AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2017GL076966

Special Section:
The Three Major Hurricanes of 2017: Harvey, Irma and Maria

Key Points:
- Models with one fourth degree grid spacing or greater should simulate few extreme hurricanes if outer winds are consistent with observations
- Comparison of models across a broad range of resolution is inhibited by the use of maximum wind as a primary evaluation metric

Supporting Information:
- Supporting Information S1

Correspondence to:
C. A. Davis,
cdavis@ucar.edu

Citation:
Davis, C. A. (2018). Resolving tropical cyclone intensity in models. *Geophysical Research Letters*, *45*, 2082–2087. https://doi.org/10.1002/2017GL076966

Received 29 DEC 2017
Accepted 12 FEB 2018
Accepted article online 16 FEB 2018
Published online 23 FEB 2018

Resolving Tropical Cyclone Intensity in Models

C. A. Davis[1]

[1]National Center for Atmospheric Research, Boulder, CO, USA

Abstract In recent years, global weather forecast models and global climate models have begun to depict intense tropical cyclones, even up to category 5 on the Saffir-Simpson scale. In light of the limitation of horizontal resolution in such models, the author performs calculations, using the extended Best Track data for Atlantic tropical cyclones, to estimate the ability of models with differing grid spacing to represent Atlantic tropical cyclone intensity statistically. Results indicate that, under optimistic assumptions, models with horizontal grid spacing of one fourth degree or coarser should not produce a realistic number of category 4 and 5 storms unless there are errors in spatial attributes of the wind field. Furthermore, the case of Irma (2017) is used to demonstrate the importance of a realistic depiction of angular momentum and to motivate the use of angular momentum in model evaluation.

1. Introduction

Global weather prediction models are now capable of resolving many aspects of tropical cyclones, and global climate models are now showing some ability to explicitly model intense tropical cyclones (Murakami et al., 2012; Shaevitz et al., 2014; Wehner et al., 2015). The question we ask is, "What intensity should such models produce given limitations of horizontal resolution?" Here intensity is defined as the maximum 1 min sustained wind at 10 m elevation. Intense tropical cyclones (category 4 or greater on the Saffir-Simpson scale) often have a relatively small inner core. If the radius of maximum wind (RMW) is near to, or smaller than, the grid spacing of the model, one would not expect models to capture storm intensity even in a statistical sense.

Numerous studies have shown that the damage produced by a tropical cyclone, including storm surge, wave damage, and inland flooding, depends both on the radial extent of strong winds and the maximum wind value (Done et al., 2015; Irish et al., 2008; Powell & Reinhold, 2007; Zhai & Jiang, 2014). Hence, it is important to define realistic expectations for the numerical representation of the intensity of tropical cyclones without sacrificing relevant attributes of the outer tropical cyclone wind field.

The physical process that limits intensity in numerical models is perhaps best viewed in terms of angular momentum, $M = rv + \frac{1}{2}fr^2$. As shown by Bryan and Rotunno (2009), strong horizontal mixing limits the inward penetration of angular momentum surfaces, thus limiting the tangential wind speed. Coarser horizontal resolution has qualitatively the same effect as larger horizontal mixing. Models that faithfully represent outer winds, but not the inward penetration of M surfaces, will underestimate the maximum wind, more-so for hurricanes with a tight inner core. A tight inner core characterizes many major hurricanes near their lifetime maximum intensity.

The present paper uses a simple filtering of observed wind profiles computed from Best Track attributes of Atlantic tropical cyclone wind fields to estimate the maximum wind that a given numerical model grid spacing could produce if its outer wind field agrees with observations. This paper does not consider the difficulty of representing physical processes within intense storms or the difficulty of deterministic prediction. In addition to computing Atlantic basin climatological intensity distributions based on different resolution and filtering assumptions, this study uses observations and forecasts of hurricane Irma in 2017 as a specific example where evaluation of the maximum wind can lead to erroneous conclusions about forecast quality.

2. Data and Methods

2.1. Wind Data and Averaging

In order to provide some quantitative expectations for the intensity distribution of Atlantic storms produced in models, we employ an algorithm that completes the inner core wind profile for observed storms, and then computes the maximum intensity of observed storms subject to averaging of their wind profiles over a prescribed length scale that is related hypothetically to a model grid spacing. The result of spatial averaging provides nothing more than an estimate of the wind averaged over a radial extent *d*, given by

$$\overline{v}(r) = \frac{\int_{r-d/2}^{r+d/2} rv(r)dr}{rd}, \quad (1)$$

The larger the averaging interval *d*, the smaller will be the maximum of $\overline{v}(r)$. This value, $\overline{v}_m$, is always less than the reported maximum wind v_m. In what follows, we describe how the radial profile of wind is computed and how the averaging interval *d* is related to the grid spacing of a model. Given revised estimates of maximum wind after averaging, we construct modified statistical distributions of lifetime maximum intensity.

We use the extended Best Track (EBT) data for the Atlantic basin (Demuth et al., 2006) as the basis for the calculations herein. These data cover the period 1988–2014 in this study. In addition to the maximum wind speed and minimum sea level pressure, the data include the RMW (R_m) and the maximum radial extent of 64, 50, and 34-knot winds within each of four storm quadrants (wind radii). There are well-documented uncertainties in the estimates of wind radii (Landsea & Franklin, 2013). Nevertheless, we assume the wind radii represent reality, although we also explore the importance of uncertainties in these values. We construct a single wind profile for a storm based on wind radii in the quadrant where the 34-knot wind radius is the greatest of any quadrant. Because the wind radii represent the greatest extent of winds of a given strength, and because we choose the quadrant with the greatest radial extent of threshold wind values, we argue that the wind profile thus constructed will provide an upper bound on $\overline{v}_m$.

2.2. Computation of r_m

Of some concern is the fact that the reported RMW, R_m, is not as carefully assessed as the wind radii and is deemed a relatively unreliable estimate. In some instances, R_m is missing or it is larger than one or more of the wind radii. To avoid problems with the reported R_m, we seek an objectively computed r_m given the innermost wind radius.

The computation of r_m requires a wind model for the inner core, of which there are many (Holland et al., 2010). We adopt the solutions presented by Chavas, Lin, and Emanuel (2015) and Chavas and Lin (2016) and focus on the inner region (Emanuel & Rotunno, 2011) as a means to extend the wind radius observations inward toward the hurricane center. This wind profile is obtained from

$$M(r) = \frac{2M_m}{1 + \frac{r_m^2}{r^2}} \quad (2)$$

where the subscript "*m*" refers to the radial location of the maximum wind and we have assumed that the ratio of enthalpy and momentum exchange coefficients is unity. The advantages of (2) over other wind models are that it derives from a solution of the steady state equations for a tropical cyclone, has a relatively simple form, and is phrased in terms of angular momentum, which is a key variable for understanding the effects of limited resolution.

Because the maximum wind speed, v_m, is relatively well known, r_m can be computed from (2) if *M* is known at some radius, r_a. In this case, r_a is the innermost nonzero wind radius. For hurricanes, $M_a = v_{64}\, r_{64} + \frac{1}{2} f r_{64}^2$, where *f* is expressed in hr^{-1}. More generally:

$$r_m = \frac{v_m - \sqrt{v_m^2 - \left(v_a^2 - \frac{r_a^2 f^2}{4}\right)}}{\frac{v_a}{r_a} - \frac{f}{2}}, \quad (3)$$

where r_a and v_a represent the innermost wind radius and wind threshold present.

We define a radial profile of 10 m wind that combines v_m, r_m, and the wind radii present. From $r = 0$ out to the innermost wind radius, (2) provides the wind profile. Beyond the innermost wind radius, a power law is fit to the outer wind radii such that $v = v_0 \left(\frac{r_0}{r}\right)^{\alpha}$, where $\alpha = \frac{\ln \frac{v_1}{v_0}}{\ln \frac{r_0}{r_1}}$ and subscripts 0 and 1 refer to

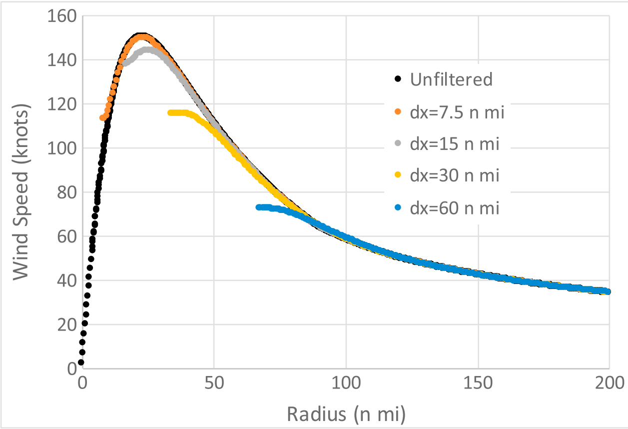

Figure 1. Reconstructed wind profile for Hurricane Katrina (black) and filtered profiles at different hypothetical grid spacing (colors). Winds are in knots, radius in nautical miles (n mi). For filtered profiles, the innermost point represents the center of the innermost averaging interval.

either the 64- and 50-knot wind radii, respectively, or to the 50- and 34-knot wind radii, respectively. Beyond the 34-knot wind radius, which exists for all storms in the data set, α is set to 0.5.

2.3. Defining the Filter Scale

In order to estimate a lower bound of the effects of finite numerical model resolution on the climatology of tropical cyclone intensity, we relate the averaging interval d to the resolved horizontal scales in a hypothetical model in Cartesian coordinates. Regional and global models have varied approaches for filtering the atmospheric spectrum. Here we consider how the cylindrical coordinate of tropical cyclone observations maps onto a Cartesian grid. To simplify matters, we consider the area A bounded by a ring of width d, the averaging interval, within a storm quadrant: $A = \pi rd/2$. We then equate the area A with the area over which the flow may be assumed roughly constant in a model, that is, over scales smaller than the filter scale of the model. The latter is not the area of grid cell within a model. Rather, it is a multiple of the grid cell area that is defined by the filter properties of the model and is generally a combination of grid spacing and numerical and physical dissipation.

For a filter scale F, representing the minimum wavelength in one dimension that contains significant energy, we may assume that the model fields capture essentially no variability over a length of $F/2$. In most grid point models, the filter scale is at least six grid lengths (Skamarock, 2004), and sometimes, it is far greater. Here we make the assumption that the filter completely removes 2-Δx variability while leaving $4\Delta x$ variations undamped. While such a filter in grid-point models is not realizable in practice, this provides a lower bound on the filter scale. Under these assumptions, we define an area of $4\Delta x^2$ that physically represents the area over which no variation occurs. Equating this area with A yields $d = 8\Delta x^2/\pi r$. Thus, the averaging interval is an inverse function of distance from the storm center. Physically, this means that more grid cells can fit into a ring of a given width at a larger radius. We define $\bar{v}_m$ as the maximum wind obtained from all averaging intervals $d(r)$ in the range from r = 0 to 300 n mi. To cover this range of radii, we slide the inner edge of the averaging interval outward in 1 n mi increments for each successive average.

An example of a reconstructed wind profile and filtered profiles for several hypothetical grid spacing values appear in Figure 1 for Hurricane Katrina at its lifetime maximum intensity. The filtered maximum winds for grid spacing values of 0.125, 0.25, 0.5, and 1° are 149, 144, 115, and 72 knots, respectively. This result indicates that Katrina could be simulated, in principle, on a one fourth-degree grid, but not on a one half-degree grid.

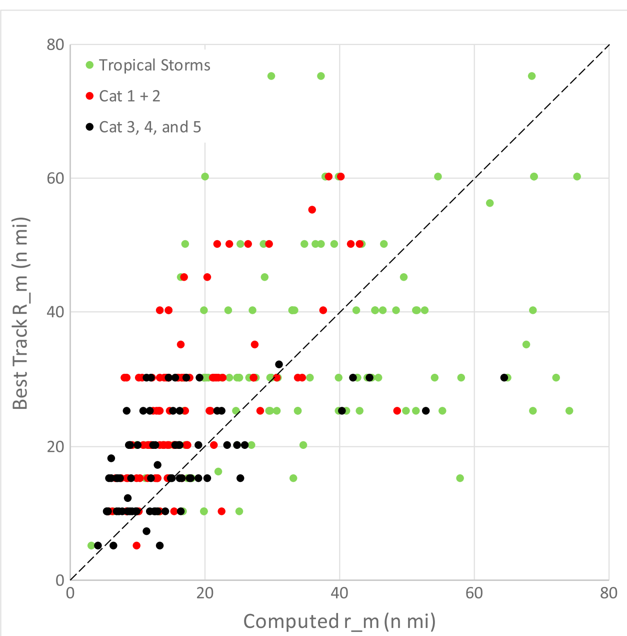

Figure 2. Computed versus Best Track radius of maximum wind (RMW) at the lifetime maximum intensity for all storms in the sample (where the RMW is less than 80 n mi). See text for method of computation.

3. Results

3.1. Climatological Aspects

The computed r_m is compared to the reported R_m for all storms in the EBT at their lifetime maximum intensity (Figure 2). While there is broad agreement, there is also considerable scatter. For major hurricanes (categories 3–5), the two agree better, but with the computed r_m slightly smaller than the reported R_m. We also examined whether there was better agreement from 2000 onward, after scatterometer measurements became routinely available. However, no obvious difference was discernible (not shown).

Applying the filtering described in section 2 to all storms in the EBT results in histograms of lifetime maximum intensity for grid spacing values of 0.125, 0.25, 0.5, and 1 degree of latitude (7.5, 15, 30, and

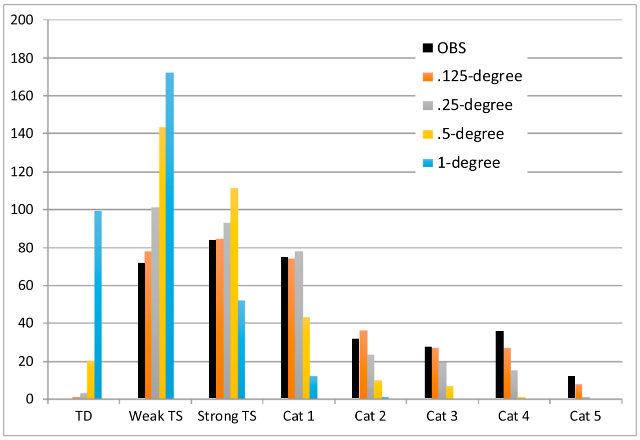

Figure 3. Counts of tropical cyclones in different Saffir-Simpson scale categories for a range of hypothetical grid spacing values.

60 n mi) (Figure 3). Roughly speaking, only for 0.125° is there a reasonable proportion of category 4 and 5 hurricanes remaining in the sample. Also apparent in Figure 3 is that the number of tropical storms plus hurricanes decreases markedly between 0.5 and 1° grid spacing. In the present calculation, a reduction of the "tropical storm" threshold to 25 knots is needed before 95% of observed tropical storms plus hurricanes are retained with a 1° grid spacing.

With realistic filtering, the kinetic energy at $4\Delta x$ falls considerably below what is expected based on power law scaling obtained from observations. The effect of complex dissipation schemes is difficult to capture in the simple framework herein. However, to a first approximation, results for a filter scale of eight grid lengths, compared to four grid lengths, should behave similarly to a doubling of the grid spacing. Thus, results for Δx = 15 n mi may approach results for Δx = 30 n mi when realistic dissipation is taken into account. This implies that major hurricanes in a model with a one fourth-degree grid should occur relatively infrequently compared with their occurrence in the atmosphere, *if* the outer wind profiles are consistent with observations.

Because the theory used in this study is based on axisymmetry, we also devised a method for computing an azimuthal mean wind profile from the EBT data (see supporting information). Filtering this profile following the above methodology results in a similar dependence of intensity on grid spacing, provided that the Saffir-Simpson intensity thresholds are adjusted to account for the effect of azimuthal averaging.

In the entire database considered here, the largest RMW at lifetime maximum intensity for any major hurricane (category 3 or higher) is 32 nautical miles. Hence, a grid spacing close to one eighth degree (7.5 n mi) is probably necessary for a statistical depiction of intense Atlantic hurricanes that preserves a realistic outer wind structure. Even with such resolution, the physical depiction of tropical cyclone dynamics, including the representation of deep convection within the eye wall, is not resolved.

3.2. Forecasts of Hurricane Irma

A useful example, not in the EBT data used for the present study, is Irma from 2017, a category 5 Atlantic hurricane. Irma was extensively reconnoitered, with a large number eye-wall penetrations and resulting estimates of the RMW (Figure 4). In this case, the RMW values computed from (3) generally agree well with the daily median of aircraft estimates of RMW and are slightly smaller than the operational estimates of the RMW. The overestimate of the computed r_m late in the evolution follows a complex interaction of the

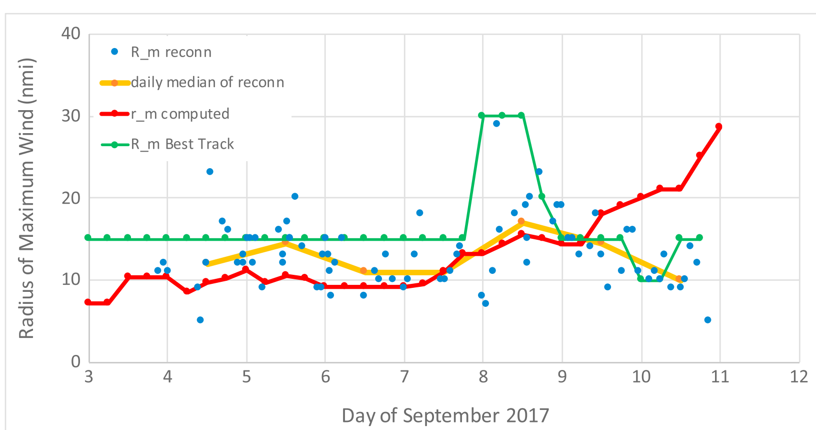

Figure 4. Estimates of the radius of maximum wind (RMW) for hurricane Irma (2017); green: RMW from operational estimates; red: RMW computed from wind model given the maximum wind and radius of hurricane force winds at each time; blue dots: RMW from vortex data messages; yellow: daily median of RMW based on vortex data messages.

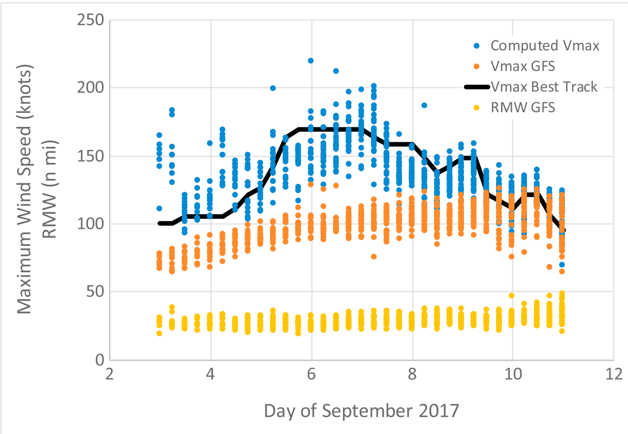

Figure 5. Maximum wind for Irma; black: Best Track; orange: National Centers for Environmental Prediction Global Forecast System (GFS) forecasts obtained from a-deck files; blue: recomputed maximum wind from wind model given the computed radius of maximum wind (RMW) and angular momentum at the RMW of the GFS; yellow: RMW in the GFS.

storm with Cuba, which almost certainly violates the assumption of nearly steady state behavior. However, the present study is mainly concerned with lifetime maximum intensity, at which time the maximum wind is at least temporarily not changing. Irma's lifetime maximum intensity of 160 knots is maintained for over 24 hr (Figure 5), and during this time, the computed r_m agrees with the aircraft data particularly well.

We examine forecasts of hurricane Irma from the operational Global Forecast System (GFS) from the National Centers for Environmental Prediction. The GFS has a grid spacing of roughly 13 km (7 n mi). Examining all forecasts begun on 1 September or later, as a function of valid time reveals that the GFS significantly underestimates the intensity of Irma around the time of its lifetime maximum intensity, and it produces more realistic forecasts of maximum wind late in the storm evolution as it approached Florida on 10 September (Figure 5). The intensity forecasts for each valid time were rather tightly clustered. While not indicated directly in Figure 5, there was no trend of improved intensity with decreasing lead time for the period 6–7 September when Irma attained its greatest maximum wind. The fact that intensity was highly underestimated, and the underestimate was insensitive to forecast length, suggests that the error may represent a fundamental limitation of the model in this case. Recall that the RMW for Irma was generally 10–15 n mi near its maximum intensity. The RMW for the GFS forecasts was consistently 25–40 n mi. Hence, it is clear that the GFS should not be expected to capture the peak intensity of Irma with a realistic wind structure.

What is less clear is whether the GFS forecasts may be considered reasonable given resolution limitations. To address this issue, we use the wind model from (2) to estimate the maximum wind that would have been produced if the GFS was able to contract the inner core of Irma to its observed RMW. For this purpose, we use the "observed" RMW computed from (3) and the angular momentum of the GFS at its own RMW:

$$v'_{mG} = \frac{M_{mG}}{2r_m}\left(\frac{r_m^2}{r_{mG}^2} + 1\right) - \frac{1}{2} f r_m, \tag{4}$$

where subscript "*G*" refers to the GFS. For each forecast at each valid time, the modified maximum wind is computed. Near the lifetime maximum intensity, the values are not far from the observed intensity (Figure 5). This result suggests that the GFS wind profile at this time was largely consistent with observations and that the underestimate of intensity could be explained to first order simply by limitations of horizontal resolution and dissipation.

A note of caution extends to GFS forecasts after September 9. While the maximum wind values were close to the Best Track values, and to the reconstructed maximum wind values, this agreement was fortuitous. The predicted storm structure departed significantly from observations in forecasts of more than 2 days lead time. The predicted radius of hurricane force winds on 10 September was nearly twice the observed estimate and the minimum pressure was as low as 878 hPa, compared to the lowest observed pressure on 10 September of 931 hPa.

4. Conclusions

An assumed upper bound on the ability of models with relatively coarse grid spacing to represent hurricane intensity has been computed using observations of Atlantic tropical cyclones from 1988 to 2014. The present results suggest that models with grid spacing of one fourth degree or coarser should seriously underestimate the number of category 4 or 5 storms if they maintain outer wind radii consistent with observations. Conversely, a realistic number of predicted intense hurricanes would indicate errors in the outer wind structure, perhaps that wind fields are too broad. Results consistent with the findings herein have been realized in practice (Manganello et al., 2012) and are broadly consistent with the findings from the U.S. Climate Variability Hurricane Working Group (Walsh et al., 2015).

We showed an example from hurricane Irma in which forecasts from the operational GFS produced maximum winds far below the observed values near the time of Irma's peak intensity. However, it was shown that the winds produced by the GFS were consistent with observations once the limited resolution was taken into account. Moreover, better forecasts of maximum wind later in the evolution of Irma occurred at the expense of serious errors in outer wind structure.

The above is further evidence that assessing hurricane representations in models using the maximum sustained wind is not optimal. Alternative metrics have been suggested such as surface pressure deficit or integrated kinetic energy (Powell & Reinhold, 2007). The surface pressure deficit varies like the square of the maximum wind and therefore may not be ideal. The integrated kinetic energy (in two or three dimensions) may be useful but is a somewhat ad hoc metric. We suggest that the radially integrated difference in angular momentum between the simulated and observed storm may be more indicative of important errors in the storm wind field than other metrics. Such a metric is physically based and emphasizes the outer winds in a way that would allow meaningful comparisons of models with widely differing horizontal resolution. We acknowledge that meaningful verification is not accomplished with a single metric. A useful goal would be to establish a small number of relatively independent metrics that relate to the hazards posed by hurricanes and would be applicable to weather and climate simulations alike.

Acknowledgments
The National Center for Atmospheric Research is sponsored by the National Science Foundation. The author acknowledges the comments of James Done and Colin Zarzycki of NCAR on an earlier version of the manuscript. The opinions expressed herein do not reflect the views of the National Science Foundation. The program and data used to produce the results presented herein may be found at http://www2.mmm.ucar.edu/people/davis/files/GRL_2018_Davis.

References

Bryan, G. H., & Rotunno, R. (2009). The maximum intensity of tropical cyclones in axisymmetric numerical model simulations. *Monthly Weather Review*, *137*(6), 1770–1789. https://doi.org/10.1175/2008MWR2709.1

Chavas, D. R., & Lin, N. (2016). A model for the complete radial structure of the tropical cyclone wind field. Part II: Wind field variability. *Journal of the Atmospheric Sciences*, *73*(8), 3093–3113. https://doi.org/10.1175/JAS-D-15-0185.1

Chavas, D. R., Lin, N., & Emanuel, K. (2015). A model for the complete radial structure of the tropical cyclone wind field. Part I: Comparison with observed structure. *Journal of the Atmospheric Sciences*, *72*(9), 3647–3662. https://doi.org/10.1175/JAS-D-15-0014.1

Demuth, J., DeMaria, M., & Knaff, J. A. (2006). Improvement of advanced microwave sounder unit tropical cyclone intensity and size estimation algorithms. *Journal of Applied Meteorology*, *45*(11), 1573–1581. https://doi.org/10.1175/JAM2429.1

Done, J. M., PaiMazumder, D., & Towler, E. (2015). Estimating impacts of North Atlantic tropical cyclones using an index of damage potential. *Climatic Change*, *146*(3-4), 561–573. https://doi.org/10.1007/s10584-015-1513-0

Emanuel, K. A., & Rotunno, R. (2011). Self-stratification of tropical cyclone outflow. Part I: Implications for storm structure. *Journal of the Atmospheric Sciences*, *68*(10), 2236–2249. https://doi.org/10.1175/JAS-D-10-05024.1

Holland, G. J., Belanger, J. I., & Fritz, A. (2010). A revised model for radial profiles of hurricane winds. *Monthly Weather Review*, *138*(12), 4393–4401. https://doi.org/10.1175/2010MWR3317.1

Irish, J. L., Resio, D. T., & Ratcliff, J. J. (2008). The influence of storm size on hurricane surge. *Journal of Physical Oceanography*, *38*(9), 2003–2013. https://doi.org/10.1175/2008JPO3727.1

Landsea, C. W., & Franklin, J. L. (2013). Atlantic hurricane database uncertainty and presentation of a new database format. *Monthly Weather Review*, *141*(10), 3576–3592. https://doi.org/10.1175/MWR-D-12-00254.1

Manganello, J. V., Hodges, K. I., Kinter, J. L., Cash, B. A., MarxT, L., Jung, D. A., et al. (2012). Tropical cyclone climatology in a 10-km global atmospheric GCM: Toward weather-resolving climate modeling. *Journal of Climate*, *25*(11), 3867–3893. https://doi-org.cuucar.colorado.edu/10.1175/JCLI-D-11-00346.1

Murakami, H., Wang, Y., Yoshimura, H., Mizuta, R., Sugi, M., Shindo, E., et al. (2012). Future changes in tropical cyclone activity projected by the new high-resolution MRI-AGCM. *Journal of Climate*, *25*(9), 3237–3260. https://doi.org/10.1175/JCLI-D-11-00415.1

Powell, M. D., & Reinhold, T. A. (2007). Tropical cyclone destructive potential by integrated kinetic energy. *Bulletin of the American Meteorological Society*, *87*, 513–526.

Shaevitz, D. A., Camargo, S. J., Sobel, A. H., Jonas, J. A., Kim, D., Kumar, A., et al. (2014). Characteristics of tropical cyclones in high-resolution models in the present climate. *Journal of Advances in Modeling Earth Systems*, *6*(4), 1154–1172. https://doi.org/10.1002/2014MS000372

Skamarock, W. C. (2004). Evaluating mesoscale NWP models using kinetic energy spectra. *Monthly Weather Review*, *132*(12), 3019–3032. https://doi.org/10.1175/MWR2830.1

Walsh, K. J., Camargo, S. J., Vecchi, G. A., Daloz, A. S., Elsner, J., Emanuel, K., et al. (2015). Hurricanes and climate: The U.S. CLIVAR Working Group on hurricanes. *Bulletin of the American Meteorological Society*, *96*(6), 997–1017. https://doi-org.cuucar.colorado.edu/10.1175/BAMS-D-13-00242.1

Wehner, M., Reed, K. A., Stone, D., Collins, W. D., & Bacmeister, J. (2015). Resolution dependence of future tropical cyclone projections of CAM5.1 in the U.S. CLIVAR hurricane working group idealized configurations. *Journal of Climate*, *28*(10), 3905–3925. https://doi.org/10.1175/JCLI-D-14-00311

Zhai, A. R., & Jiang, J. H. (2014). Dependence of US hurricane economic loss on maximum wind speed and storm size. *Environmental Research Letters*, *9*(6), 0640191. https://doi.org/10.1088/1748-9326/9/6/064019