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Sensitivity of Limiting Hurricane Intensity to SST in the Atlantic from Observations and GCMs

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ABSTRACT

A statistical model for the intensity of the strongest hurricanes has been developed and a new methodology introduced for estimating the sensitivity of the strongest hurricanes to changes in sea surface temperature. Here, the authors use this methodology on observed hurricanes and hurricanes generated from two global climate models (GCMs). Hurricanes over the North Atlantic Ocean during the period 1981–2010 show a sensitivity of $7.9 \pm 1.19\,\mathrm{m\,s^{-1}\,K^{-1}}$ (standard error; SE) when over seas warmer than 25°C. In contrast, hurricanes over the same region and period generated from the GFDL High Resolution Atmospheric Model (HiRAM) show a significantly lower sensitivity with the highest at $1.8 \pm 0.42\,\mathrm{m\,s^{-1}\,K^{-1}}$ (SE). Similar weaker sensitivity is found using hurricanes generated from the Florida State University Center for Ocean–Atmospheric Prediction Studies (FSU-COAPS) model with the highest at $2.9 \pm 2.64\,\mathrm{m\,s^{-1}\,K^{-1}}$ (SE). A statistical refinement of HiRAM-generated hurricane intensities heightens the sensitivity to a maximum of $6.9 \pm 3.33\,\mathrm{m\,s^{-1}\,K^{-1}}$ (SE), but the increase is offset by additional uncertainty associated with the refinement. Results suggest that the caution that should be exercised when interpreting GCM scenarios of future hurricane intensity stems from the low sensitivity of limiting GCM-generated hurricane intensity to ocean temperature.

1. Introduction

Assessment of possible future changes to tropical cyclone activity is important for society. Estimates of the sensitivity of hurricane strength to ocean heat are needed to better understand how fierce hurricanes might become in the future. Maximum intensities are increasing, especially over the warming Atlantic Ocean (Elsner et al. 2008), but estimates of sensitivity based on time series data are not precise enough. Sensitivity estimates for the most intense hurricanes are made using quantile regression (Elsner et al. 2008); however, because the variation of sea surface temperature (SST) over time is rather small, it is difficult to obtain a precise value. Studies using paired values of intensity and SST (Evans 1993; DeMaria and Kaplan 1994; Emanuel 2000, 2007) might also be limited because most pairs come from hurricanes in environments that are less than dynamically optimal.

Because a strong hurricane is more likely, on average, to be in a dynamically optimal environment, Elsner et al. (2012) developed a method for estimating the sensitivity of the strongest hurricanes to changes in SST. The methodology uses a spatial tessellation of the hurricane track data and a statistical model for the limiting intensity. The present paper differs from Elsner et al. (2012) in that we apply the method to observed and GCM-generated hurricane data in order to make comparisons of the sensitivity of limiting hurricane intensity with SST. Results indicate significantly lower sensitivity in GCM data.

The paper is outlined as follows: In section 2, we briefly describe the observed and modeled data used in the study. In section 3, we outline the methodology. We show the spatial tessellation and define limiting

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hurricane intensity. In section 4, we give the results making a comparison of the estimated sensitivity from observed and modeled cyclones. In section 5, we provide a summary and a list of the main conclusions.

2. Data

We use observational data from the Atlantic basin hurricane database (HURDAT). Information about these data is available from Jarvinen et al. (1984). The data are available at 6-hourly intervals but have been interpolated to hourly values using the method described in Elsner and Jagger (2013). We use observational data from 1981 to 2010 both because of improved data reliability as a result of satellite coverage and because this is the time period over which the models were run. We find that 69% of all cyclone wind speeds in the North Atlantic over this period are less than $33\,\mathrm{m\,s^{-1}}$.

Model-derived track data are obtained from experiments performed by the Hurricane Working Group of the U.S. Climate Variability and Predictability Research Program (CLIVAR; http://www.usclivar.org/working-groups/hurricane). We use data from two different uncoupled atmospheric GCMs: the Geophysical Fluid Dynamics Laboratory (GFDL) High Resolution Atmospheric Model (HiRAM; Zhao et al. 2009, 2012) and the Florida State University Center for Ocean–Atmospheric Prediction Studies (FSU-COAPS) global spectral model (Cocke and LaRow 2000; LaRow et al. 2008). We apply the same algorithm used on the observations to interpolate the 6-hourly model data to hourly values.

The GFDL HiRAM data are from a control simulation forced with prescribed SST and sea ice concentrations from the Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST; Rayner et al. 2003). We use data from three realizations of the HiRAM that differ only in their initial conditions. The HiRAM has 32 vertical levels and a horizontal resolution of approximately 50 km. A vortical eddy in the model is considered a potential tropical cyclone if it has a local maximum in relative vorticity, a minimum in sea level pressure, and a maximum in the local 300–500-hPa-averaged temperature field (Vitart et al. 2003). The vortex was tracked and classified as a tropical cyclone trajectory if the maximum surface winds exceed $15.2\,\mathrm{m\,s^{-1}}$ during at least 3 days (Zhao et al. 2009).

The FSU-COAPS model, like the GFDL HiRAM, is an uncoupled model forced with SSTs from the HadISST. The FSU-COAPS spectral model has 27 vertical levels and a T126 horizontal resolution, which corresponds to roughly 0.94° of latitude. A detection and tracking algorithm similar to that used with the HiRAM model was employed to extract the track data. As with the HiRAM, we use track data from three realizations of the FSU-COAPS model, differing only in initial conditions.

3. Methodology

The method for estimating sensitivity of hurricane intensity to SST developed in Elsner et al. (2012) involves three steps. Step one tessellates the spatial domain over which hurricanes occur. This is done using a hexagonal grid that better captures the directional variability of hurricane tracks relative to a rectangular grid. The hexagons are constructed in two steps. First the set of hurricane ($33\,\mathrm{m\,s^{-1}}$ or stronger) locations (tenths of a degree latitude/longitude) are projected onto a Lambert conformal conic (LCC) projection (true at 30° and 60°N and centered at 60°W) planar coordinate system. For each hurricane, the raw best-track estimates are 6 h apart so they are interpolated to 1-h intervals using splines and spherical geometry. The area of each hexagon is a compromise between being large enough to capture a sufficient number of hurricanes to reliably estimate model parameters and being small enough that regional variations in maximum intensity are meaningful. The set of hexagons and the number of hurricanes passing through each is plotted in Fig. 1. The red number inside the hexagon indicates the grid ordering starting from the southwestern corner. Only hexagons with at least 15 hurricanes are retained. The area of each hexagon is slightly larger than the state of California.

Step two determines the limiting intensity (LI) in each hexagon grid. This is done by statistically modeling the historical set of wind speeds minus 60% of the forward speed (Emanuel et al. 2006) for hurricanes that passed through each grid. The statistical model combines a generalized Pareto distribution (GPD) with a Poisson distribution to give an estimate of the LI from a set of hurricane wind speeds (Jagger and Elsner 2006). A GPD describes the set of the fastest winds above some high intensity threshold. Some years contribute no values to the set and some years contribute two or more. The threshold choice is a compromise between having enough values to estimate the distribution parameters with sufficient precision but not too many that the intensities fail to be described by a GPD. Here, we set the threshold to the 25th percentile wind speed in each grid. The method of maximum likelihood is used to estimate the model parameters. A linear equation of the parameters provides an estimate of the LI. A more complete description of the statistical theory supporting this model is given in Coles (2001). Examples of its application in the field of hurricane climatology are provided in Jagger and Elsner (2006) and Malmstadt et al. (2010).

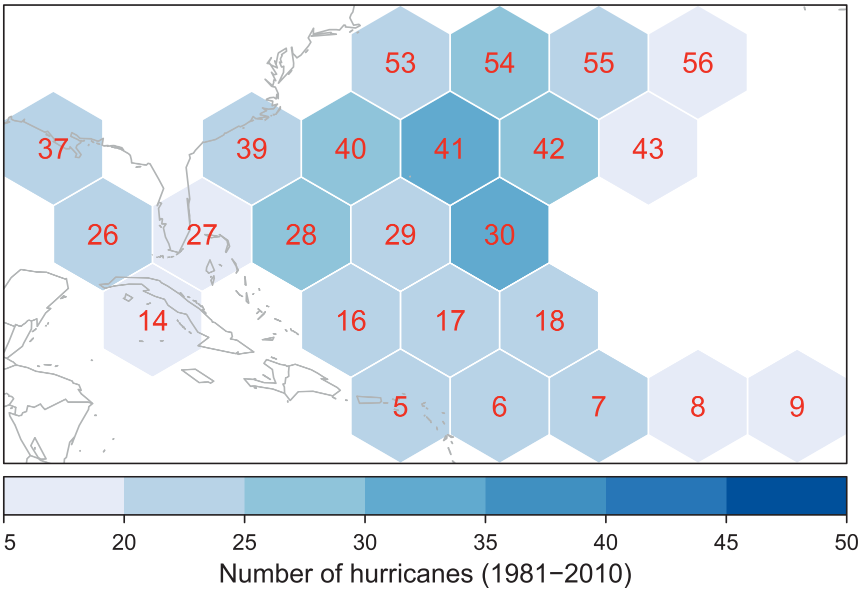

FIG. 1. Hexagon tessellation of the North Atlantic hurricane basin. Each hexagon contains at least 15 hurricanes over the period 1981–2010. The number of hurricanes is given by the color ramp shown along the bottom. The hexagon order is given as a red number inside each grid.

Figure 2 shows the maximum per hurricane wind speeds and a GPD model of them from hexagon 37 over the northern Gulf of Mexico. The threshold wind speed for this grid is 35 m s^{-1} (green line) and the limiting intensity is 75 m s^{-1} (red line). The set of highest intensities in each grid provides the data and extreme-value theory provides the rationale for a statistical model to estimate each grid's LI. Uncertainty on the return level wind speed is shown by the vertical line indicating the 95% confidence interval. For longer return periods the highest intensity is constrained from above by the limiting intensity so the uncertainty is less than for shorter return periods.

Similar GPD models are fit to the wind speeds in each grid. Threshold values range from 26 m s^{-1} in grids along the far northern part of the basin to 44 m s^{-1} for the grid near Hispaniola. The scale parameter indicates

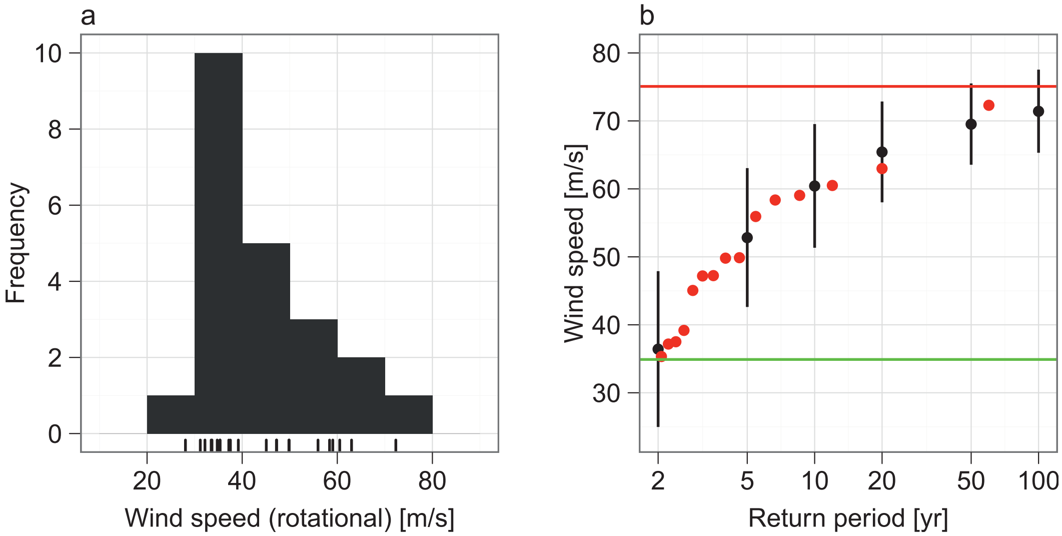

FIG. 2. (a) Histogram of wind speeds where 60% of the forward speed of the hurricane is subtracted from the best-track value (bin width is 10 m s^{-1} beginning at 20 m s^{-1}) and (b) statistical model for the observed maximum per hurricane wind speeds in hexagon number 37 (northern Gulf of Mexico). The model values (black dots) are shown at return periods of 2, 5, 10, 20, 50, and 100 yr. The 95% confidence intervals on these estimates are shown as vertical lines. The red dots are empirical estimates. The green line is the threshold intensity and the red line is the LI.

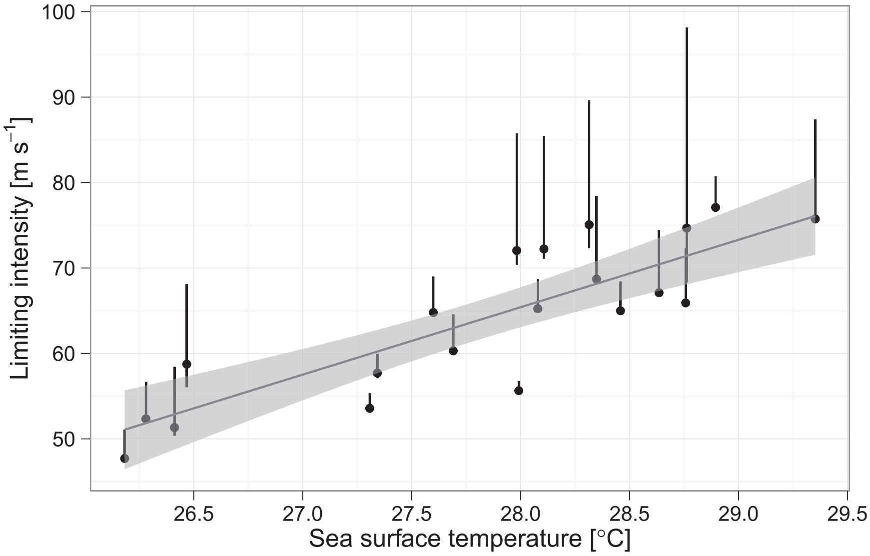

FIG. 3. Limiting hurricane intensity as a function of SST based on the National Hurricane Center (NHC) best track. The line is a weighted regression where the weights are proportional to the number of hurricanes in each grid. The slope of the line is 7.9 m s^{-1} K^{-1} and represents the sensitivity of LI to SST. The 95% confidence band about this slope is shown in gray. The 80% uncertainty about the per grid LI estimates is shown by the vertical lines.

the spread of speeds above the threshold and how fast the cumulative probability function decays for values near the threshold. Larger values indicate slower decay. Spreads are largest in grids over the Caribbean, Gulf of Mexico, and tropical central Atlantic and smallest in grids farther north. The shape parameter describes the behavior of the fastest winds. Limiting intensities are highest over the western Caribbean and Gulf of Mexico where the ocean surface is the hottest. Step three regresses the LI onto the grid-averaged SST. A weighted regression is used that assigns greater weight to grids having more hurricanes. The grid average uses the months of August–October over the period 1981–2010. The correlation between the number of hurricanes and SST is −0.19 (not statistically significant). Details of the procedure are given in Elsner et al. (2012).

4. Results

a. Observed sensitivity

The sensitivity of limiting intensity to SST using the best-track observations is indicated in Fig. 3 (top left). Each point represents the LI–SST pair for a particular hexagon. The slope shows a significant upward trend indicating a sensitivity of 7.9 ± 1.19 m s^{-1} K^{-1} (standard error; SE). The value is close to the estimate of 8.7 m s^{-1} K^{-1} from DeMaria and Kaplan (1994) (inferred from their Fig. 1). The shaded region is the 95% confidence band on the slope estimate.

Sensitivity is a consequence of an increase in the threshold and scale with increasing SST over the range between 25° and 30°C (four grids having SST less than 25°C are removed). However, the shape parameter is largely independent of ocean temperature (see Elsner et al. 2012). In moving over a warmer part of the ocean, the threshold shifts to higher values and there is a greater spread of values above the increasing threshold. Uncertainty levels about the sensitivity estimate assume the regression residuals are spatially uncorrelated. We test this using Moran's I (Moran 1950) with neighbors defined by contiguity and find no evidence of residual spatial correlation. We also find no relationship between LI and distance from the equator after accounting for SST.

We include uncertainty estimates on our values of LI using a bootstrap resampling of the track wind speeds in each hexagon independently. The set of per hexagon per hurricane wind speeds are resampled with replacement 100 times and the model parameters and limiting intensities are re-estimated for each sample. The bootstrap sample of limiting intensities is sorted from highest to lowest and the limiting intensity of the 10th highest (90th percentile) and 10th lowest (10th percentile) are used as a confidence interval. The confidence intervals are shown as vertical lines on the graph. Connecting uncertainty quantiles results in sensitivities that are similar in magnitude to the average sensitivity.

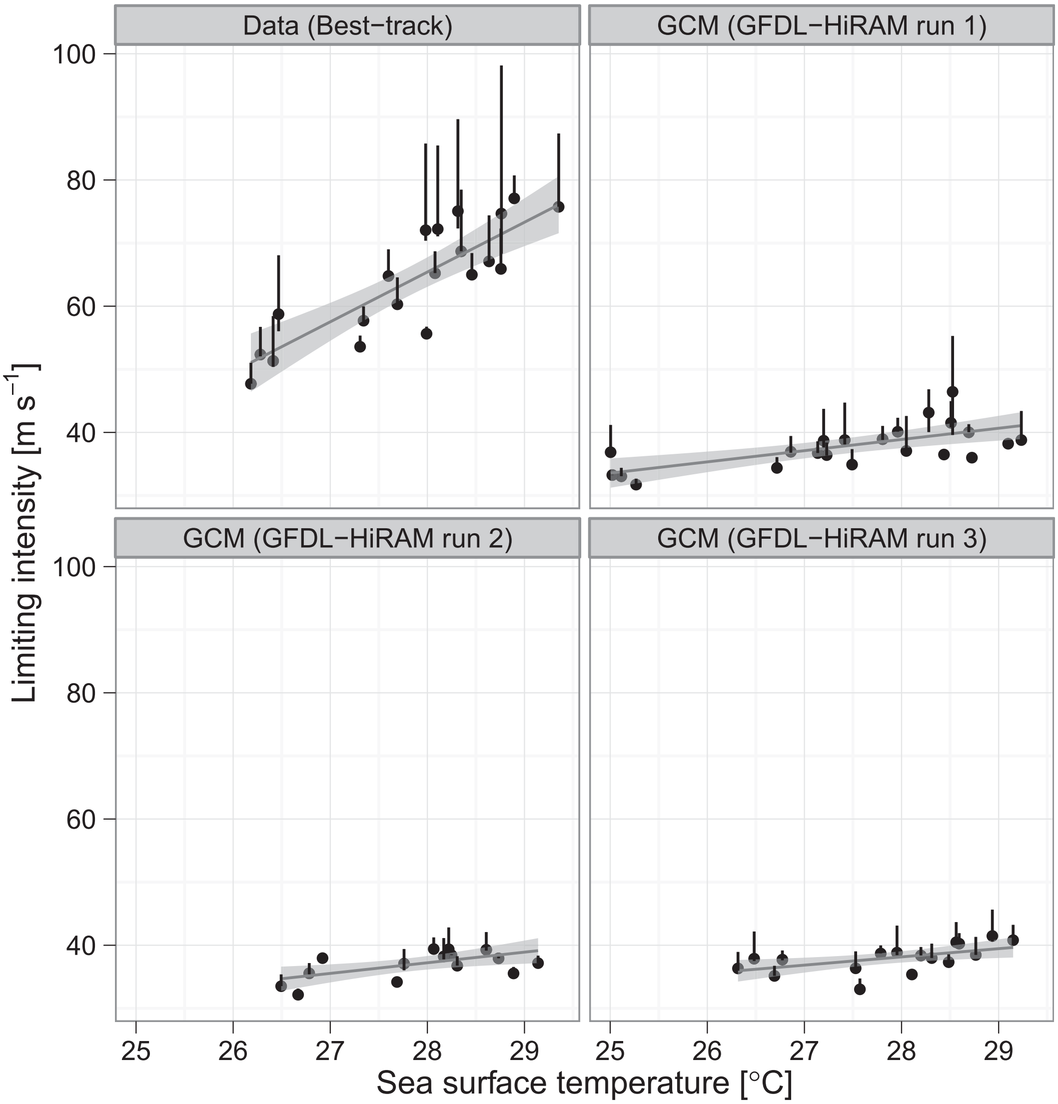

FIG. 4. Limiting hurricane intensity as a function of SST. (top left) Sensitivity computed using the best-track data as in Fig. 3. (top right),(bottom) Sensitivity computed from runs 1 to 3 of the GFDL HiRAM model.

b. Model sensitivity

Next we examine the sensitivity of LI to SST using wind speeds along cyclones tracked in output from two high-resolution GCMs. We obtain cyclone track information from three runs of the HiRAM. The 6-hourly track data from each of the runs are first interpolated to hourly values and projected to LCC coordinates using the same procedure as used on the best-track observations. The 69th percentile wind speed ($\sim 25\,\mathrm{m\,s^{-1}}$) is used as the hurricane threshold to match the percentile used on the observed data. Also 60% of the forward speed is subtracted from the model wind speeds as an estimate of the hurricane's rotational velocity. The same procedure to estimate the LI and its relationship with SST as used on the observed winds is applied to the HiRAM winds from three runs. The results are plotted in Fig. 4 alongside the results from the best-track data.

The slopes indicate a significant sensitivity to SST. The obvious difference is the smaller slopes indicating lower sensitivity of hurricane intensity to SST from the modeled cyclones compared with the observed sensitivity. In run 1 of the HiRAM, the sensitivity amounts to $1.8 \pm 0.43\,\mathrm{m\,s^{-1}\,K^{-1}}$ (SE) or about a quarter of the observed sensitivity. In run 2, the sensitivity is slightly lower at 1.7 and in run 3 it is $1.3\,\mathrm{m\,s^{-1}\,K^{-1}}$. Sensitivity statistics for all runs are listed in Table 1. The mean

TABLE 1. Sensitivity of the limiting hurricane intensity to spatial variations in SST. In the data/model column, r1, r2, and r3 refer to the different runs.

Data/model	Year range	Sensitivity ($\mathrm{m\,s^{-1}\,K^{-1}}$)	SE ($\mathrm{m\,s^{-1}\,K^{-1}}$)	p value	No. hexagon grids
Best-track data	1981–2010	7.89	1.188	<0.001	20
GFDL HiRAM r1	1981–2009	1.78	0.425	<0.001	22
GFDL HiRAM r2	1981–2009	1.68	0.577	0.012	15
GFDL HiRAM r3	1981–2009	1.30	0.464	0.013	17
FSU-COAPS r1	1982–2009	2.86	2.640	0.290	24
FSU-COAPS r2	1982–2009	0.64	0.551	0.258	23
FSU-COAPS r3	1982–2009	0.49	0.372	0.201	21

sensitivity is $1.59\,\mathrm{m\,s^{-1}\,K^{-1}}$. The between run variation is $0.25\,\mathrm{m\,s^{-1}\,K^{-1}}$ giving a standard error of $0.15\,\mathrm{m\,s^{-1}\,K^{-1}}$. This standard error is added to the mean standard error of $0.489\,\mathrm{m\,s^{-1}\,K^{-1}}$ giving a p value of 0.006 as compelling evidence against the null hypothesis that the sensitivity is zero.

In addition, we obtain cyclone track information from three runs of the FSU-COAPS global spectral model.

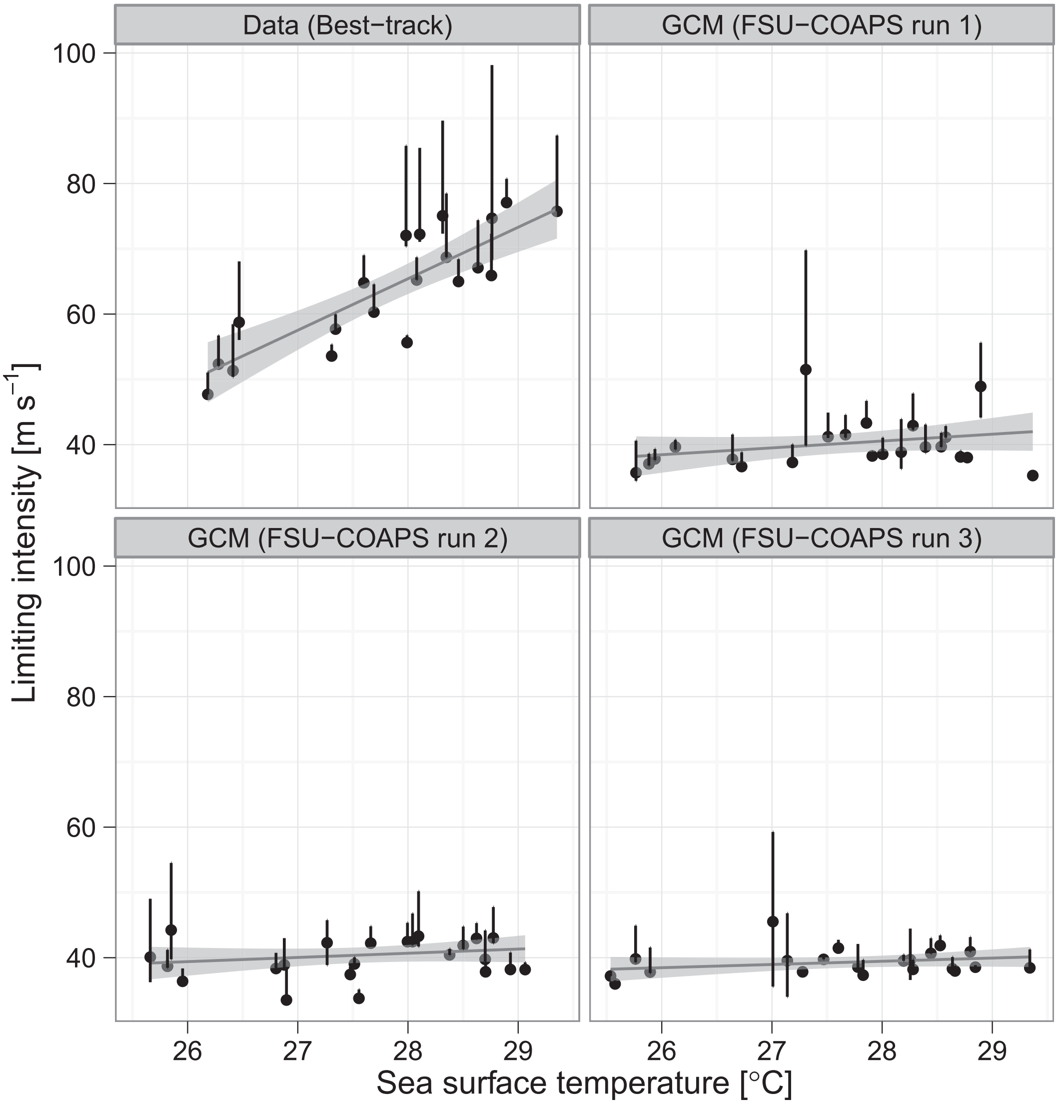

FIG. 5. Limiting hurricane intensity as a function of SST. (top left) Sensitivity computed using the best-track data as in Fig. 3. (top right),(bottom) Sensitivity computed from runs 1 to 3 of the FSU-COAPS model.

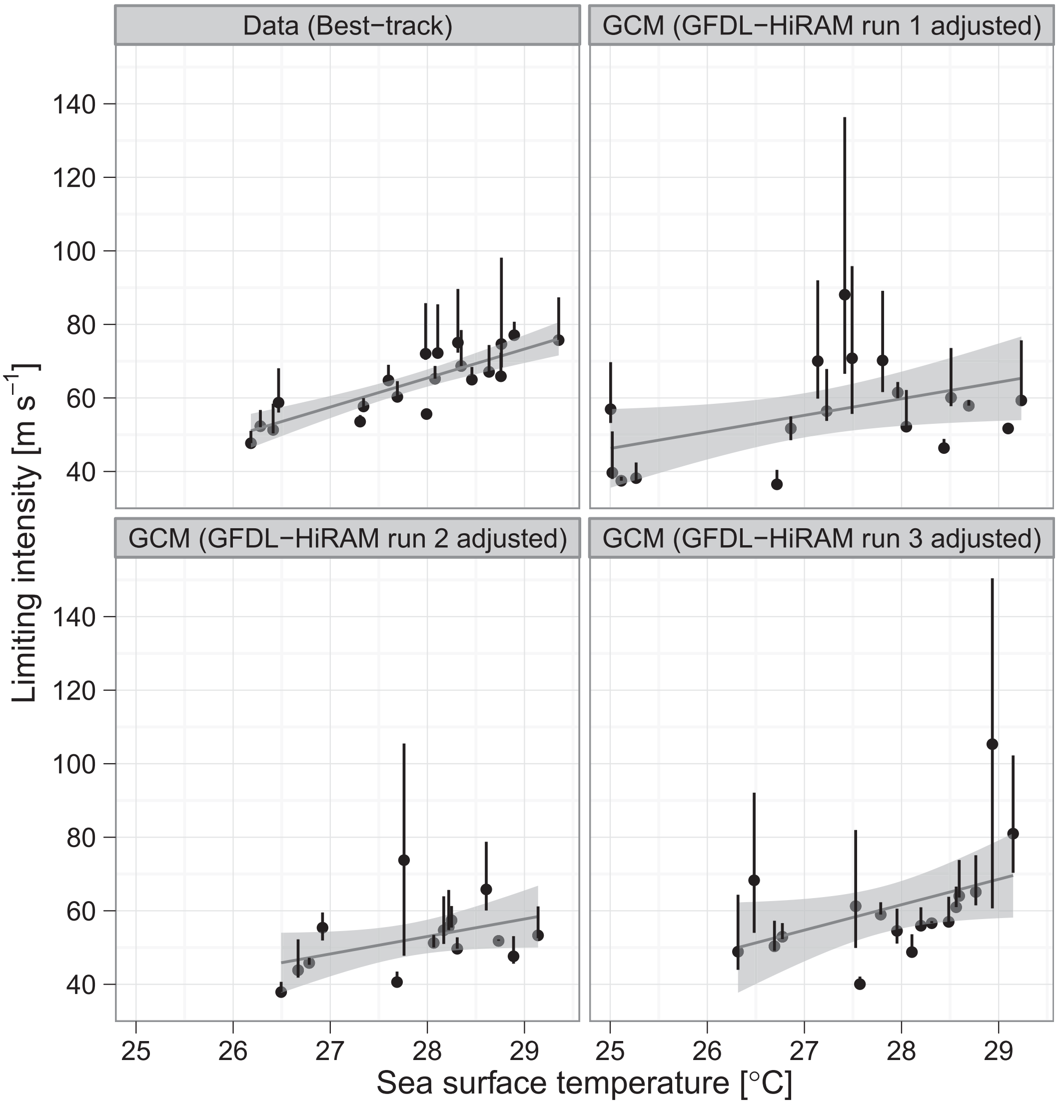

FIG. 6. Limiting hurricane intensity as a function of SST. (top left) Sensitivity computed using the best-track data as in Fig. 3. (top right),(bottom) Sensitivity computed from runs 1 to 3 of the HiRAM model after the winds are adjusted (refined) using the algorithm of Zhao and Held (2010).

The 1982–2009 simulations are forced using the same observed SST. A detection and tracking algorithm similar to that used with the HiRAM model was employed to extract the track data. The results are plotted in Fig. 5 alongside the results from the best-track data. None of the runs show a sensitivity that is statistically distinguishable from zero at the 0.1 level (see Table 1).

Finally we adjust the HiRAM cyclone winds using Eq. (1) in Zhao and Held (2010) to better match the right tail of the distribution of the observed winds. The sensitivity calculations are then repeated for the set of adjusted winds and the results are plotted in Fig. 6. Sensitivity increases but the adjustment adds noise to the relationship so the standard error also increases leading to wider confidence bands. The increased uncertainty is anticipated because the wind speed adjustments are made without direct reference to location or SST. Similar results are noted for all model runs (see Table 2).

TABLE 2. Sensitivity of the limiting hurricane intensity to SST variations using adjusted wind speeds. In the model column, r1, r2, and r3 refer to the different runs.

Model	Sensitivity (m s^{-1} K^{-1})	SE (m s^{-1} K^{-1})	p value
GFDL HiRAM r1	4.51	2.063	0.044
GFDL HiRAM r2	4.75	2.450	0.075
GFDL HiRAM r3	6.92	3.330	0.055

The mean sensitivity over the three runs is 5.39 $\mathrm{m\,s^{-1}\,K^{-1}}$, giving a p value of 0.055 as suggestive but inconclusive evidence against the null hypothesis that the sensitivity is zero.

Lower sensitivity of LI to geographic variations in SST in the GCM runs is not simply because of a shift in tracks as the Elsner et al. (2012) methodology adjusts the spatial domain over which the calculation is made using the available tracks. Rather we speculate that it is because of the inability of a GCM-derived tropical cyclone to operate as an idealized heat engine (dissipative), where the maximum potential intensity is directly related to the underlying ocean heat (Emanuel 1991). This is likely a consequence of the inability of the GCM to resolve the inner-core thermodynamics where heat is converted to work (Michaud 1995).

5. Summary and conclusions

What hurricanes might be like in the future as the climate continues to warm is a topic of considerable social and scientific interest. The sensitivity of hurricane intensity to ocean heat is a key physical link needed to advance understanding of this important topic. A method has recently been developed to estimate the sensitivity using the spatial distribution of cyclone winds and sea surface temperature. Here, we reapply this method to the observed wind speeds from the best-track dataset and then apply it to cyclone track output from two GCMs. These include track data from GFDL HiRAM and FSU-COAPS made available to the Hurricane Working Group of the U.S. CLIVAR program. The code to reproduce the results is available online (at http://rpubs.com/jelsner/1040). The key findings are:

(i) The sensitivity of limiting hurricane intensity to SST is estimated from data to be 7.9 ± 1.19 $\mathrm{m\,s^{-1}\,K^{-1}}$ (SE) when the hurricanes are over seas hotter than 25°C.

(ii) Over similar conditions, the sensitivity of limiting intensity to SST in models where it is significantly different from zero ranges from 1.3 to 1.8 $\mathrm{m\,s^{-1}\,K^{-1}}$ (SE). The lower magnitude results from the lack of sensitivity in the scale parameter. In moving over regions where the ocean is warmer, the distribution of modeled hurricane winds shifts to higher values similar to the observed hurricane winds but, unlike the observed winds, there is no change in the spread of modeled winds above the increasing threshold.

(iii) Sensitivity estimates are positive but statistically indistinguishable from zero using data from the FSU-COAPS model.

(iv) An adjustment to the HiRAM-generated hurricane wind speeds to make them better correspond to the observed wind speed distribution increases the sensitivity of LI to SST. However, the adjustment adds more uncertainty to the sensitivity estimate so the significance against a null hypothesis of no sensitivity decreases.

The SST–intensity relationship described here is derived using spatial data and is not directly relevant to potential changes in hurricane intensity as ocean temperatures continue to warm. However, the finding that the sensitivity of hurricanes to variation in SST is lower in the GCM runs compared with the observations suggests that the sensitivity to temporal changes in SST is also likely to be somewhat muted in projections of future tropical cyclone intensity.

Our study is limited by its sole focus on SST. Air temperature aloft where the heat is vented (outflow temperature) is important for the potential intensity of a tropical cyclone (Bister and Emanuel 1998). Inclusion of a near-tropopause temperature variable would improve the sensitivity estimates as well as their interpretation. Furthermore, our results might be more valuable if ocean heat content was used in place of SST. Nevertheless, this study is important in showing a way to compare observed and modeled cyclone data in a physically meaningful setting.

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