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Tropical Cyclones Tracks in Present and Future Climates

Suzana J. Camargo[1](PI), Adam H. Sobel[1,2], Kerry A. Emanuel[3],
Timothy M Hall[4], James P. Kossin[5]
1 Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY
2 Department of Applied Physics and Applied Mathematics,
Columbia University, New York, NY
3 Massachusetts Institute of Technology, Cambridge, MA
4 NASA Goddard Institute of Space Studies, New York, NY
5 National Oceanic and Atmospheric Administration, Madison, WI

1 Results and Accomplishments

1.1 Overview

The main goal of this research was to improve our understanding of the climate influence on tropical cyclone tracks. In this project our focus was to determine if tropical cyclone tracks could be influenced by climate change, especially due to the most robust projected changes in the tropical circulation. We used various complementary techniques to examine this problem.

We will describe below what was done to accomplish this goal and will list the main resulting publications of this project, which includes a few publications currently in the final stages of preparation. Additional publications that were complementary to this project were listed in the annual progress reports.

1.2 Main Results

In [Camargo, 2013] we tracked and the tropical cyclone-like storms in the CMIP5 multi-model dataset, with a focus in the frequency track changes in the globe, as well as the Atlantic and eastern North Pacific with climate change. Figure 1 shows the mean number of TCs globally in the historical and two future scenarios. We didn't find a consistent signal in the track changes in future climates in the CMIP5 models in these basins. Furthermore, the models generate some tracks types that do not exist in observations, as shown in Fig. 2. Highlights of these results appeared in the the MAPP publications Sheffield et al. [2013] and Maloney et al. [2014].

We showed that genesis indices developed for the current climate have to be modified to explain changes in TC frequency in future climates [Camargo et al., 2014]. In the case of the HiRAM model, only a genesis index that includes the saturation deficit and the and potential intensity as predictors reproduces the reduction of TC frequency in fugure climates as shown in Figs. 3 and 5. We also used the ventilation index developed by Tang and Emanuel [Tang and Emanuel, 2012] to explain the changes in TC frequency in the CMIP5 models [Tang and Camargo, 2014] (Fig. 4).

Co-PI Kerry Emanuel used his dynamic downscaling techniques on the CMIP5 model data and generated tropical cyclone tracks based on the environmental conditions of the CMIP5 models [Emanuel, 2013]. The main result of this paper are (i) the intensity of these downscaled storms increases in the 21st century, in agreement with previous results in the literature (Fig. 6); (ii) in contrast to storms that appear explicitly in the global models, the frequency of downscaled tropical storms increases over the 21st century in most locations (Fig. 7).

Super-storm Sandy had a very unusual track, which was partially responsible for the enormous impact it had over New Jersey and New York. Using Tim Halls statistical track generator technique, co-PIs Timothy Hall and Adam Sobel examined the probability of storms having this rare track. From this synthetic set we calculate that under long-term average climate conditions, a hurricane of Sandys intensity or greater (category 1+) makes NJ landfall at an angle at least as close to perpendicular as Sandys at an average annual rate of 0.0014 yr1; i.e., a return period of 714 years (see Fig. 8). This analysis was published in Hall and Sobel [2013]. Sobel also contributed to a paper that examined if the persistent large-scale patterns that steered Sandy will become more frequent as the climagte warms [Barnes et al., 2013]. Timothy Hall used his sythetic tracks to explore the dependence of North American tropical cyclone landfall on sea surface temperature [Hall and Yonekura, 2013] as well.

Co-PI Jim Kossin showed the poleward migration of the location of the tropical cyclone maximum intensity in Kossin et al. [2014] (see Fig. 9). In a recent follow up study we examined in more detail the poleward migration in the western North Pacific in the past, as well in future projections [Kossin et al., 2016] (Figs. 10 and 11). We have a manuscript in final stages of preparation analyzing if relationship of the environmental fields at genesis with this poleward shift [Daloz and Camargo, 2016].

We examined the ability of climate models to represent North Atlantic tropical cyclone tracks in present and future climates using cluster analysis. Tracks from two types of climate models are evaluated: explicit tracks are obtained from tropical cyclones simulated in regional or global climate models with moderate to high horizontal resolution and downscaled tracks, obtained using a downscaling technique with large-scale environmental fields from a subset of these models. We show that, except for the seasonality, the downscaled tracks better capture the observed characteristics of the clusters (see genesis positions of the downscaled tracks by cluster in Fig. 12. We also use three different idealized scenarios to examine the possible future changes of tropical cyclone tracks. The response to each scenario is highly variable depending on the simulation considered [Daloz et al., 2015], as shown in Fig. 13 for the downscaled tracks. We are currently in the final stages of preparation for two manuscripts that do very similar analysis for the western North Pacific [Nakamura et al., 2016] and southern hemisphere TC tracks [Ramsay et al., 2016].

We also investigated if there was a change in the seasonality of tropical cyclones in future climates, using a global climate model (HiRAM), as well as downscaled tracks [Dwyer et al., 2015]. The downscaled tracks project a longer season (in the late twenty-first century compared to the twentieth century) in most basins when using CMIP5 environmental data but a slightly shorter season using CMIP3. While the HiRAM model forced with either CMIP3 or CMIP5 SST anomalies projects a shorter tropical cyclone season in most basins (see Figs. 14 and 15). Season length is measured by the number of consecutive days that the mean cyclone count is greater than a fixed threshold, but other metrics give consistent results. The projected season length changes are also consistent with the large-scale changes, as measured by a genesis index of tropical cyclones. The season length changes are mostly explained by an idealized year-round multiplicative change in tropical cyclone frequency, but additional changes in the transition months also contribute.

Tim Hall applied the statistical TC track model oanalyze the unprecedented current nine-year period (2005-2013) without major US hurricane landfall [Hall and Hereid, 2015]. By repeat simulations of the period 1950-2013 and counting of simulated droughts of various length we estimated an average weight time of 177 years for a major US landfall drought of nine or more years. However, the rareness of major (category 3 and higher) landfalls and the variations in SST anomalies one year to the next appears to result in no significant inter-annual memory in major US landfall. They concluded that the current drought does not indicate any sustained shift in hurricane landfall characteristics and found no dependence of major US hurricane landfall probability (about 0.38 annually) on drought length.

We contributed to a few review papers and a book chapter related to this project during this grant: Woodruff et al. [13], Camargo and Hsiang [2015], Walsh et al. [2015], Camargo and Wing [2016], Walsh et al. [2016].

2 Highlights of Accomplishments

- Tracked tropical cyclone-like storms in the multi-model CMIP5 simulations and analyzed changes in tracks with climate change [Camargo, 2013]. The CMIP5 models tropical cyclone activity still has large biases compared to observations. There is no consistent signal in the changes in global and regional (Atlantic and eastern North Pacific) TC frequency in future climates among the CMIP5 models

- Downscaled CMIP5 model tracks and their changes with future environmental conditions. The intensity and frequency of the storms is expected to increase in future climates, the frequency increase opposes most other projections [Emanuel, 2013].

- Based on long-term average climate conditions and a statistical model for synthetic Atlantic hurricane tracks, the return period for a hurricane of Sandys intensity or greater (category 1+) to make NJ landfall at an angle at least as close to perpendicular as Sandys is 714 years [Hall and Sobel, 2013].

- Explored the relationship of TC frequency and the large-scale enviroment in future climates using genesis indices [Camargo et al., 2014] and the ventilation index [Tang and Camargo, 2014].

- Poleward shift in the TC location of maximum intensity in the past 30 years, as well as in future projections [Kossin et al., 2014, 2016].

- Analysis of North Atlantic tracks in the US CLIVAR hurricane working group models and downscaled tracks in present and future climates [Daloz et al., 2015].

- Examined changes in tropical cyclone season length using a global climate model and downscaled tracks [Dwyer et al., 2015].

- The current U.S. hurricane drought does not indicate any sustained shift in hurricane landfall characteristics [Hall and Hereid, 2015].

3 Publications

- E.A. Barnes, L.M. Polvani and **A.H. Sobel**, 2013. Model projections of atmospheric steering of Sandy-like superstorms. *Proc. Nat. Acad. Sci.*, **110**, 15211-15215, doi: 10.1073/pnas.1308732110.

- **S.J. Camargo**, 2013. Global and regional aspects of tropical cyclone activity in the CMIP5 models, *J. Climate*, **26**, 9880-9902, doi: 10.1175/JCLI-D-12-00549.1.

- **S.J. Camargo**, M.K. Tippett, **A.H. Sobel**, G.A. Vecchi, and M. Zhao, 2014. Testing the performance of tropical cyclone genesis indices in future climates using the HIRAM model. *J. Climate* **27**, 9171-9196 doi: 10.1175/JCLI-D-13-00505.1.

- **S.J. Camargo** and S.M. Hsiang, 2015. Tropical Cyclones: From the influence of climate to their socio-economic impacts, in *Extreme Events: Observations, Modeling and Economics*, M. Chaves, M. Ghil and J. Urrutia-Fucugauchi, editors, AGU Monograph, Chapter 18, pp. 303-342, Willey-Blackwell, ISBN: 978-1-119-15701-4.

- **S.J. Camargo** and A.A. Wing, 2016. Tropical cyclones in climate models. *WIREs Climate Change*, **7**, 211-237, doi: 10.1002/wcc373.

- A.S. Daloz, **S.J. Camargo**, **J.P. Kossin**, **K. Emanuel**, M. Horn, J.A. Jonas, D. Kim, T. LaRow, Y.-K. Lim, C.M. Patricola, M. Roberts, E. Scoccimarro, D. Shaevitz, P.L. Vidale, H. Wang, M. Wehner, and M. Zhao, 2015. Cluster analysis of explicitly and downscaled simulated North Atlantic tropical cyclone track, *J. Climate*, **28**, 1333-1361, doi: 10.1175/JCLI-D-13-00646.1.

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- **J.P. Kossin**, **K.A. Emanuel**, and G.A. Vecchi, 2014. The poleward migration of the location of tropical cyclone maximum intensity. *Nature*, **509**, 349-352.

- **J.P. Kossin**, **K.A. Emanuel**, and **S.J. Camargo**, 2016. Past and projected changes in western North Pacific tropical cyclone exposure. *J. Climate*, **29**, 5725-5739, doi: 10.1175/JCLI-D-16-0076.1.

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- B. Tang and **S.J. Camargo**, 2014. Environmental control of tropical cyclones in CMIP5: A ventilation perspective.*J. Adv. Model. Earth Sys.*, **6**, 115-128, doi: 10.1002/2013 MS000294.

- K.J.E. Walsh, **S.J. Camargo**, G.A. Vecchi. A.S. Daloz, J. Elsner, **K. Emanuel**, M. Horn, Y.-K. Lim, M. Roberts, C. Patricola, E. Scoccimarro, **A.H. Sobel**, S. Strazzo, G. Villarini, M. Wehner, M. Zhao, **J. Kossin**, T. LaRow, K. Oouchi, S. Schubert, H. Wang, J. Bacmeister, P. Chang, F. Chauvin, C. Jablonowski, H. Murakami, T. Ose, K.A. Reed, R. Saravanan, Y. Yamada, C.M. Zarzycki, P.L. Vidale, J.A. Jonas, and N. Henderson, 2015. Hurricanes and climate: the U.S. CLIVAR Working Group on hurricanes. *Bull. Amer. Meteor. Soc.*, **96**, 997-1017, doi: 10.1175/BAMS-D-13-00242.1. Erratum, *Bull. Amer. Meteor. Soc.*, **96**, 1440, doi: 10.1175/BAMS-D-15-00232.1.

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4 PI Contact Information

Suzana J. Camargo

Lamont-Doherty Earth Observatory

61 Rt. 9W, Palisades, NY 10964-8000

Tel: (845)365-8640

Email: suzana@ldeo.columbia.edu

4.1 Manuscripts currently in preparation

- Daloz, A.S., and **S.J. Camargo** 2016: Examination of a potential poleward shift in tropical cyclone genesis between 1980 and 2013. In preparation.

- Nakamura J. **S.J. Camargo**, **A. H. Sobel**, N. Henderson, **K. A. Emanuel**, A. Kumar, T. E. LaRow, H. Murakami, M. J. Roberts, E. Scoccimarro, P. L. Vidale, H. Wang, M. F. Wehner, and M. Zhao, 2016. Western North Pacific tropical cyclone model tracks in present and future climates. In preparation.

- Ramsay, H., S. Chand, and **S.J. Camargo**, and the Hurricane Working Group 2016: How well models reproduce southern hemisphere tropical cyclone tracks? In preparation.

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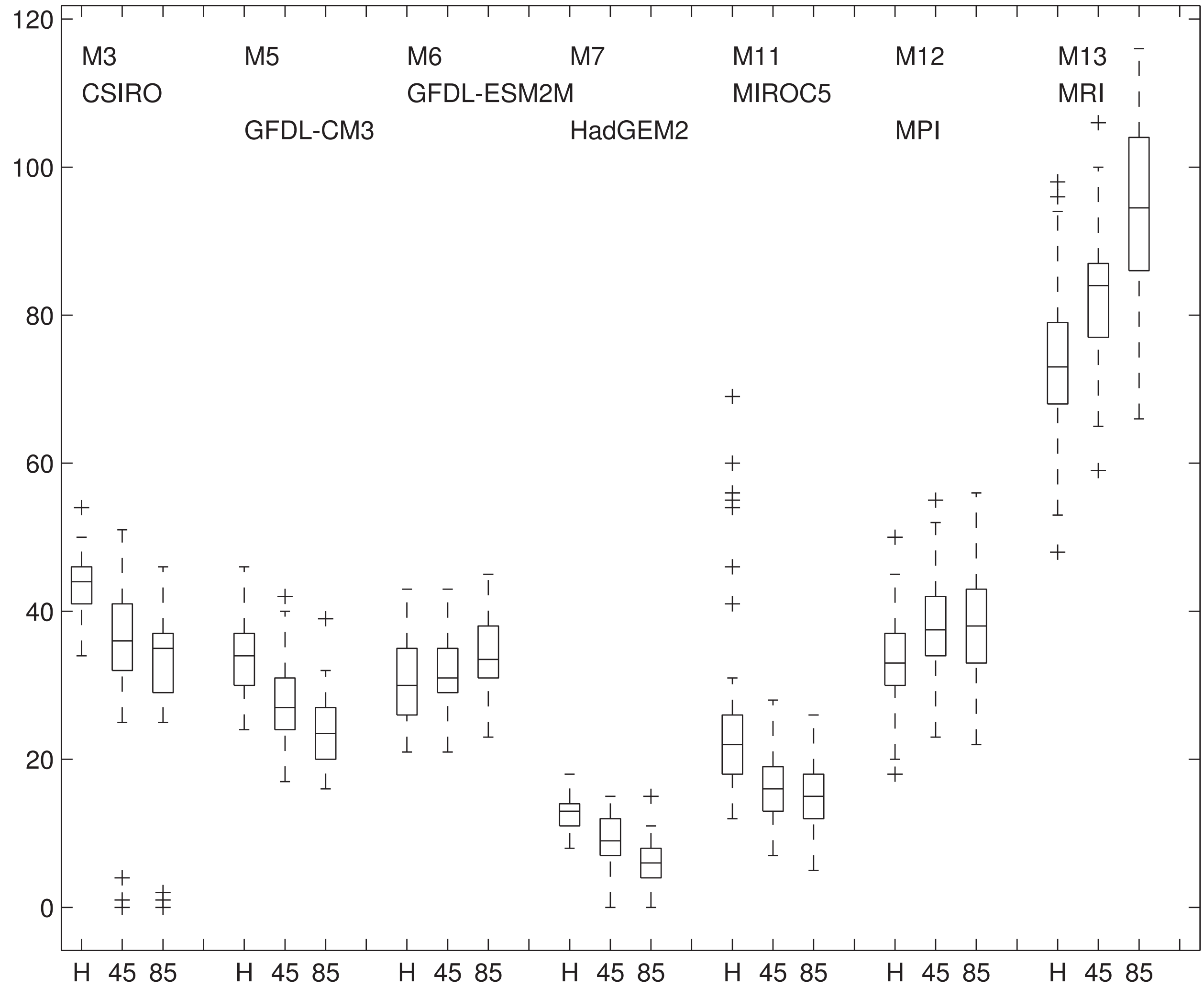

Figure 1: Global number of TCs per year in models for the historical (H) run for the period 19512000 and in the future scenarios RCP4.5 (45) andRCP8.5 (85) in 20512100. The box denotes the range from the 25th to 75th percentile of the distributions, with the median marked by the line inside the box and the values outside of the middle quartile being marked by dashes and crosses. Fig. 7 in Camargo [2013].

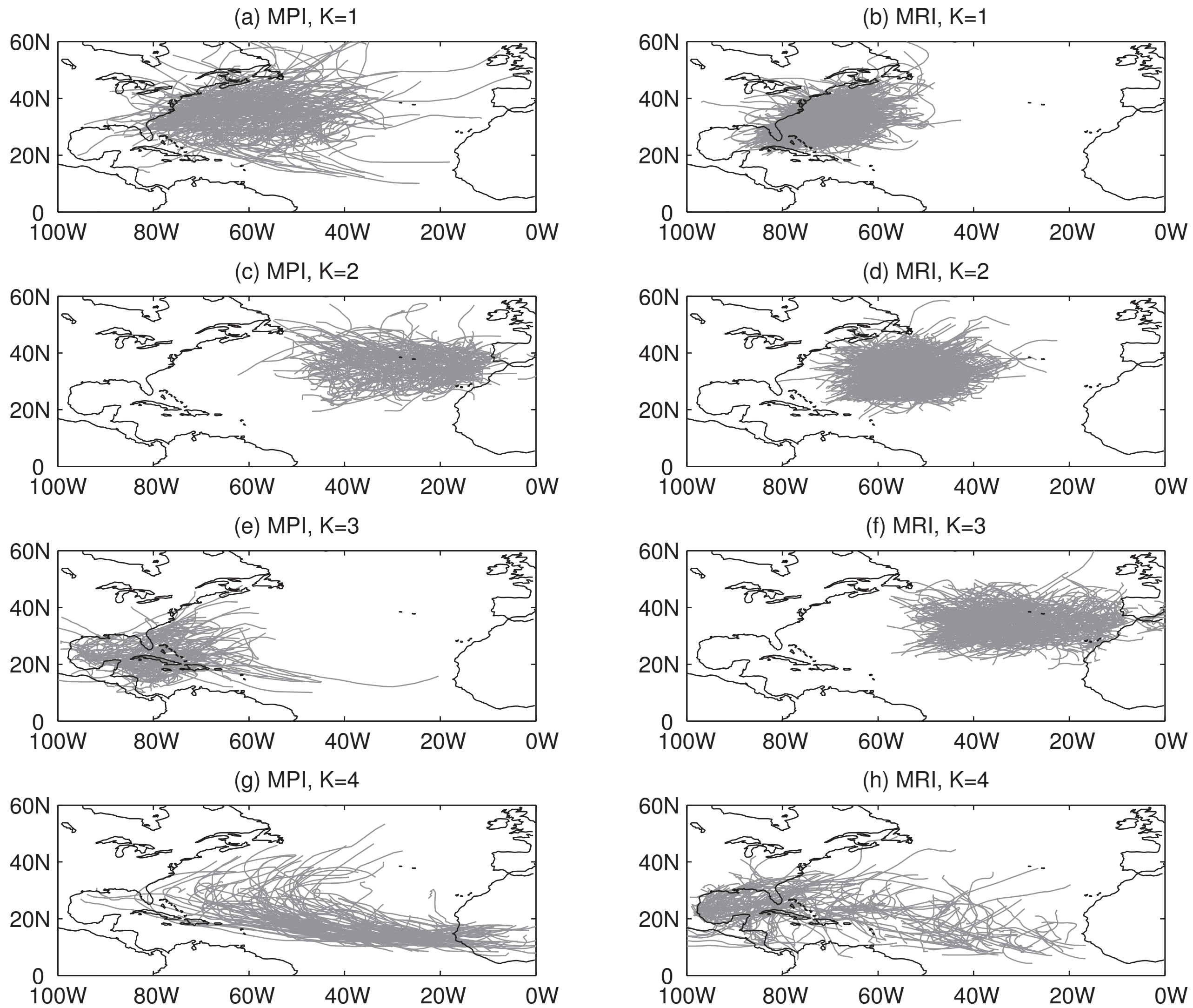

Figure 2: North Atlantic TCs tracks by cluster (K1 to K4) for the (left) MPI-ESM-LR and (right) MRI-CGCM3 models. Tracks for one ensemble member of the historical, RCP4.5, and RCP8.5 runs are shown together for each cluster and model. Fig. 11 in Camargo [2013].

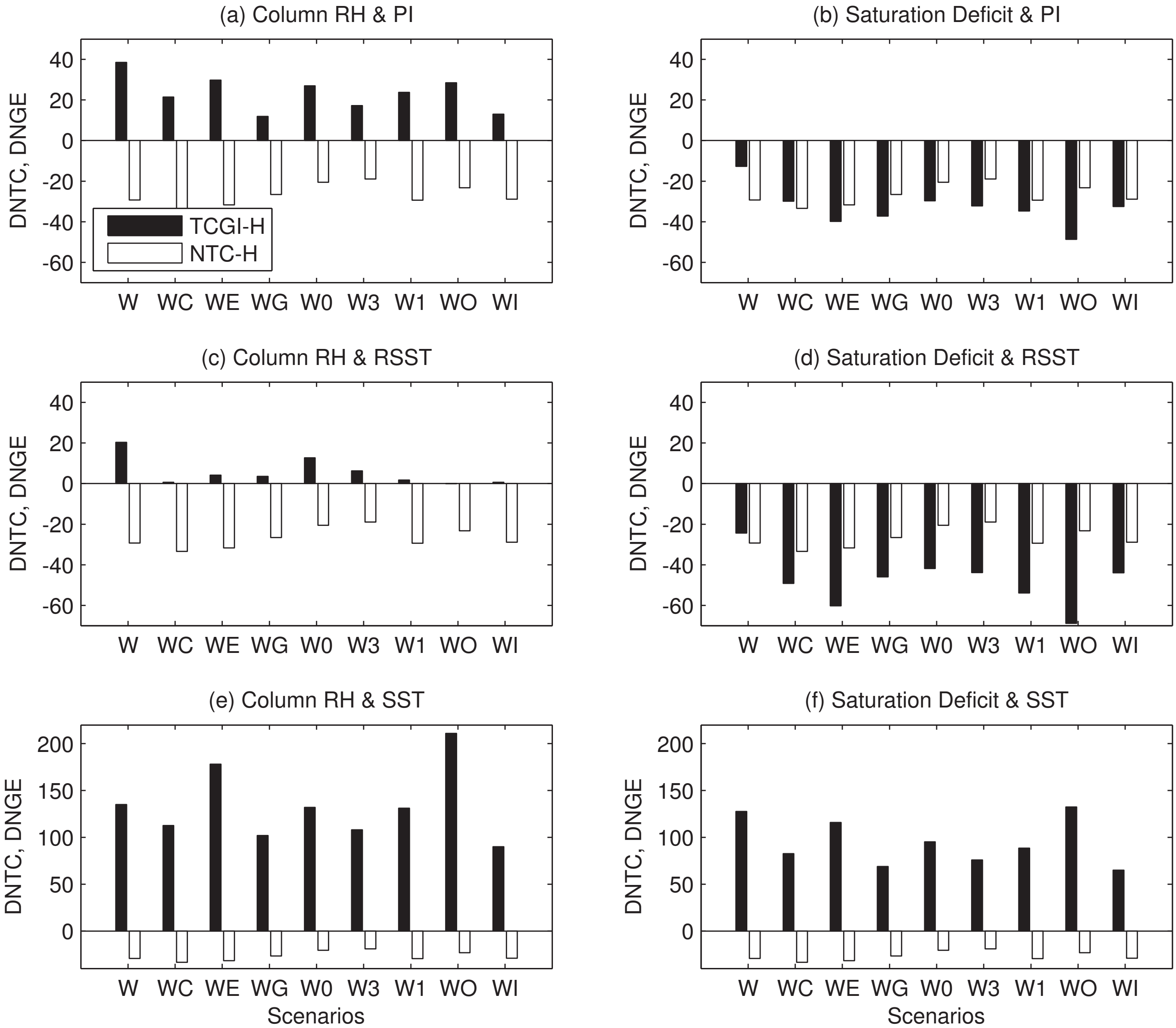

Figure 3: Difference of globally integrated indices, (DNGE in black bars) in the future (all warm scenarios) and the control simulation, using as predictors low-level vorticity, vertical wind shear, and either (left) column relative humidity or (right) saturation deficit, as well as (top) PI, (middle) RSST, or (bottom) SST. Difference of mean global NTC in future scenarios and present climatology for HiRAM (DNTC in white bars). Fig. 10 in Camargo et al. [2014].

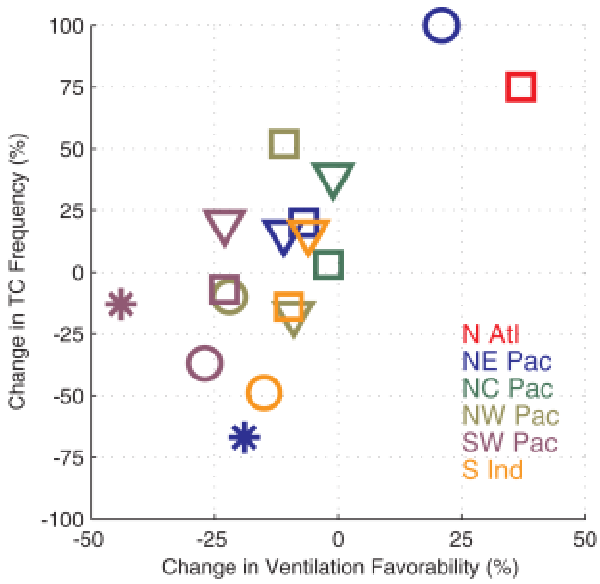

Figure 4: Change in ventilation favorability, defined as the percent change in the cumulative distribution of the daily ventilation index at the 25th percentile of the historical experiment period, versus the change in TC frequency. Data points are separated by basin, as given by the color in the legend, and model: CSIRO-Mk3.6.0 (circles), GFDL-ESM2M (squares), MIROC5 (asterisks), and MRI-CGCM3 (triangles). Fig. 8 in Tang and Camargo [2014].

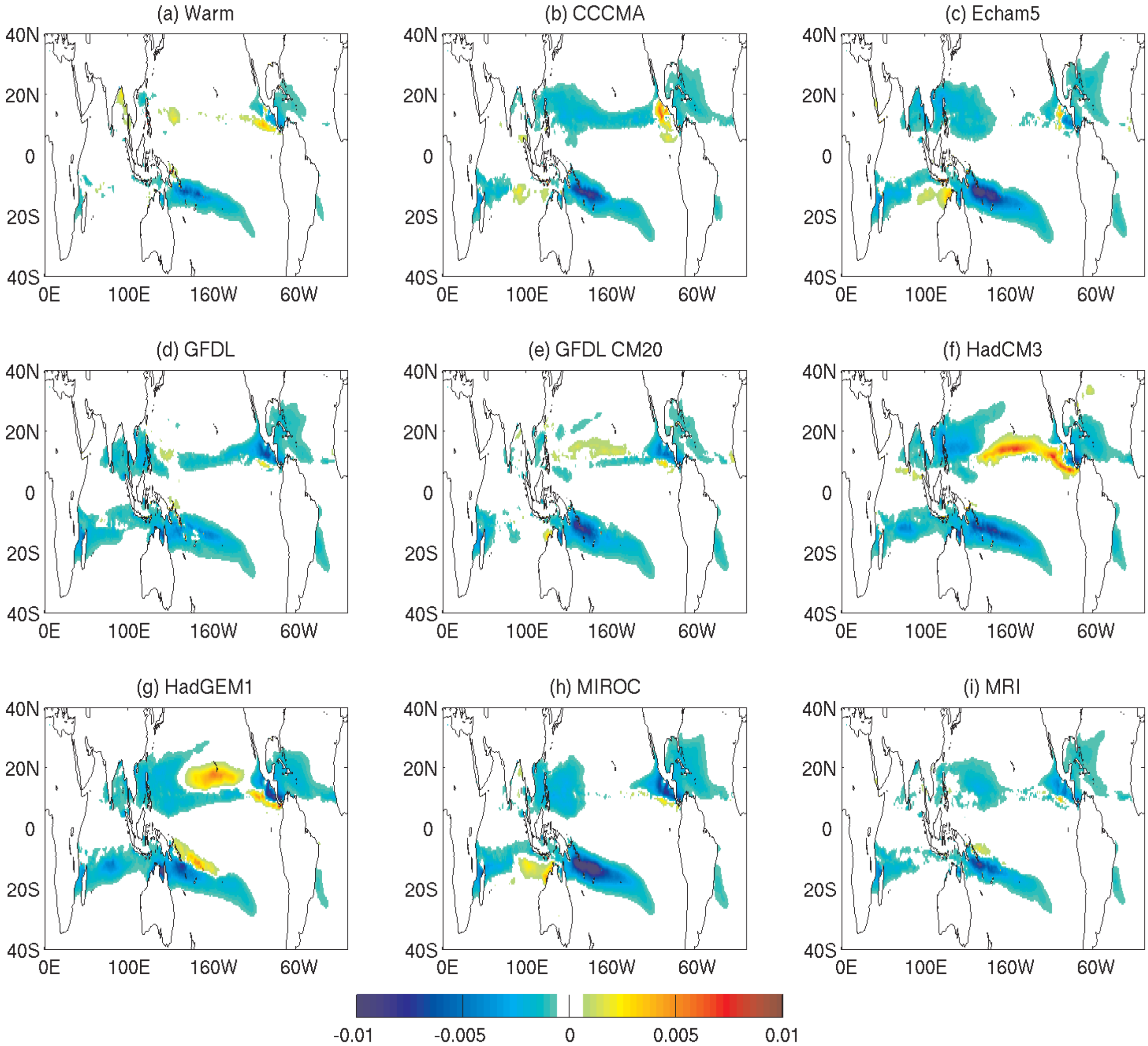

Figure 5: Difference in the climatology of TCGI-H for the future simulations with different SST anomalies and the present control simulation, using the following as TCGI-H predictors: vorticity, vertical shear, saturation deficit, and potential intensity. The TCGI-H is defined as the tropical cyclone genesis index for the HiRAM model, obtained by a Poisson fit of the HiRAM model environmental fields and tropical cyclone genesis density in the present climate. Fig 12 in Camargo et al. [2014].

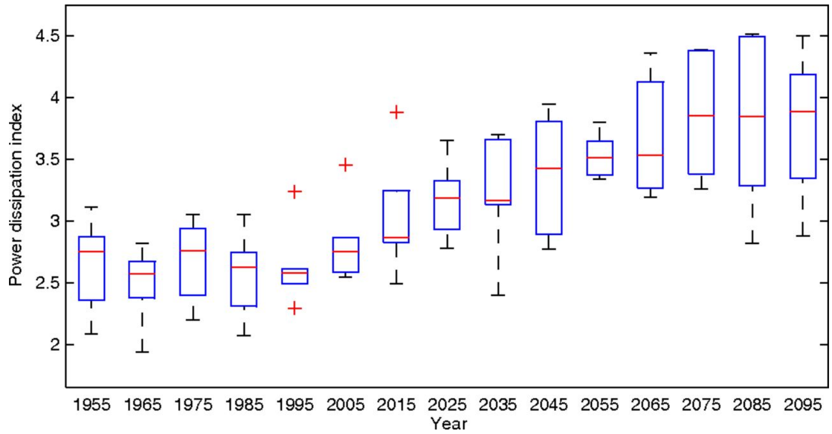

Figure 6: Power dissipation index of tropical cyclones averaged in 10-years blocks for the period 1950-2100, using historical simulations for the period 1950-2005 and the RCP8.5 scenario for the period 2006-2100. In each box, the red line represents the median among six models, and the bottom and top of the boxes represent the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme points not considered outliers, which are represented by the red + signs. Points are considered outliers if they lie more than 1.5 times the box height above or below the box. Units are 10^{12} $m^3s{-}2$. Fig. 3 in Emanuel [2013].

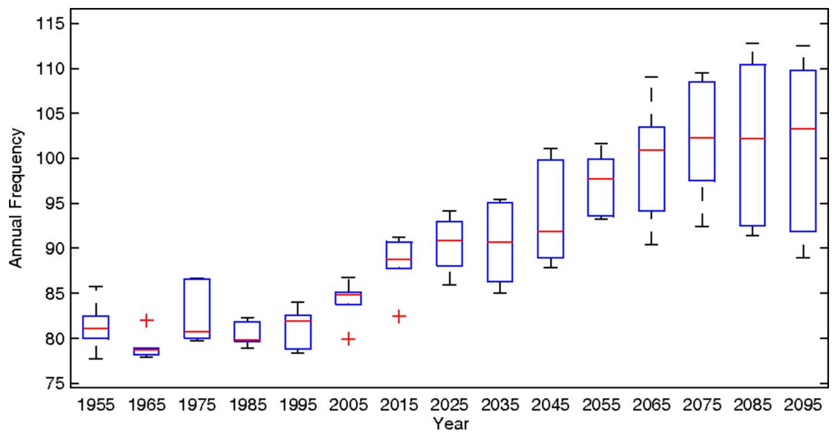

Figure 7: As in Fig. 6, but for global annual frequency of tropical cyclones. Fig. 1 in Emanuel [2013].

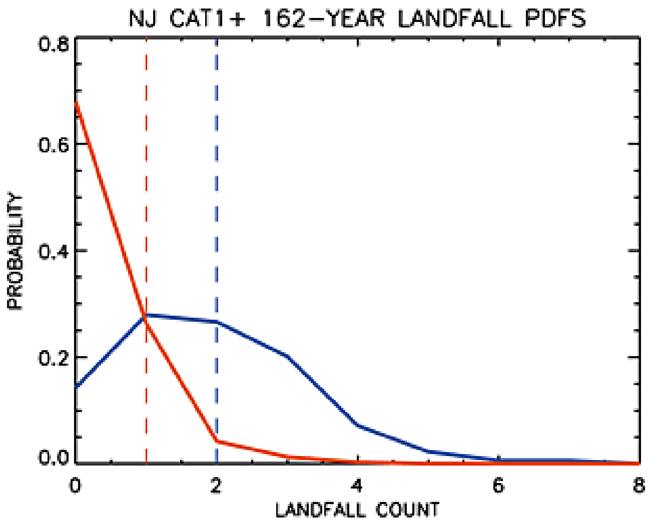

Figure 8: Normalized distributions of New Jersey category 1 or higher hurricane landfall counts in 162 year windows from a 50,000 year model simulation. Blue is for all land-falling impact angles, and red is for angles within 30° of perpendicular. The dashed lines at values 2 and 1 indicate the corresponding historical counts that occurred. Fig. 4 in Hall and Sobel [2013].

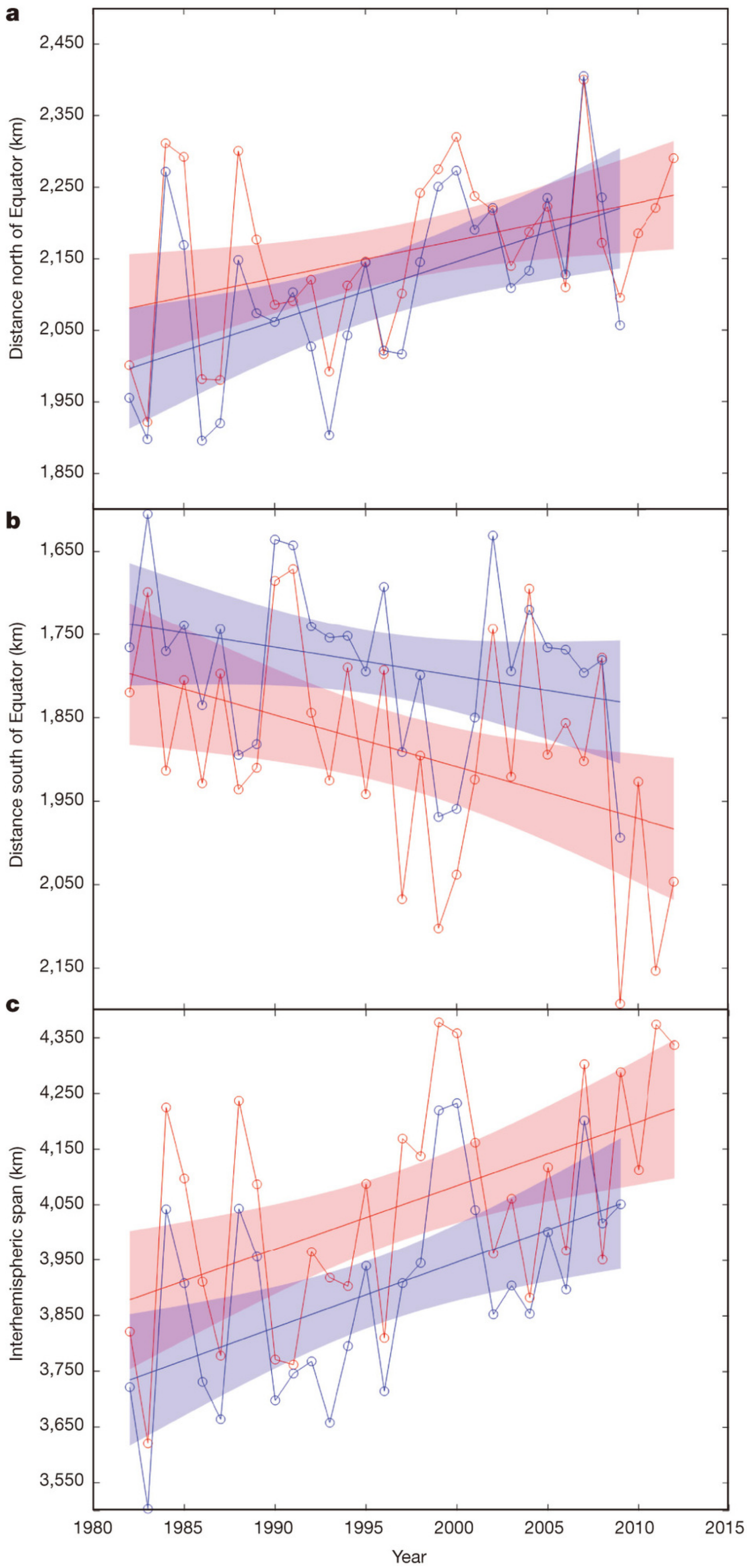

Figure 9: Time series of annual-mean latitude of tropical cyclone lifetime maximum intensity (LMI) calculated from the best-track historical data (red) and a satellite based homogeneous reanalysis dataset (ADT-HURASAT, blue) in the Northern (a) and Southern (b) hemispheres. (c) The annual-mean difference between a and b shows the global migration of the latitude of LMI away from the tropics. Linear trend lines are shown with their 95% two-sided confidence intervals (shaded). Note that the yaxis in b increases downwards. Fig. 1 in Kossin et al. [2014]

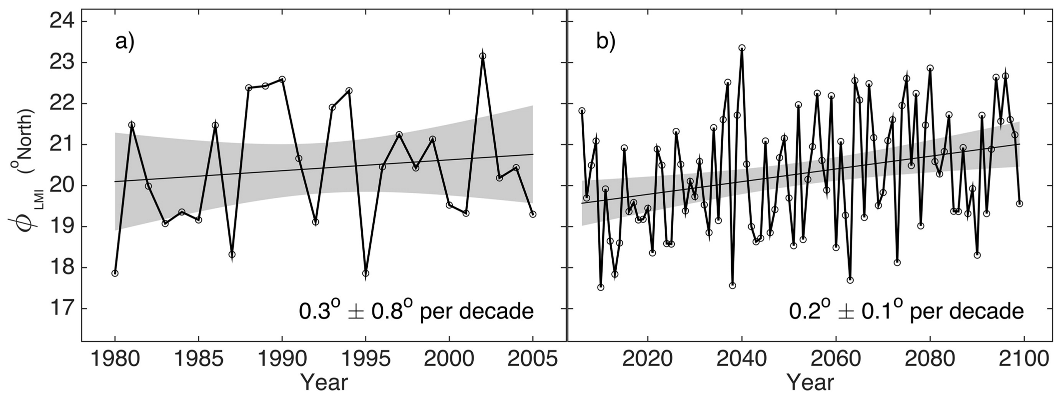

Figure 10: Time series (° latitude per decade) of annually averaged ensemble mean latitude lifetime maximum intensity (ϕ_{LMI}) for from Western North Pacific tropical cyclones explicitly generated in ten CMIP5 models for (a) historical and (b) twenty-first-century projection simulations. Shading shows 95% confidence bounds. Annotated values represent the mean migration rates and their 95% confidence intervals (in ° per decade). Fig. 7 in Kossin et al. [2016].

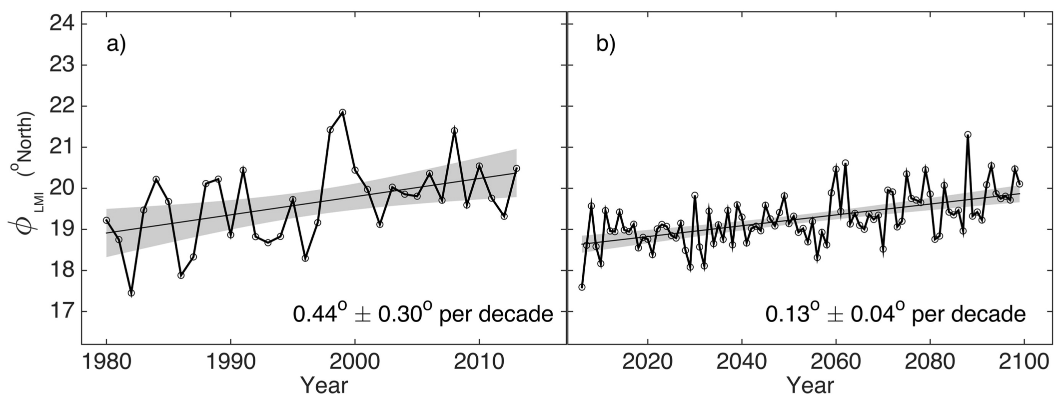

Figure 11: As in Fig. 10 but for Western North PacificTCs downscaled from (a) reanalysis data and (b) model environmental data from eight CMIP5 twenty-first-century projection simulations. Fig. 11 in Kossin et al. [2016].

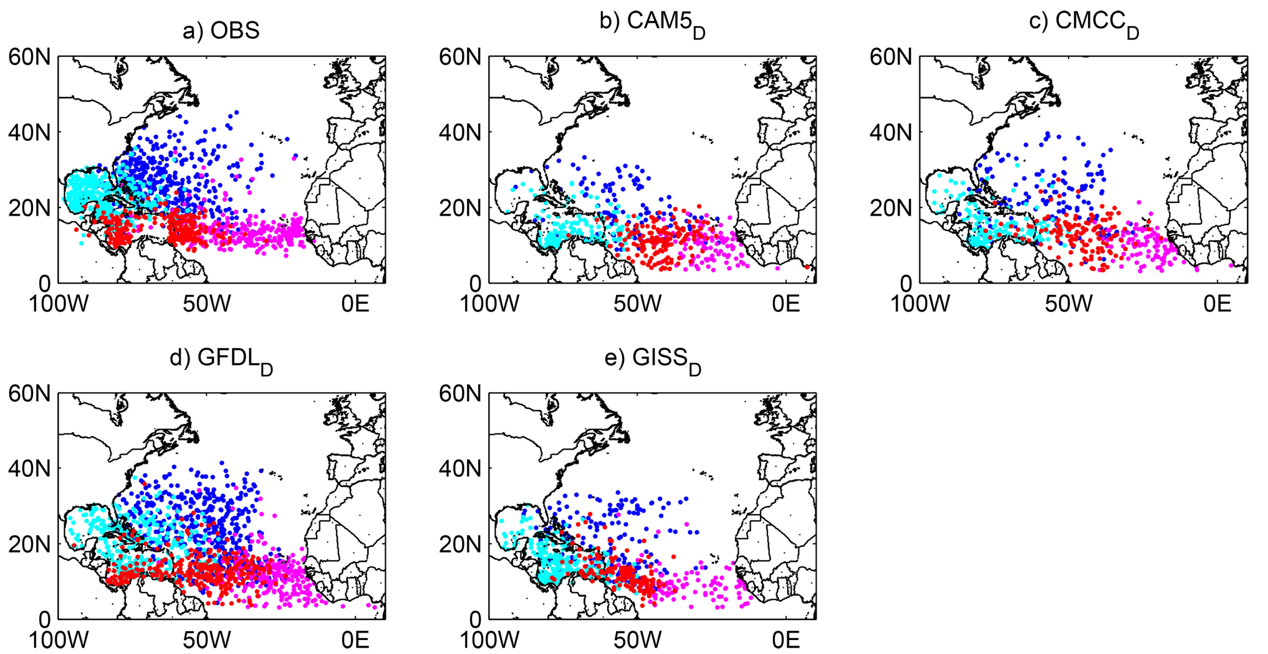

Figure 12: North Atlantic tropical genesis locations of the tracks for observations and downscaled simulations, as separated by the cluster analysis. Cluster 1 is in dark blue, cluster 2 is in light blue, cluster 3 is in pink, and cluster 4 is in red. Fig. 8 in Daloz et al. [2015].

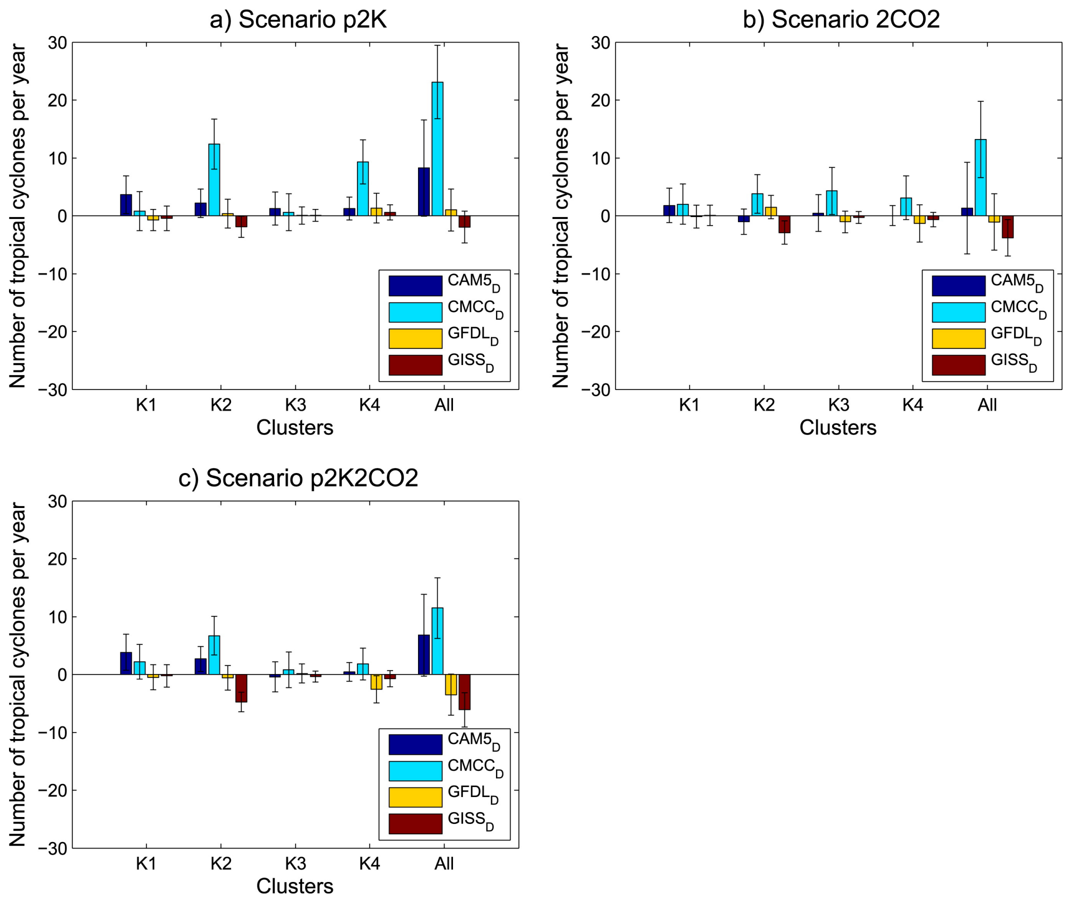

Figure 13: Difference in number of North Atlantic tropical cyclones per year for each cluster membership and the total number of tropical cyclones, between each idealized climate change experiment (p2K, 2xCO2, and both) and the control experiment. These results are presented for the downscaled simulations. Error bars represent 90% confidence interval and were based on a Students t test. Fig. 10 in Daloz et al. [2015].

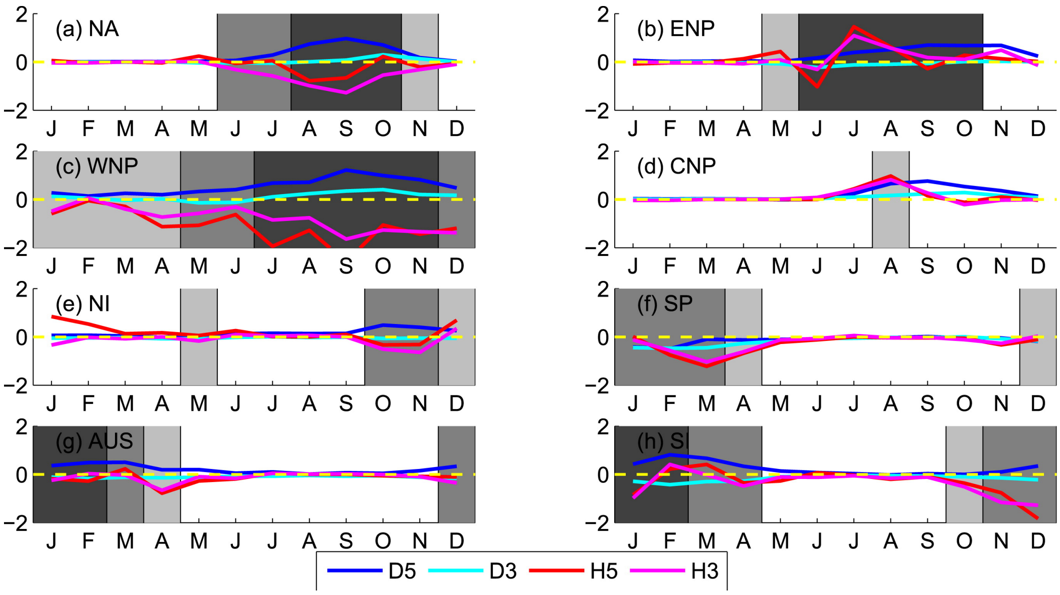

Figure 14: Projected changes in the number of TCs in different ocean basins, as indicated by colored lines. Black shading shows months where the climatology has more than 2 TCs per month, medium gray shading is for between 1 and 2 TCs per month, and light gray shading is for between 0.5 and 1 TCs per month on average. The blue line shows the changes in D5, the downscaling model forced with CMIP5 data; the cyan line shows the changes for D3, the downscaling model forced with CMIP3 data; the red line shows the changes in H5, HiRAM forced with SST anomalies from CMIP5; and the magenta line shows the changes in H3, HiRAM forced with SST anomalies from CMIP3. Fig. 3 in Dwyer et al. [2015].

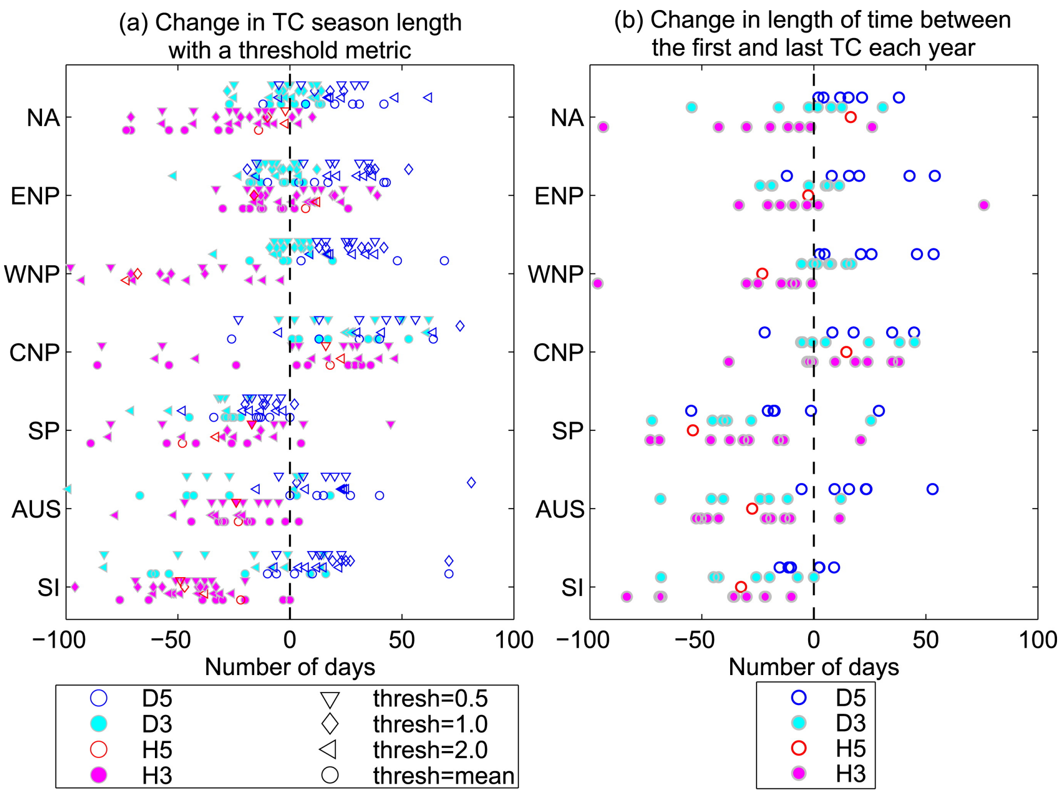

Figure 15: Projected changes in the season length of the number of TCs as measured by (a) the number of days that the data are above a threshold and (b) the number of days between the first and last TC each year. In (a), we use thresholds of 0.5, 1, and 2 TCs per month, and the mean of the late twentieth-century TC frequency, which varies by model and basin. Fig. 4 in Dwyer et al. [2015].