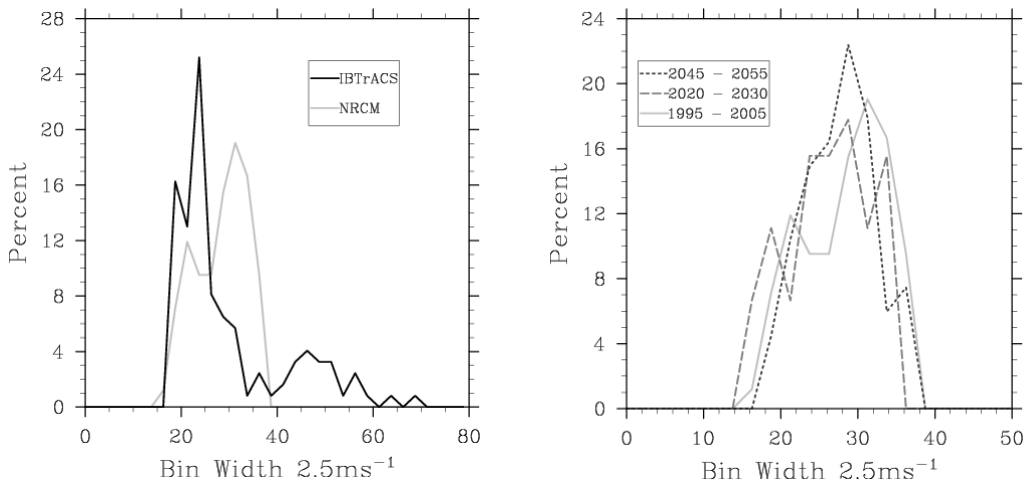


**Fig 11: Distributions of maximum winds at 10m above the surface at 6-h intervals for all cyclones moving over the area occupied by offshore energy facilities in the Gulf of Mexico: comparison with observations (left); and predictions for each time slice (right).**

## Concluding Discussion

We have presented initial results from a comprehensive modeling program aimed at providing predictions of future tropical cyclone frequency in the North Atlantic. Our main findings are:

- Tropical cyclone frequency in the North Atlantic is predicted to increase at an accelerated rate during the next 50 years, from a rate of ~3% per decade at present to ~10% per decade towards 2050. If correct this implies a 25% increase in average annual cyclone number to around 20 per year by 2050, significant at the 99% level;
- The observed equatorward shift in cyclone frequency 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;
- Intensity is predicted to increase consistently throughout the period, with the major increases of ~3.5 ms$^{-1}$ occurring at the extreme cyclone end of the spectrum;
- The proportion of all cyclones entering the Gulf of Mexico is predicted to go through a multidecadal oscillation, down then up, with a net increase of 25% being similar to the North Atlantic basin as a whole. Mean cyclone intensity is predicted to decrease, then increase, with little net change, but the changes are not statistically reliable because of the small number of storms being considered;
- Application of the Willis Hurricane Index to the predicted storms indicates that overall damage from hurricanes may decrease from the present to 2025, but then increase through to 2050. The average hurricane damage decreases, but that due to the most damaging hurricane increases. Again, these results are uncertain due to the small number of storms involved;
- Upper level 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 five-fold, also significant at the 99% level.

Care needs to be taken with interpretation of model predictions based on a limited number of simulations (and a limited number of published studies). However, our results are consistent with statistical associations and physical processes[2], as discussed below.

We fully acknowledge that there are considerable uncertainties in the results presented in this initial analysis. Nevertheless there are a number of internal consistencies that provide some confidence in the findings.

There has been some debate on whether the observed increase in equatorial development resulted from changing observing capacity, natural variability, or the commencement of a climatic trend (e.g. Holland and Webster 2008, CCSP 2008, Landsea 2008, Holland 2008, Mann and Emanuel 2006, Mann et al. 2009). Our model predictions of a sustained future trend towards increased density of hurricane occurrence in the eastern equatorial Atlantic (Fig. 6) supports the view that there is a significant component of climate trend embedded in the observed past changes. The predictions are also consistent with other recent studies. For example, Wu et al. (2010) found that a relative increase in eastern Atlantic SSTs, similar to that in the bottom panels of Fig. 3, leads to distinct atmospheric circulation changes that can explain the observed increase in tropical hurricane frequency. This physical process is consistent with our predictions of increasing tropical development through to 2050.

The dynamical downscaling approach predicts strong multi-decadal variability in future hurricanes over the Gulf of Mexico, not only in tropical cyclone frequency but also in the hurricane parameters of critical importance to the O&G industry including intensity of the strongest storms, areal extent of the wind field and the translation speed. All these multi-decadal changes have an impact of the same sign on the expected damage obtained through the Willis Hurricane Index resulting in a decrease in the average expected damage towards the 2020s followed by a return to elevated levels by the 2050s.

A limitation to the Nested Regional Climate Model approach is that the nested atmospheric model is not coupled to a full ocean model. Inspection of the thermal structure of the ocean in the global climate model showed a striking upward trend in the Tropical Cyclone Heat Potential over the Gulf of Mexico over the next 100 years. Work is currently underway to fully couple the Nested Regional Climate Model to a full ocean model to fully realize the impact of this increasing energy source on tropical cyclone variability and trends, and to ascertain whether changing frequencies of tropical cyclones will effect this ocean warming.

Confidence in these results is of course limited by the small sample size. A sample size of one or two tropical cyclones in the Gulf per year can not provide stable statistics. However, we can explore changes in the large-scale and slowly varying climate and attempt to understand the physical mechanisms for the apparent multi-decadal variation in hurricane activity. For example, the observational record shows the strongest hurricanes form at lower latitudes (Holland and Webster 2008). Assuming a similar relationship in the nested regional climate model it follows that the trend to lower latitude hurricane development across the tropical North Atlantic predicted in this study may be contributing to changes in the average and maximum hurricane intensities in the Gulf of Mexico, i.e. a remote rather than a local control on Gulf storm variability. Changes in the latitudes of development are also important due to the different mechanisms of genesis and development and related changes in the clustering of storms (R. Vitolo, personal communication 2009) and in their modulation by tropical modes of variability. An observational study by Maloney and Hartmann (2002), for example, showed that Gulf of Mexico and western Caribbean hurricane genesis was four times more likely when lower tropospheric winds associated with the Madden-Julian Oscillation are easterly.

Finally, assessments of future changes and prediction uncertainties will become more comprehensive not only as we begin to incorporate all four complementary methods of extracting tropical cyclone climatologies from the global climate models but also through an increased physical understanding of tropical cyclone climate interactions.

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[2] Apart from the apparent conundrum that the predicted substantial increase in tropical cyclone heat potential for the Gulf of Mexico does not produce a substantial increase in hurricane intensity. This is a subject ongoing investigation.

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