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Regional Increases in Landfall Frequency and Intensity of Atlantic Hurricanes in a Stochastic Model Forecast

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1. Introduction

Good assessments of hurricane landfall risk that are highly localized to particular geographic locations are needed for a range of applications, such as for insurance pricing, disaster planning and mitigation. Risk assessments are traditionally performed using the full historical record, even though hurricane activity is well-known to exhibit non-stationarity. The scientific literature addressing periodicity and secular changes in hurricane activity is usually focused on broad metrics, such as basin-wide frequency, which have only limited utility to local risk assessment. Stochastic hurricane models are often used for this purpose but are usually created to mimic the long-term average of historical data. This study will present results from a novel stochastic model capable of making predictions of near future shifts in hurricane activity, with a focus on geographical shifts in landfall frequency and intensity.

The existence of multidecadal variability in hurricane activity in the Atlantic, alternating between phases of high and low frequency, is well-known (Delworth and Mann 2000; Goldenberg et al. 2001; Elsner et al. 2004; Jewson and Penzer 2006; Holland and Webster 2007; Klotzbach and Gray 2008). The current high-activity phase began in 1995. Multidecadal phases of hurricane frequency are almost certainly linked to multidecadal phases of increased or decreased sea surface temperature (SST) anomalies in the main development region (MDR). Fluctuations in MDR SST have alternatively been classified as the Atlantic Multidecadal Oscillation (AMO) (Delworth and Mann 2000; Goldenberg et al. 2001; Gray et al. 2004; Knight et al. 2006; Enfield and Cid-Serrano 2009) or the Atlantic Meridional Mode (Kossin and Vimont 2007; Vimont and Kossin 2007). In addition to the multidecadal variability, some researchers have found an increasing trend in frequency (Emanuel 2005; Mann and Emanuel 2006; Emanuel 2008) and intensity (Webster et al. 2005; Elsner 2006; Elsner et al. 2008) linked with anthropogenic climate change. Recent papers have also emphasized the importance of the tropical mean SST, which is dominated by the tropical Indo-Pacific (IP), rather than SST strictly local to the developing storm (Vecchi and Soden 2007; Swanson 2008).

Dynamical models with coupled atmosphere-ocean physics have been used to examine future possible changes in hurricane activity in a warmer world (Bengtsson et al. 2007; Camargo et al. 2007; Caron and Jones 2008; Knutson et al. 2008; Zhao et al. 2009; Bender et al. 2010) and could in theory be used for near future predictions. However, since none of the global circulation models or downscaled regional models can simulate modes of unforced internal variability, they do not correctly capture the current multidecadal variability in the Atlantic. Numerical models also struggle to simulate realistic hurricane intensities (in general producing storms that are too weak) and they are too computationally expensive to generate more than few hurricane seasons. Typically these models are used for experiments simulating climate at the end-of-century or for an environment with doubled atmospheric $C0_2$ whereas this paper is focused on the near-term future.

Stochastic hurricane models have the ability to simulate very large numbers of synthetic hurricanes having similar statistical characteristics to the historical data. This increases the sample size and geographic coverage of events, allowing for risk assessment at a much finer spatial resolution than is possible using only historical events. It also enables the simulation of storms that are physically plausible but are not reproductions of the historical dataset. In general, stochastic models sample from distributions representing various aspects of hurricane activity, genesis density or translational velocities for example, with the parameters of the distributions fit to observations. These types of models are often proprietary and consequently only limited descriptions exist in the published literature. However, some examples can be found (Darling 1991; Chu and Wang 1998; Casson and Coles 2000; Vickery et al. 2000; James and Mason 2005; Rumpf et al. 2007). We will use a stochastic model to examine spatial shifts in hurricane activity characteristics given a prescribed MDR and IP SST which is higher than the historical mean but similar to the mean since 1995.

This chapter is presented in the following way. Section two describes the historical data used, a brief description of the model and the methodology of the experiment. Results are presented in section four along with some discussion of underlying physical mechanisms of the results. Section five gives the conclusions.

2. Data and methodology

a. *Data*

A database of historical, six-hourly observations, called HURDAT, is maintained by the United States' National Hurricane Center (Jarvinen et al. 1984; Landsea et al. 2004). This database was used in the creation and calibration of the stochastic model. Landfall information in the United States for hurricane categories 1-5 is considered accurate after 1900, when the coastal areas were relatively densely populated. However, because data quality away from the North American landmasses is known to be poor in the early years of the dataset, only use data after 1950 was used for hurricane characteristics over water, after which time aircraft reconnaissance became common.

Historical, global, gridded SSTs over the period 1950-2008 from the United Kingdom's Hadley Centre (Rayner et al. 2003) and SST predictions from the A1B scenario of the CMIP3 ensemble of global climate models were also used. The CMIP3 models were incorporated into the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report (IPCC 2007). Finally, the NCEP/NCAR reanalysis was used for upper-air analysis (Kalnay et al. 1996).

b. *Model Description*

The stochastic model used for this paper's near future forecast is based on the track model described in Hall and Jewson (2007). It was developed with the HURDAT historical data, Hadley Centre SSTs and NCEP/NCAR reanalysis, as described in section 2a. The model is fast to run and capable of simulating millions of hurricane tracks from genesis through lysis, with zonal and meridional translational speed and central pressure simulated at six-hourly time steps. At genesis and thereafter at each time step until lysis, the characteristics of the hurricane are simulated from a distribution, the shape of which is dependent on predictors. If a hurricane characteristic is represented by y, then the mean of the distribution to be simulated from can be represented by

$$\bar{y} = f(\beta_0 + \beta_1 X_1 + ... + \beta_n X_n)$$

where $\bar{y}$ is the mean of the variable being simulated, X is a predictor variable and β is a coefficient determining the relationship between the predictor and $\bar{y}$. The β coefficients are scalar constants that vary spatially. They were calculated on a 1˚x1˚ latitude-longitude grid using smoothed historical data to represent $\bar{y}$. Two predictor variables in the model are the area-averaged, July-September MDR (15-70 West, 10-20 North) and IP (IP, 40 East –80 West, 0-15 North) SSTs.

Simulation of an individual track begins with the latitude and longitude of genesis using a spatial Poisson distribution. After genesis location has been determined, the track path and pressure is simulated from

$$x(t + \Delta t) = x(t) + u(t)\Delta t$$

$$y(t + \Delta t) = y(t) + v(t)\Delta t$$

$$p_c(t + \Delta t) = p_c(t) + \frac{\Delta p_c}{\Delta t}\Delta t$$

where Δt is the 6-hourly time step, u and v are the zonal and meridional components of the translational speed and p_c is the central pressure. Axisymmetric wind fields are generated using a modified version of Willoughby et al. (2006). The moment of lysis is simulated using a regression method based on the historical difference between ambient atmospheric pressure and the storm's central pressure; the closer these two values are the more likely the storm will undergo lysis.

c. *Methodology*

Previously, the stochastic model used in this paper was described. Important components of the model are its predictors, two of which are the MDR and IP SST. The model was developed using historical values of these quantities; however, assuming that the β coefficients remain valid, explorations of hurricane activity can then be made using different SSTs. Predictions of the regionalization of near future hurricane activity using this model require only a prediction of future SSTs. We have chosen the five year period 2010-2014 as a prediction period. It is long enough to average over high frequency, unpredictable variability (El Niño variability for example) but short enough for stationarity to be assumed.

To create a prediction of average annual hurricane activity from 2010-2014, the mean and standard deviation of the MDR and IP SST over this period must be predicted.

The SST predictions are taken from a bias corrected ensemble mean of the CMIP3 climate models, concatenated with the twentieth-century radiative forcing runs without volcanoes. The twentieth-century runs do a good job of representing the observed upwards trend in SSTs, but the absolute values must be bias corrected. An optimal window over which to bias correct was found using out-of-sample hindcasts. Since the window length will depend on the magnitude of the trend and variability around the trend, the window length is different in the MDR and the IP. Greater detail on the bias correction can be found in Laepple et al. (2008). Out-of-sample, five-year mean SST hindcasts using the bias-corrected ensemble mean shows skill compared with persistence. For the prediction over 2010-2014, an assumption is made that the probability of a shift from the warm phase to cold in the MDR is very small. The MDR has been in the warm phase since 1995 whereas the length of both the AMO and AMM types of variability is several decades.

For the remainder of this chapter, the output of the stochastic model originally fit and run using the historical values of SST will be called the historical scenario and the output using predicted SSTs will be called the warm scenario. After the mean MDR and IP SSTs are calculated from the method described in the previous paragraph, the standard deviation must be calculated in order to characterize the distribution of SSTs for use in the stochastic model. A normal distribution is assumed, and the standard deviation is taken to be the root-mean-squared-error of the out-of-sample hindcasts of bias-corrected CMIP3 ensemble mean twentieth-century runs. This standard deviation is smaller than the historical standard deviation of the SST in the MDR and IP.

Table 1 shows the mean and standard deviation for the historical and warm scenario predictions. It can be seen that the MDR is historically cooler and has greater variability than the IP. In the warm scenario, the SST in the MDR is increased less than 1°C, but almost 2 standard deviations of its natural variability. The IP SST is also increased, but by a smaller fraction of its natural variability. Therefore the warm scenario has MDR SSTs high relative to the IP SSTs, as is true during active phases of the Atlantic.

		MEAN	STANDARD DEVIATION
MDR	Historical	27.34	0.31
	Warm	27.93	0.26
IP	Historical	28.05	0.27
	Warm	28.40	0.22

Table 1. The mean and standard deviation of the MDR and IP SST distributions for the historical and warm model scenarios.

Given an MDR and IP SST distribution, the stochastic model can be run using these predictors. Comparisons of the two scenarios, historical and warm, will be made, with an emphasis on the regionalization of landfall and intensity shifts. Although the model output can be examined at very high resolution, this paper will present results for the regions shown in Figure 1.

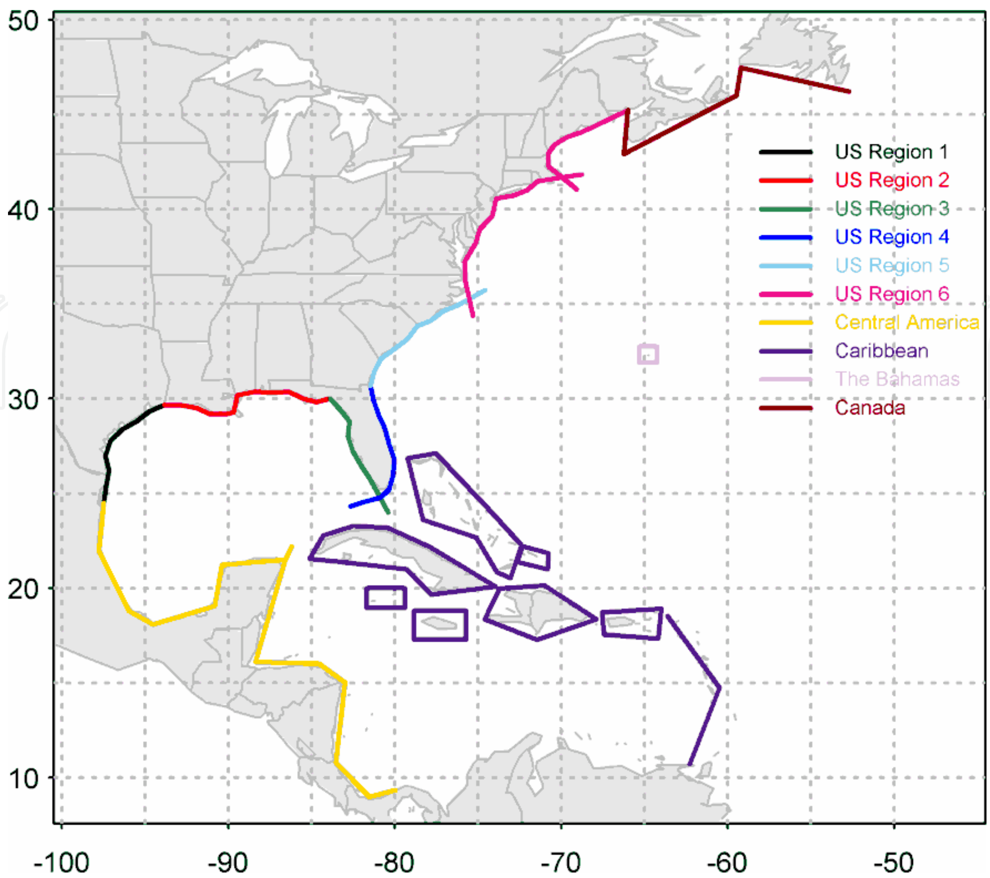

Fig. 1. Landfall comparison regions. There are extensions into the Atlantic to include by-passing storms in some areas.

3. Results

a. *Landfall rate regionalization*

One of the metrics of regionalization is the spatial distribution of landfall rates. In the warm scenario of the stochastic model genesis rates increase significantly in the main development region. As a consequence, landfall rate density increases everywhere, although with geographic regionalization of the increases. Figure 2 shows the percentage change in landfall rate by region (Fig. 1) for the warm scenario compared to historical, for categories 1-2 and 3-5. Landfall rate increases are larger for categories 3-5 than for categories 1-2, implying that intense storms are more strongly affected by increased SSTs. The Caribbean, Central America and the southeast United States from Atlantic Florida to North Carolina have the largest increases geographically.

Having discussed the regionalization shifts of landfall rate in the warm scenario compared to the historical, we will now examine the causes of this regionalization. That is, why the warm scenario has smaller increases in landfall rate along the Texas and northeastern coasts and larger increases from Louisiana to North Carolina. To address that question, Figure 3 shows the percentage change in genesis density in the warmed scenario compared to the historical, for hurricanes going on to make landfall in each of the six U.S. regions (Fig. 1), in 1˚x1˚ latitude-longitude bins. Included in the figure are the mean, 10th and 90th percentile of tracks making landfall in each region, for both warm and historical scenarios. The track

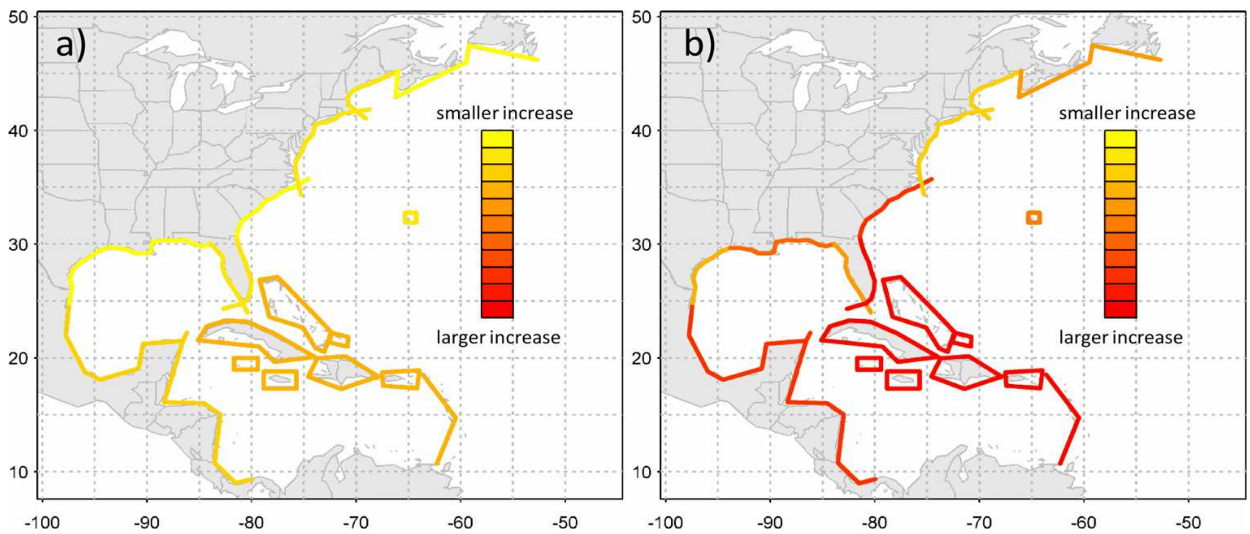

Fig. 2. Percentage increase in the warm scenario compared to historical for hurricane landfall at a) categories 1-2 and b) categories 3-5.

lengths represent the mean, 10th and 90th percentile of hurricane lifetime from genesis to landfall in the region. Average annual rate of genesis density in five boxes is given with the percentage change in inset text.

Mean hurricane lifetimes (indicated by the track length) increase in the warm scenario, another consequence of a shift in genesis density towards the eastern MDR and further from land. Other than increasing in length, the mean tracks do not change direction in the warm scenario. This indicates that the landfall rate regionalization patterns (Fig. 2) can be explained by changes in patterns of genesis rather than changes in track geometry.

Overall, genesis density in the eastern MDR (box 5) increases most in the warm scenario, even in regions where it is not the largest contributor to the total landfall rate (i.e. regions 1-3). In regions 4-6, storms originating in the eastern MDR become the largest contributors to landfall in the warm scenario while the western MDR (box 4) was the largest contributor to landfall in the historical scenario. Landfalls from hurricanes originating in the western MDR also increase in each region, although with smaller magnitude than those from the eastern MDR.

Unlike the increases in MDR genesis density, there are decreases in the eastern Gulf of Mexico and in the north Caribbean Sea. For example, region 1 (the Texas coast in Figure 3a) has one of the smaller magnitude increases in landfall rate (Fig. 2) in the United States. Texas receives a large proportion of its landfalls from storms with a genesis in the Gulf of Mexico (0.1 per year from box 2, compared with 0.07 from box 4 and 0.04 from box 5 in the historical scenario). However, genesis density in box 2 increases only a small amount compared to the MDR boxes because the eastern Gulf of Mexico has a significant decrease in genesis density.

Region 2 (Fig. 3b) receives a proportion of its landfalls from the Gulf of Mexico but there are also large increases in MDR hurricanes making landfall in region 2 in the warm scenario. Region 2 many landfalls also originate from box 3, the western Caribbean Sea around the Gulf of Honduras. Box 3 has an increase in genesis density in the warm scenario. The last Gulf of Mexico region is region 3, the west coast of Florida (Fig. 3c). Region 3 also has a large contribution to its landfalls from box 3. Storms with genesis in this box track westward on

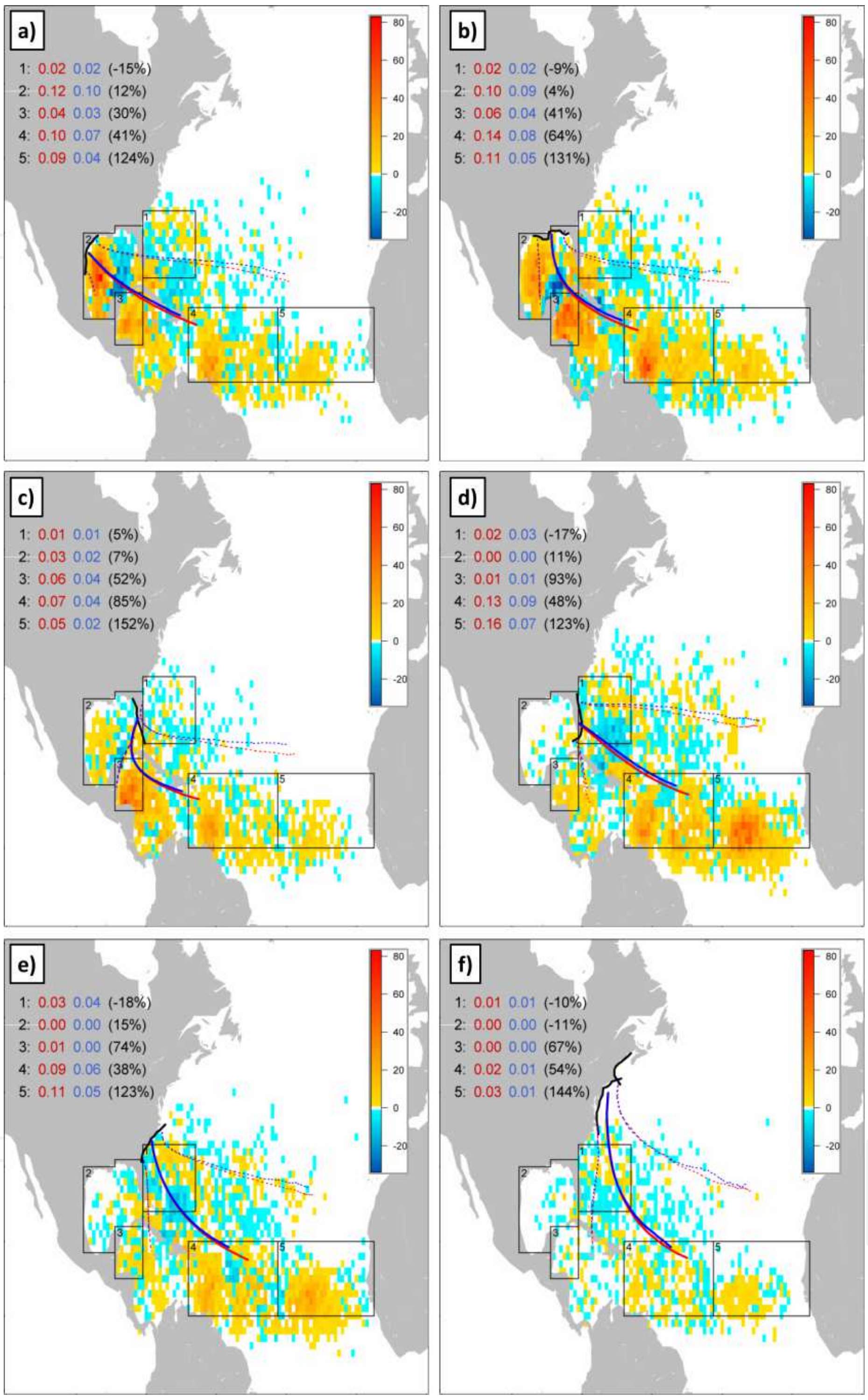

Fig. 3. Percentage change in hurricane genesis density of storms making landfall in a-f) regions 1-6 in the warm scenario compared to the historical. Warm (cool) colors indicate increased genesis density in the warm (historical) scenario. Mean, 10th and 90th percentile tracks are also shown for the warm (red) and historical scenario (blue). Average annual rate of genesis density in five boxes are given in inset text for the warm scenario (red) and historical scenario (blue) with the percentage change (black).

average, crossing into the Bay of Campeche and making landfall in Mexico. However, many of them also track northward to make landfall in western Florida.

Regions 4 (Fig. 3d) and 5 (Fig. 3e) have the largest increase in landfall rate in the United States (Fig. 2), especially for categories 3-5. These regions are very commonly hit by both western and eastern MDR-originating hurricanes. The combined annual landfall rate of storms from boxes 4 and 5 is 0.16 and 0.11 in the historical scenario for region 4 and 5 respectively. This increases to 0.29 and 0.20 in the warm scenario - almost a doubling. For region 5, this increase is somewhat reduced by the decreases in genesis density in the north Caribbean in the warm scenario. Finally, region 6, the northeast (Fig. 6f) experiences only small increases in landfall rate in the warm scenario (Fig. 2). This region does not experience frequent landfall in either the warm or historical scenarios. The landfalls it does receive originate largely in box 1, a box with decreased genesis density in the warm scenario.

b. *Physical mechanisms affecting genesis density regionalization*

It has been shown in the previous section that the regionalization of landfall rates in the warm scenario (Fig. 2) can be explained by regionalization of genesis density. The most significant change in the warm scenario was an increase in genesis density in the eastern MDR, the region of Cape Verde-type developments. If the MDR is very warm, African easterly waves leaving the coast of Africa can develop quickly. The shift towards the east in genesis with warmer MDR SSTs has been found in at least one dynamical modelling study. Wu et al. (2010) ran the ECHAM 4.8 global, atmosphere-ocean coupled model with a warmed tropical Atlantic and found an increase in hurricane formation in the eastern MDR. This shift can also be found in the HURDAT observational record. For example, over the period 1950-2009, 2.2 hurricanes had their genesis east of 25W on average, compared with 3 on average in the post-1995 active regime. The observed shift could be spurious because of increased observations in the eastern Atlantic in later years, although the hurricane count is believed to be complete after satellite observations begin in the 1960s (Holland and Webster 2007; Emanuel 2008).

The overall increase in MDR genesis and the shift towards the east in the warm scenario can be explained in part with reference to simple physical mechanisms known to be related to SST in the MDR and IP. If all other atmospheric variables are held constant and the local SST is increased, the potential intensity for a hurricane is also increased (Emanuel 1987). Figure 4 shows the correlation coefficient of July-September local SST in the Hadley Centre dataset and the July- September MDR predictor used in the fitting of the stochastic model's β coefficients. It can be seen that SSTs across the MDR and southern Caribbean Sea are highly correlated with the model's MDR predictor.

Local SST changes alone cannot explain the patterns of genesis density regionalization in the warm scenario because SSTs in the eastern and western half of the MDR are both highly correlated with the predictor MDR. Another important environmental factor affecting hurricane genesis and development is the wind shear, usually defined as the vector difference between monthly mean 850 hPa and 200 hPa winds ($V_s = \left| u_{850} - u_{200} \right|$). Local wind shear is known to act against hurricane development and is correlated with both MDR and IP SSTs. Aiyyer and Thorncroft (2006) regressed an MDR index (with a slightly different but similar areal definition of MDR to that used in this paper) and the Niño 3.4 index (a measure of IP warmth) on July-October vertical wind shear in European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year reanalysis dataset (ERA-40). They showed that, whereas the MDR SSTs are associated with decreased wind shear in the MDR, the Niño 3.4 region SSTs are associated with increased wind shear, especially in the western MDR and

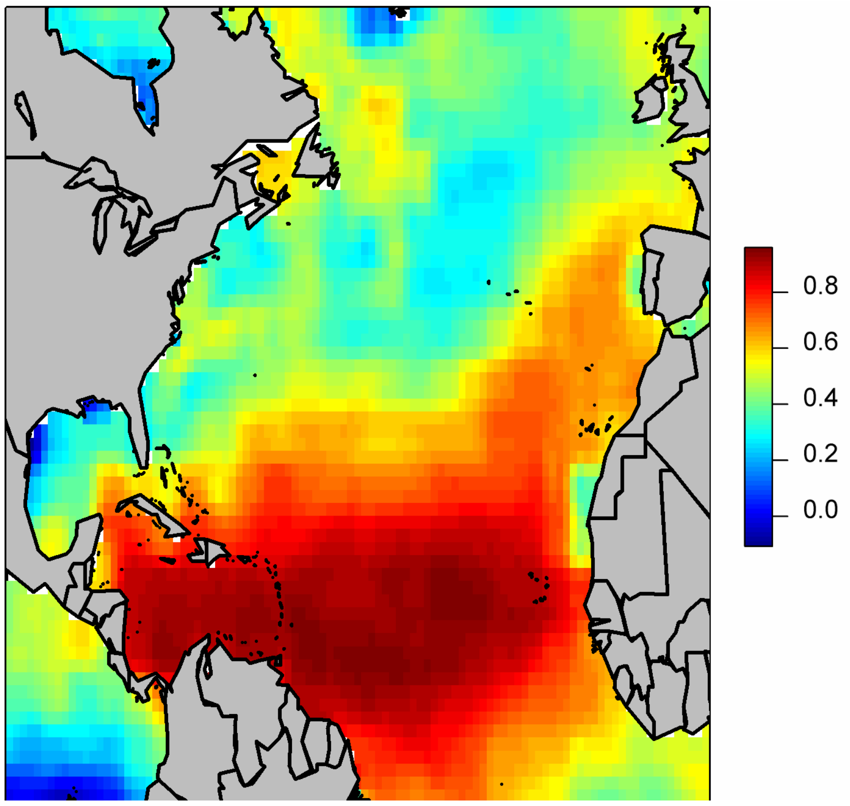

Fig. 4. Correlation coefficient of July-September local SST from the Hadley Centre dataset and the model's MDR SST predictor over the period 1880-2009.

southern Caribbean regions. We speculate that the genesis density regionalization found in the warm scenario is the result of a combination of the interaction between increased wind shear in the western MDR and south Caribbean owing to increased IP SST in the warm scenario, and an overall increase in genesis from increased local SST across the MDR.

Tropical transition-type storms with a mid-latitude synoptic precursor are most likely to form in the Gulf of Mexico, near the east coast of the United States and north Caribbean Sea, areas much less correlated with the MDR predictor (Fig. 4). Geneses of tropical transition storms are more dependent on atmospheric dynamics than local SST (Bracken and Bosart 2000; Hulme and Martin 2009). They often make landfall on the Gulf of Mexico or east coasts of the United States, especially from South Carolina to Maine. These regions had a smaller increase in landfall rate in the warm scenario (Fig. 2) and small increases or decreases in hurricane genesis density in the warm scenario (Fig. 3).

c. *Intensity Changes*

We have shown how landfall rates are regionalized in the warm scenario owing to regionalization changes in genesis density (Section 3). In the warm scenario the intensity distribution of hurricanes also shifts towards more intense storms. Figure 5 shows the 95th percentile of hurricane central pressure in storms passing through 1˚x1˚ longitude-latitude bins in the warm and historical scenarios. It can be seen the central pressure decreases in most areas of the Atlantic in the warm scenario, especially in the central Caribbean Sea, Gulf of Mexico and around Atlantic Florida. Hurricane intensity, besides being intensified by local SST, is also determined by the length of time the storm has spent over warm water. In the warm scenario, the average lifetime of hurricanes is longer because their genesis shifts towards the east, further from land masses. This shift provides a greater length of time over which to intensify before reaching the Caribbean or Gulf of Mexico.

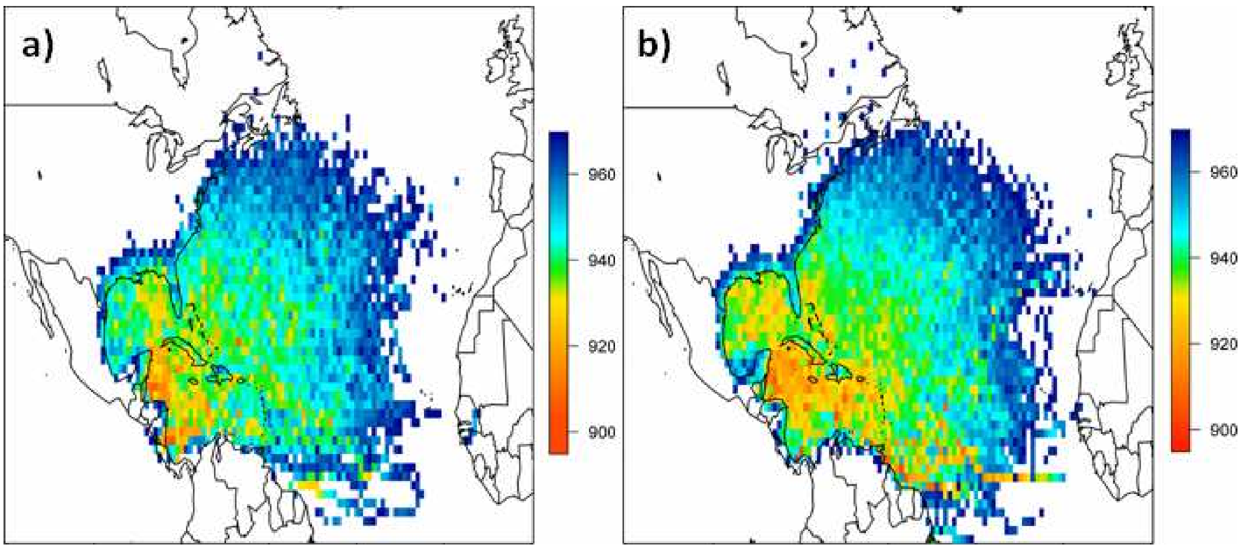

Fig. 5. 95th percentile of central pressure in $1^0 x 1^0$ latitude-longitude bins for the a) historical scenario and b) warm scenario.

Increased hurricane intensity in the Atlantic translates to increased intensity at landfall. Figure 6 shows the distribution of central pressure at landfall for all regions in the historical and warm scenarios. It can be seen the distribution has shifted towards higher intensities.

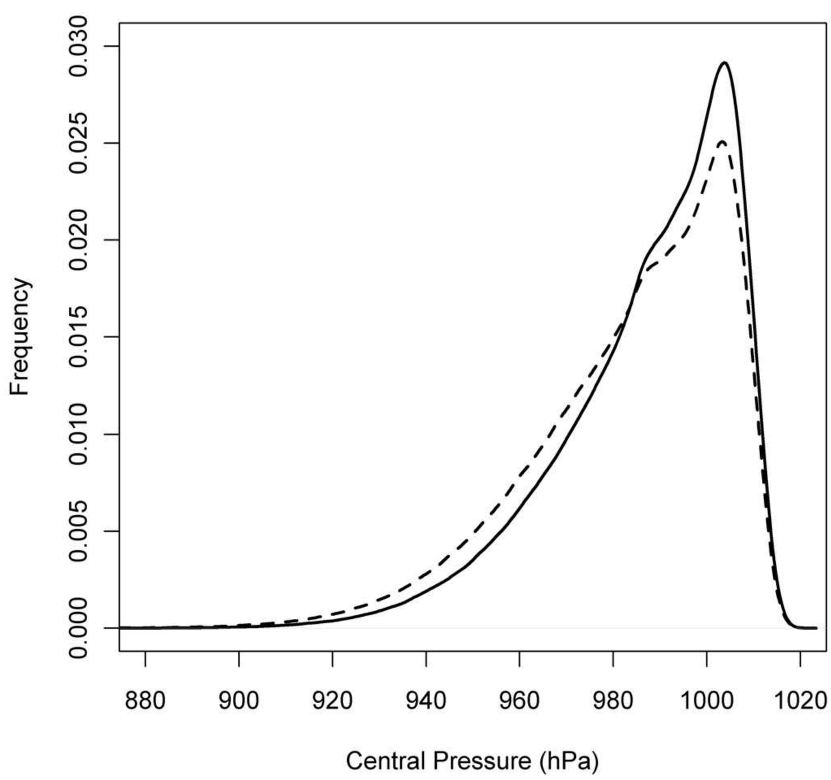

Fig. 6. Distribution at landfall of central pressure for all regions in the historical scenario (solid line) and warm scenario (dashed line).

Overall, central pressure at landfall shifts towards lower pressure in the warm scenario. However, it was seen in Figure 6 that there was basin-wide regionalization to the intensity increases; therefore, regionalization in landfall intensity can be expected. Table 2 gives the mean, 5th and 95th percentile of maximum 1 minute sustained, 10 meter height wind speed at landfall (maximum wind speed is strongly correlated with damage and storm surge height) for the regions in Figure 1. Regional patterns in percentage increases in intensity are similar to the patterns of frequency increases (Fig 2). There is no change in the 95th percentile of wind speed in Region 1, Texas, and only a 3% increase in the northeast of the United States. Atlantic Florida, Central America and the Caribbean experience the largest changes in the 95th percentile in the warm scenario, ranging from 5% to 8% increases. The pairing of frequency and intensity increases in the warm scenario is expected, since it was shown (Fig. 3) that the regionalization changes are driven by a shift in genesis density to the MDR, especially the eastern MDR. These Cape Verde storms hit Atlantic Florida, Central America and the Caribbean the most frequently, spend the longest time over warm, tropical water and have the highest wind speeds.

	Historical (m s^{-1})			Warm (m s^{-1})			Percentage Change (m s^{-1})		
	5th Percentile	Mean	95th Percentile	5th Percentile	Mean	95th Percentile	5th Percentile	Mean	95th Percentile
Region 1	15	33	57	16	32	57	7%	-3%	
Region 2	15	31	55	15	33	58		6%	5%
Region 3	13	31	56	14	33	59	8%	6%	5%
Region 4	13	32	58	14	35	61	8%	9%	5%
Region 5	14	29	51	14	31	53		7%	4%
Region 6	11	24	40	12	24	41	9%		3%
Central America	14	32	61	14	34	65		6%	7%
Caribbean	13	32	60	13	35	65		9%	8%
Bermuda	14	30	52	14	32	54		7%	4%
Canada	12	22	33	12	23	34		5%	3%

Table 2. Mean, 5th and 95th percentile of peak wind speed at landfall by region for the historical and warm scenarios. The percentage change in the warm scenario compared to the historical scenario is given.

4. Summary and conclusions

An experiment was performed using a stochastic Atlantic hurricane model with main development region (MDR) and tropical Indo-Pacific (IP) sea surface temperatures (SSTs) as predictors. The model has genesis, track displacement and intensity components fit to these predictors using historical data. The stochastic model was run once using historical values of the SST predictors and then again using a forecast of SSTs for the period 2010-2014.

Regionalization changes in landfall rate in the warm scenario compared to the historical scenario were shown (Fig. 2). The largest increases in landfall rate were for the major hurricanes (categories 3-5). Increased rates were found everywhere in the warm scenario but they were particularly high in the Caribbean, Central America and Atlantic Florida. This pattern of rate increases was shown to be owing to an increase in MDR originating storms, particularly the easternmost Cape-Verde type storms, compared to other types (Fig. 3). For some regions there was a smaller increase in landfall rate, including the United States' Texas and northeastern coasts. These regions receive a smaller percentage of landfalls from MDR and Cape Verde originating storms in the warmed and historical runs but receive more of their landfalls from storms having genesis in the Gulf of Mexico in the case of Texas and from the north Caribbean Sea in the case of the northeast. Both the Gulf of Mexico and north Caribbean Sea were shown to be decreasing in genesis density in the warm scenario (Fig. 3).

Changes in the intensity distribution of hurricanes in the warm scenario were also examined. Intensities were found to be increasing in the warm scenario compared to the historical scenario, especially in the Gulf of Mexico and Caribbean Sea (Fig. 5). Local SSTs act to increase hurricane intensity and in addition, a shift in genesis density towards the eastern MDR gives storms a longer period over water, increasing the time over which they have to intensify. This was found to have a consequence on both the distribution of central pressure (Fig. 6) and on wind speeds at landfall (Table 2). The geographic pattern of intensification follows that of the landfall rate pattern. The largest intensifications in mean wind speed at landfall are in Atlantic Florida, the southeastern United States and the Caribbean. These areas are particularly vulnerable to intense MDR and Cape Verde storms and are shown by our stochastic model to be at the highest risk of hurricane damage.

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This book represents recent research on tropical cyclones and their impact, and a wide range of topics are covered. An updated global climatology is presented, including the global occurrence of tropical cyclones and the terrestrial factors that may contribute to the variability and long-term trends in their occurrence. Research also examines long term trends in tropical cyclone occurrences and intensity as related to solar activity, while other research discusses the impact climate change may have on these storms. The dynamics and structure of tropical cyclones are studied, with traditional diagnostics employed to examine these as well as more modern approaches in examining their thermodynamics. The book aptly demonstrates how new research into short-range forecasting of tropical cyclone tracks and intensities using satellite information has led to significant improvements. In looking at societal and ecological risks, and damage assessment, authors investigate the use of technology for anticipating, and later evaluating, the amount of damage that is done to human society, watersheds, and forests by land-falling storms. The economic and ecological vulnerability of coastal regions are also studied and are supported by case studies which examine the potential hazards related to the evacuation of populated areas, including medical facilities. These studies provide decision makers with a potential basis for developing improved evacuation techniques.

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