FREDI EXTREMES | TROPICAL CYCLONES

1. Introduction

This standalone package projects the future change in the frequency of tropical cyclones, ranging from tropical storms to category 5 hurricanes, that made landfall in the contiguous U.S. and Puerto Rico, by degree of warming. The following describes the origins of the underlying dataset, the additional analysis to derive annual frequencies of these storms by state or territory, followed by additional notes on interpretation of these outputs.

2. Background

The frequencies of tropical cyclones are statistics derived from a large ensemble of events that were produced with the Tropical Cyclone Simulator Model, which uses a dynamic downscaling technique to generate tropical cyclone tracks from seven coarse-resolution global climate models (GCMs). The model is described in detail in Emanuel et al. (2006; 2008)[1] with updates in Emanuel (2013)[2] and Komurcu et al. (2018).[3]

Tracks are produced for both a hindcast period (1985-2014) and a late-century period (2071-2100) under a high warming scenario. While this scenario is not a likely outcome of current emissions (Sarofim et al. 2024[4]), it is used here to generate the change in tropical cyclone frequency by degree of warming (Sarofim et al. 2021),[5] over the widest possible range of future simulated warming levels. Previous analyses of by-degree impacts suggest that projected impacts at low levels of warming are not biased by using high warming scenarios to develop impact functions (EPA, 2024).[6] Each tropical cyclone track in the ensemble has a location, radius of maximum wind speed, and information that can be used to derive a wind speed profile from the center to the outer edge.

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[1] Emanuel, K. (2006). Climate and Tropical cyclone activity: A new model downscaling approach. Journal of Climate, 19(19), 4797–4802. https://doi.org/10.1175/jcli3908.1 and Emanuel, K., Sundararajan, R., & Williams, J. (2008). Hurricanes and Global Warming: Results from Downscaling IPCC AR4 Simulations. Bulletin of the American Meteorological Society, 89(3), 347–368. https://doi.org/10.1175/bams-89-3-347

[2] Emanuel, K. A. (2013). Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century. Proceedings of the National Academy of Sciences, 110(30), 12219–12224. https://doi.org/10.1073/pnas.1301293110

[3] Komurcu, M., Emanuel, K. A., Huber, M., & Acosta, R. P. (2018a). High-resolution climate projections for the Northeastern United States using dynamical downscaling at convection-permitting scales. Earth and Space Science, 5(11), 801–826. https://doi.org/10.1029/2018ea000426

[4] Sarofim, M.C., Smith, C.J., Malek, P. et al. High radiative forcing climate scenario relevance analyzed with a ten-million-member ensemble. Nat Commun 15, 8185 (2024). https://doi.org/10.1038/s41467-024-52437-9

[5] Sarofim, M.C., Martinich, J., Neumann, J.E., Willwerth J., Kerrich Z., Kolian M., Fant C., Hartin C. (2021). A temperature binning approach for multi-sector climate impact analysis. Climatic Change, 165(1):1-18.

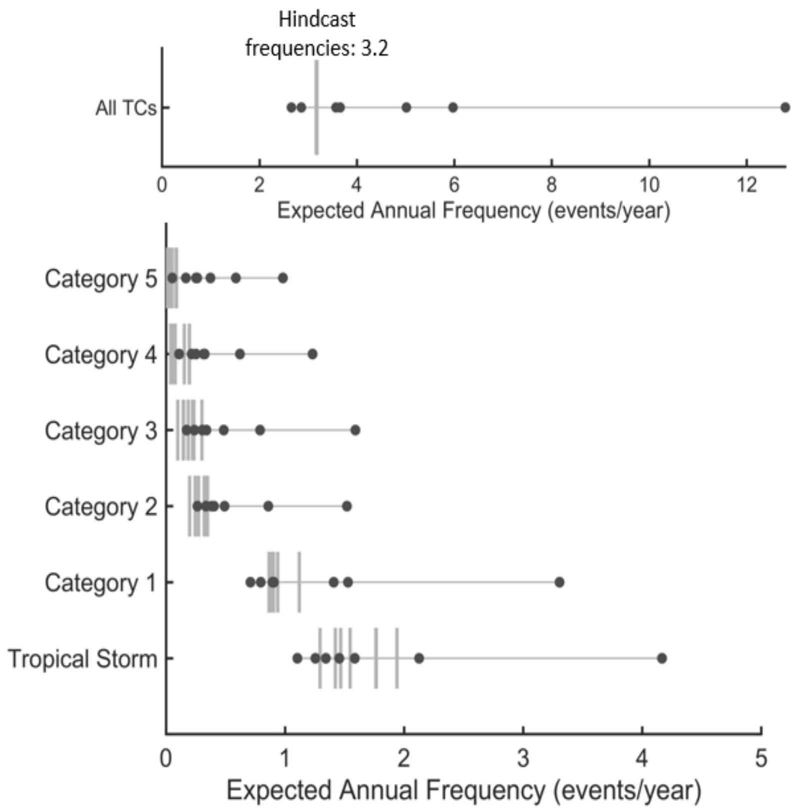
[6] EPA. 2024. Technical Documentation for the Framework for Evaluating Damages and Impacts (FrEDI). U.S. Environmental Protection Agency, EPA 430-R-24-001. www.epa.gov/cira/FrEDI

As described in the underlying study, Guikema et al. (in press),[7] the tropical cyclone tracks were estimated with a well-established dynamic downscaling technique that simulates ensembles of tropical cyclones tracks from coarse-resolution global climate models. The approach, described in detail in Emanuel et al. (2006[8]; 2008[9]), uses monthly sea surface temperature, atmospheric temperature, humidity, and daily horizontal wind speeds to a storm intensity model. Weak proto-vortices are used to initialize the intensity model, seeded randomly in space and time. Storm intensity is driven by a coupled ocean-atmosphere quasi-balanced axisymmetric numerical model. Most of these seeds fail to meet either an intensity threshold of 7m/s within two days or a maximum wind speed of 40 knots are discarded. Those that are placed in suitable thermodynamic and kinematic environments are included in the ensembles. The number of both the storms that fail and succeed are noted and the frequency of success is used to estimate the change in frequency in the future by comparing to the frequency estimated with the ERA 5 reanalysis climate (Herbach et al. 2020[10]). The modeled frequency and power dissipation from the hindcasts are used to select a set of seven CMIP-6 GCMs: EC-Earth3, MRI-ESM2-0, MPI-ESM1-2-HR, UKESM1-0-LL, CESM2, MIROC6, and CNRM-CM6-1. More detail on this process is in the Supplemental information of Guikema et al. With this process, over 2,000 tropical cyclone tracks were generated for each GCM hindcast (1985-2014) and a late century period (2071-2100) for a total of more than 28,000 events that cross the coastline of the Atlantic or Gulf Coast. To determine frequencies for CONUS, the Saffir-Simpson category of the event, e.g., tropical storm or category 1-5, is recorded the first time the center of the event crosses over the coastline, making landfall.

Figure 1 shows the projected changes in the annual frequency of tropical cyclones by Saffir-Simpson category classification, based on the maximum wind speed at first U.S. landfall. Five out of seven GCMs project an overall increase in the frequency of tropical cyclones by the end of the century. However, these increases are not uniformly distributed across the cyclone categories. Specifically, five of the seven GCMs project a decrease in the frequency of tropical storms, compared to their respective hindcast, while all seven GCMs project an increase in Category 5 hurricanes. These findings indicate that overall, tropical cyclones are likely to be more intense and damaging by the late century.

[7] Guikema, S., Z. Pagan-Cajigas, C. Fant, B. Boehlert, K. Emanuel, C. Hartin, and M. Sarofim. Changes in Hurricane-Induced Power Outage Risk in Future Climate Conditions. PNAS, In press.
[8] Emanuel, K. (2006). Climate and Tropical cyclone activity: A new model downscaling approach. Journal of Climate, 19(19), 4797–4802. https://doi.org/10.1175/jcli3908.1
[9] Emanuel, K., Sundararajan, R., & Williams, J. (2008). Hurricanes and Global Warming: Results from Downscaling IPCC AR4 Simulations. Bulletin of the American Meteorological Society, 89(3), 347–368. https://doi.org/10.1175/bams-89-3-347
[10] Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D. and Simmons, A., (2020). The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146(730), 1999–2049. https://doi.org/10.1002/qj.3803

Figure 1: Annual frequency of all tropical cyclones (TCs) included in the analysis (upper panel) and the annual frequency of tropical cyclones by Saffir-Simpson scale (lower panel). The gray solid vertical lines show the GCM hindcasts representing 1985-2014, where each vertical line represents a GCM. The projected frequency for each of the seven GCMs at 3 degrees is represented by dots.



Source: Guikema et al. (in press), Figure 1

3. Deriving state and territory frequencies

In addition to the event set for the Gulf and Atlantic coasts, representing the region of CONUS vulnerable to tropical cyclones, another event set was created with the same process and GCMs for Puerto Rico and the Virgin Islands. This set is smaller with over 500 per GCM, hindcast, and future, for a total exceeding 7,000 events. Other than the smaller number of events and the region of interest, this event set is identical to the event set for the Gulf and Atlantic Coasts, with the same GCMs, time periods, etc.

Using both event sets, we determine the Saffir-Simpson category the first time the event enters each state. While the center of the event was used for the CONUS estimate, we use the radius of maximum wind speed, recording the category the first time that radius crosses the border of the state or territory. The radius is used to account for instances when a state or territory is impacted by a tropical cyclone even if the center of the storm does not cross the border. This is especially important for smaller states and territories.

4. Additional notes on interpretation

While the values focus on the annual frequency, it is important to consider the storm intensity as well, as lower intensity events cause much less damage than higher intensity events. In fact, major hurricanes, categories 3-5, cause the overwhelming majority of damage compared to tropical storms or minor hurricanes, categories 1 and 2 (see Table 1, from NOAA).[11]

Table 1: Saffir-Simpson hurricane wind scale and the types of damage caused by associated hurricane winds and rain. Source: https://www.nhc.noaa.gov/aboutsshws.php

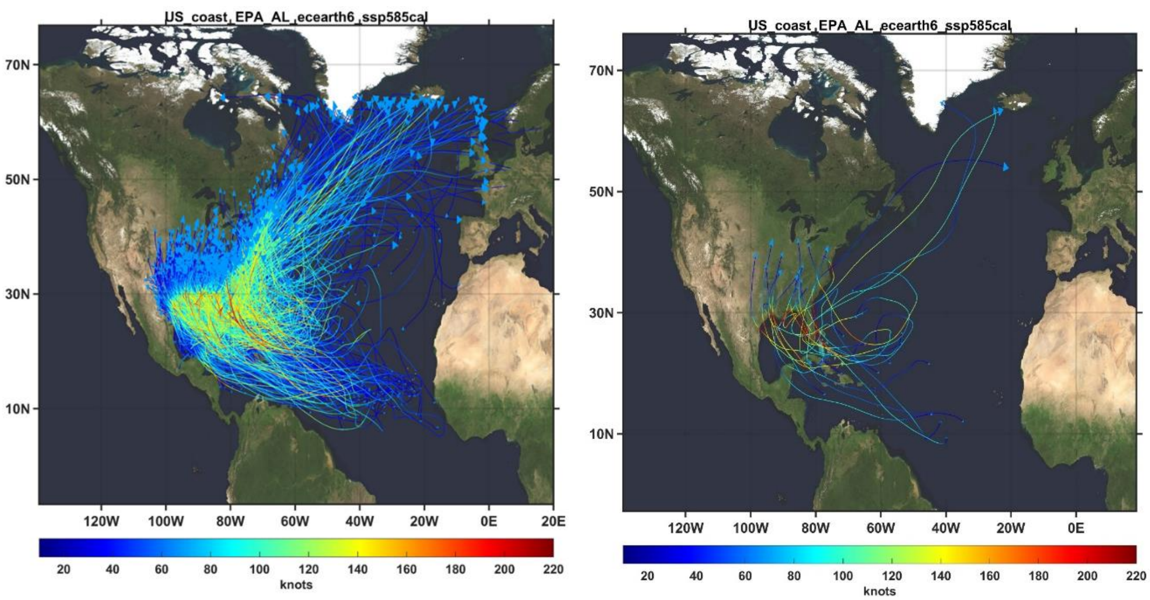
Category	Sustained Winds	Types of Damage Due to Hurricane Winds
Tropical storm	46-73 mph 40-63 kt 74-118 km/h	**Potentially dangerous winds and rain:** While tropical storms do not typically cause significant damage, wind-related impacts such as roof and siding damage, fallen trees, and flying debris, as well as water-related impacts like storm surge and heavy rainfall causing flooding.
1	74-95 mph 64-82 kt 119-153 km/h	**Very dangerous winds will produce some damage:** Well-constructed frame homes could have damage to roof, shingles, vinyl siding and gutters. Large branches of trees will snap and shallowly rooted trees may be toppled. Extensive damage to power lines and poles likely will result in power outages that could last a few to several days.
2	96-110 mph 83-95 kt 154-177 km/h	**Extremely dangerous winds will cause extensive damage:** Well-constructed frame homes could sustain major roof and siding damage. Many shallowly rooted trees will be snapped or uprooted and block numerous roads. Near-total power loss is expected with outages that could last from several days to weeks.
3 (major)	111-129 mph 96-112 kt 178-208 km/h	**Devastating damage will occur:** Well-built framed homes may incur major damage or removal of roof decking and gable ends. Many trees will be snapped or uprooted, blocking numerous roads. Electricity and water will be unavailable for several days to weeks after the storm passes.
4 (major)	130-156 mph 113-136 kt 209-251 km/h	**Catastrophic damage will occur:** Well-built framed homes can sustain severe damage with loss of most of the roof structure and/or some exterior walls. Most trees will be snapped or uprooted and power poles downed. Fallen trees and power poles will isolate residential areas. Power outages will last weeks to possibly months. Most of the area will be uninhabitable for weeks or months.
5 (major)	157 mph or higher 137 kt or higher 252 km/h or higher	**Catastrophic damage will occur:** A high percentage of framed homes will be destroyed, with total roof failure and wall collapse. Fallen trees and power poles will isolate residential areas. Power outages will last for weeks to possibly months. Most of the area will be uninhabitable for weeks or months.

[11] Available here, https://www.nhc.noaa.gov/aboutsshws.php

In addition to the intensity, note that the output from this model, annual frequencies from tropical cyclones by state or territory, may seem counterintuitive in some cases. For example, the total number of events by state will not sum to the total number of events for CONUS. The sum over states will be larger because tropical cyclones often cross into multiple states before dissipating. While each event is only counted once for the national total, as well as only once for each individual state, it is counted for each state it crosses.

Another important note is that as the intensity of the tropical cyclone changes, it may be counted as a different category depending on its intensity as it enters each state. For example, an event may start as a Category 4 hurricane when it first crosses the coast of CONUS, counting as a Cat-4 for CONUS and the first state it enters, but then weakens to Cat-2 before entering the next state, then to a tropical storm as it enters the third. Examples of an ensemble of tropical cyclone tracks are shown in Figure 2. These show how the intensity can change on its path.

Figure 2: Tropical cyclone tracks for the EC-EARTH6 future period (2071-2100) for all tracks (left) and the 20 tracks with the highest maximum windspeeds (right)



5. Availability of code

The code for this package is available at: https://github.com/USEPA/Extremes_by_Degree. See the README file in the Github repository for instructions on how to install and run the package in R.