Supplemental Material

Supplement to North Atlantic tropical cyclone outer size and structure remain unchanged by the late 21st century

Benjamin A. Schenkel,[a,b] Daniel Chavas,[c] Ning Lin,[d] Thomas Knutson,[e] Gabriel Vecchi,[f,g] and Alan Brammer[h]

[a] *Cooperative Institute for Severe and High-Impact Weather Research and Operations, University of Oklahoma, Norman, Oklahoma, USA*

[b] *NOAA National Severe Storms Laboratory, Norman, Oklahoma, USA*

[c] *Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, IN, USA*

[d] *Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ, USA*

[e] *NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA*

[f] *Department of Geosciences, Princeton Environmental Institute, Princeton, NJ, USA*

[g] *Cooperative Institute for Modeling the Earth System, Princeton University, Princeton, NJ, USA*

[h] *Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, CO, USA*

Corresponding author: Benjamin A. Schenkel, benschenkel@gmail.com

1. Introduction

This document provides information about the supplementary figures including: 1) differences in the relationship between TC maximum 10-m winds versus minimum sea-level pressure in the current climate and late 21st century compared to IBTrACS (Fig. S1), 2) changes in lifetime maximum intensity by the late 21st century (Fig. S2), and 3) differences in the latitude of lifetime maximum intensity between the current and late 21st century (Fig. S3).

2. Supplemental Figure S1: TC Wind-Pressure Relationship

Figure S1 of the supplement shows the differences in the relationship between the maximum 10-m wind speed versus the minimum sea-level pressure for TCs from the simulations in this study with IBTrACS. Unlike TC outer size, maximum TC wind speeds in the GFDL hurricane model are defined at a 10-m height. One key difference is that the simulated TCs tend to have lower pressures and broader radii of maximum wind, especially at stronger wind speeds (Knutson et al. 2015; Murakami et al. 2015). This is likely due to the inability to resolve the fine radial pressure gradients associated with a given wind speed since the horizontal grid spacing is not sufficiently fine (Walsh et al. 2007; Davis 2018). As expected, there are also fewer of the most intense TCs in the control simulations consistent with expectations from the horizontal grid spacing (Walsh et al. 2007; Davis 2018). Last, there are fewer than expected TCs with the weakest intensities (i.e., maximum 10-m winds of 35–40 kt), which may be due to the genesis criteria imposed (i.e., ≥24-h with maximum 10-m winds >17.5 m s^{-1}). However, we believe that these simulations are still useful for understanding changes in TC outer size for the reasons given in the manuscript.

3. Supplemental Figure S2: Lifetime Maximum Intensity

Figure S2 of the supplement shows the distribution of lifetime maximum intensity for the TCs from our simulations and IBTrACS. In contrast to TC outer size, most projections show a statistical shift towards stronger intensities in ≥1 distribution statistics by the late 21st century including 7 of the 12 Zetac-downscaling GFDL hurricane model simulations and both the HiFLOR and HiRAM-downscaling GFDL hurricane model simulations. Moreover, several simulations also show ≥2 statistics statistically shifting towards stronger TC intensities indicative of larger changes in the distribution, whereas only the Zetac-downscaling A1B HADGEM1 simulation shows similar

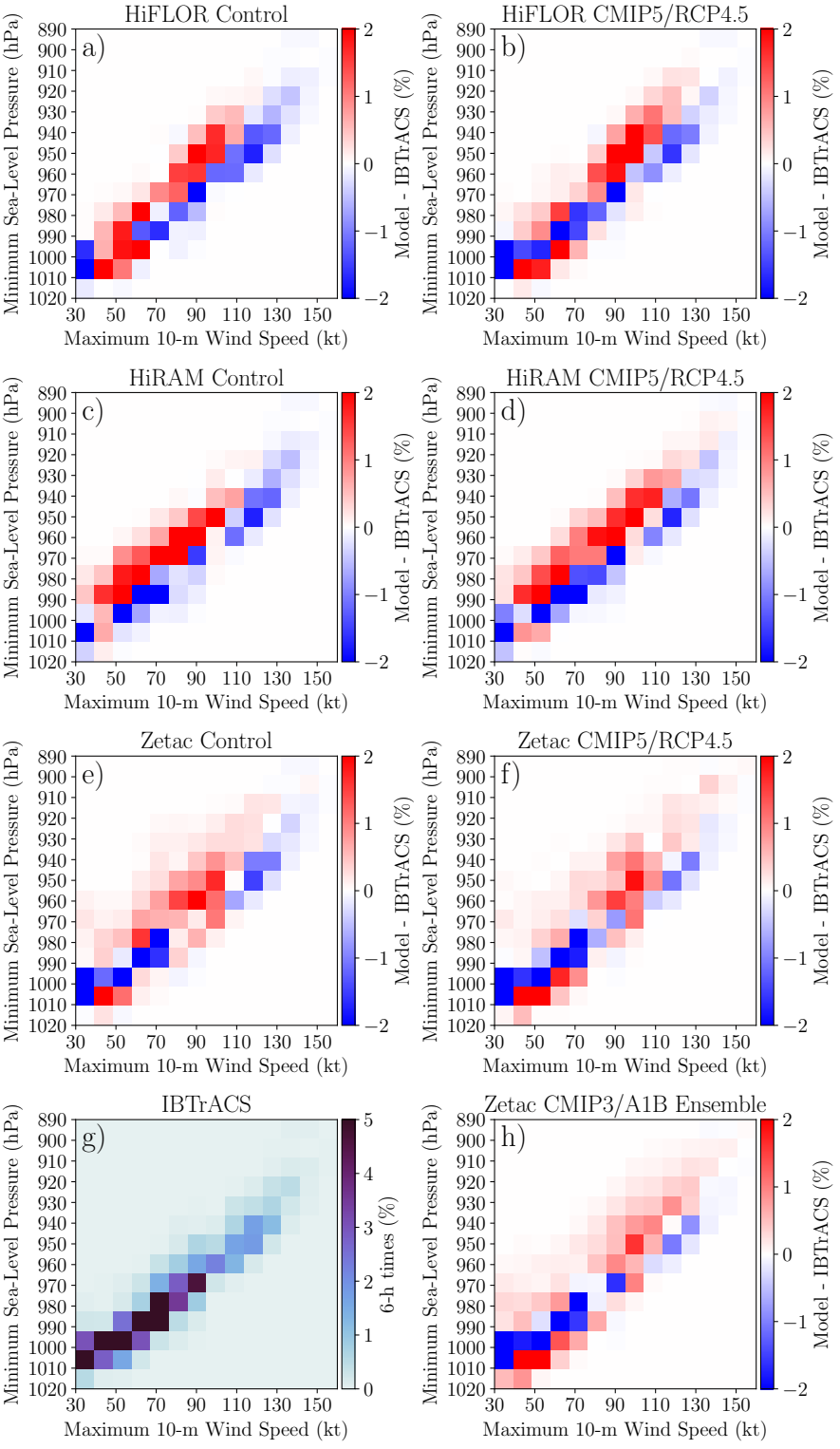

FIG. S1. Joint histogram of maximum 10-m wind (kt) versus minimum sea-level pressure for TCs in (a), (b) HiFLOR, (c), (d) HiRAM-downscaling GFDL hurricane model, (e), (f), (h) Zetac-downscaling GFDL hurricane model, and (g) IBTrACS data. Each set of simulations shows its difference from IBTrACS data.

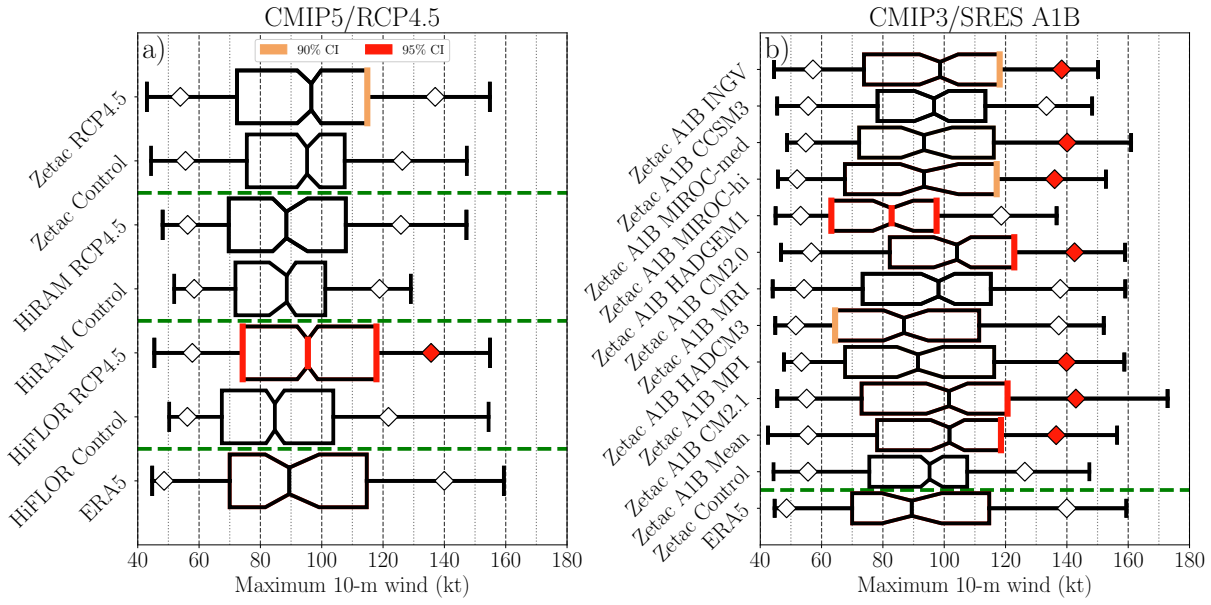

FIG. S2. As in Fig. 1 from manuscript, but for lifetime maximum intensity (kt).

large shifts in TC outer size distributions. Two of the Zetac-downscaling simulations, the A1B HADGEM1 and HADCM3, also show statistical decreases in at least one distribution statistic towards weaker intensities. Comparing the distributions of lifetime maximum intensity (Fig. S2) and lifetime maximum r_8 (Fig. 8 in the revised manuscript), only the Zetac-downscaling A1B HADGEM1 simulation shows strong changes in the same sign for both TC outer size and intensity. Nonetheless, the Zetac-downscaling A1B HADGEM1 simulation is an outlier compared to the other simulations partially due to the large-scale warming of the upper-troposphere temperatures in the Atlantic that is much stronger than the other ensemble members (Knutson et al. 2013, 2022). Together, these results suggest differences in the projected changes in TC intensity and outer size in the simulations.

4. Supplemental Figure S3: Gridded Sample Size of TCs

Figure S3 of the supplement shows the number of 6-h TC track points in each simulation for a 5° longitude × 5° latitude grid. The sample size of 6-h track times is maximized within the subtropics typically within the western or central Atlantic. Figure S3 serves as a reference for the 6-h TC track sample sizes in Figs. 3 and 13 of the revised manuscript.

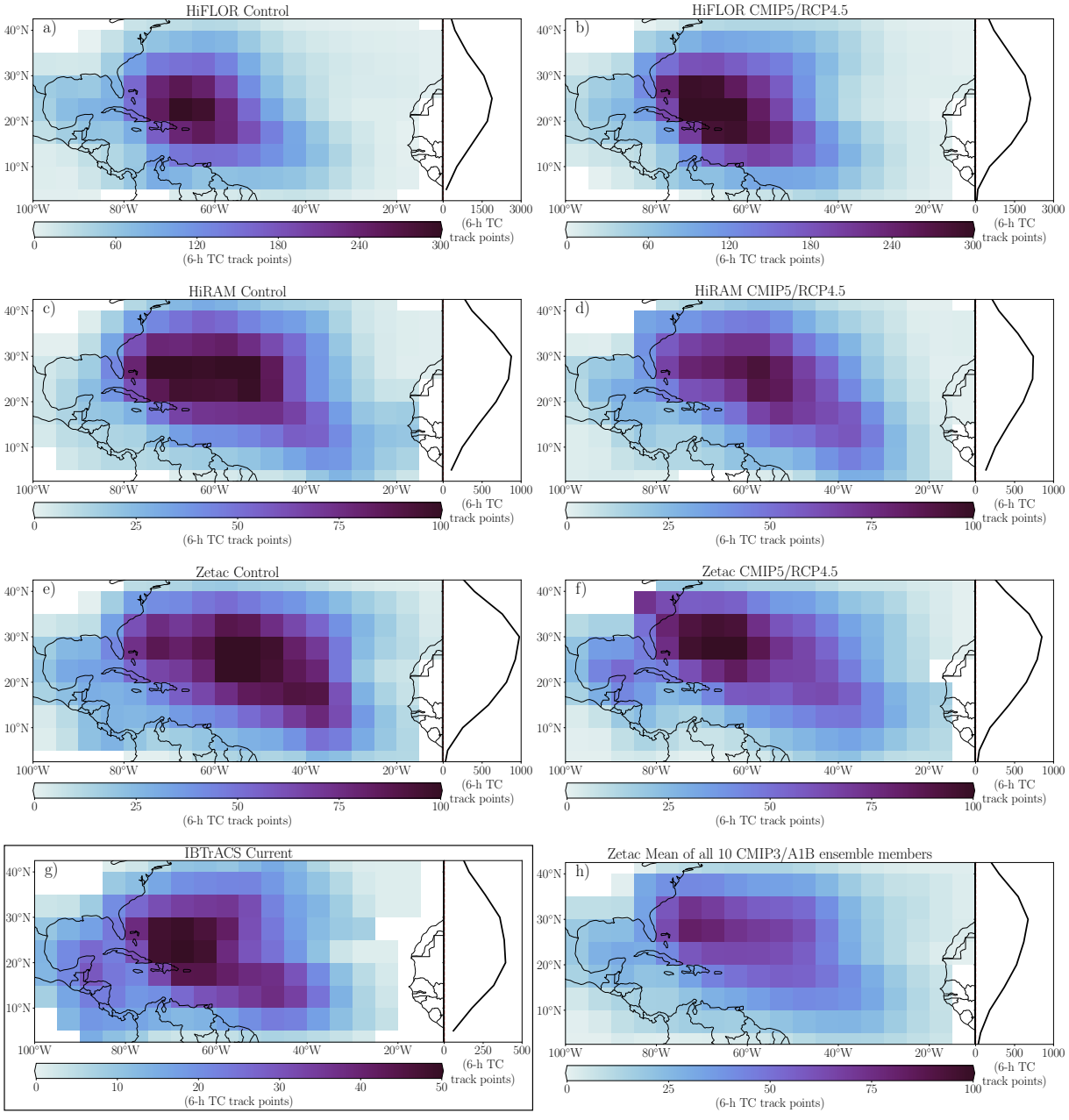
HiFLOR Control
a)
HiFLOR CMIP5/RCP4.5
b)
HiRAM Control
c)
HiRAM CMIP5/RCP4.5
d)
Zetac Control
e)
Zetac CMIP5/RCP4.5
f)
IBTrACS Current
g)
Zetac Mean of all 10 CMIP3/A1B ensemble members
h)
40°N
30°N
20°N
10°N
100°W
80°W
60°W
40°W
20°W
0
(6-h TC track points)

FIG. S3. As in Fig. 3 from manuscript, but for the number of 6-h TC times. The late 21st century simulations shown in panels (b), (d), (f), and (h) show raw values instead of the differences with the control simulation to clearly highlight sample size differences. The colorbar range also differs among the simulations due to the differences in the years or simulation periods used.

References

Davis, C., 2018: Resolving tropical cyclone intensity in models. *Geophys. Res. Lett.*, **45 (4)**, 2082–2087.

Knutson, T., J. Sirutis, M. A. Bender, and R. E. Tuleya, 2022: Dynamical downscaling projections of late 21st century U.S. landfalling hurricane activity. *Climate Change*, **171**, 1–23.

Knutson, T. R., J. J. Sirutis, M. Zhao, R. E. Tuleya, M. Bender, G. A. Vecchi, G. Villarini, and D. Chavas, 2015: Global projections of intense tropical cyclone activity for the late twenty-first century from dynamical downscaling of CMIP5/RCP4. 5 scenarios. *J. Climate*, **28**, 7203–7224.

Knutson, T. R., and Coauthors, 2013: Dynamical downscaling projections of twenty-first-century Atlantic hurricane activity: CMIP3 and CMIP5 model-based scenarios. *J. Climate*, **26**, 6591–6617.

Murakami, H., and Coauthors, 2015: Simulation and prediction of category 4 and 5 hurricanes in the high-resolution GFDL HiFLOR coupled climate model. *J. Climate*, **28**, 9058–9079.

Walsh, K., M. Fiorino, C. Landsea, and K. McInnes, 2007: Objectively determined resolution-dependent threshold criteria for the detection of tropical cyclones in climate models and reanalyses. *J. Climate*, **20**, 2307–2314.