TECHNICAL DOCUMENTATION

UrbanFootprint Hurricane Winds Methodology

Last Updated: Jun 28, 2024

Overview

Hurricanes (tropical cyclones formed in the North Atlantic, central North Pacific, and eastern North Pacific Oceans) are among the most catastrophic natural phenomena affecting the United States. As the planet warms due to anthropogenic climate change, hurricanes have not only become more frequent but also more intense, posing a heightened threat to coastal and inland communities alike. The increasing severity of these storms has resulted in significant economic and humanitarian impacts, particularly in vulnerable regions with limited adaptive capacity. The challenge is compounded by the unpredictability and variability of cyclone paths and intensities, which make effective planning and response strategies crucial yet difficult to develop.

Currently, there are no publicly available datasets describing the risk posed by high winds due to hurricanes. While the International Best Track Archive for Climate Stewardship (IBTrACS) dataset provides historical tropical cyclone tracks, the relative rarity of these events makes it difficult to evaluate risk directly from this dataset. This document provides the technical documentation for the UrbanFootprint Hurricane Winds dataset, which aims to resolve this gap by providing a nationwide dataset on a 0.1-degree grid showing the rates at which hurricane winds exceed a given wind speed. The following figure shows a visual representation of the rates for one exceedance threshold from this dataset, for gust speeds greater than 33 m/s (approximately a Category 1 hurricane).

This dataset can be used as a general indicator of exposure to various wind speeds.

Source Data

STORM IBTrACS Present Climate Synthetic Tropical Cyclone Tracks

- ➔ **Source:** 4TU.ResearchData
- ➔ **Link:** STORM IBTrACS Present Climate Synthetic Tropical Cyclone Tracks

STORM Climate Change Synthetic Tropical Cyclone Tracks

- ➔ **Source:** 4TU.ResearchData
- ➔ **Link:** STORM Climate Change Synthetic Tropical Cyclone Tracks

Specifications

Source Data

Our hurricane wind exceedance dataset relies on two datasets, both created by Bloemendaal et al using their STORM algorithm[1,2]. Both datasets are 10,000 years of synthetic tropical cyclone tracks. Each track has data at 3-hour intervals, including maximum 10-minute wind speed, cyclone radius to maximum wind speed, and other variables. The first of the datasets is derived from the International Best Track Archive for Climate Stewardship (IBTrACS), and represents cyclone risk under current climate conditions. The second dataset uses IBTrACS and extrapolates the average climate conditions from 2015 to 2050 using four future-looking climate models.

Wind Speeds

UrbanFootprint publishes wind speeds as 1-minute sustained winds. There are three commonly used wind speeds for a hurricane: 10-minute sustained winds, 1-minute sustained winds, and 3-second gusts. While the damage associated with hurricanes is typically a result of 3-second gusts (see the American Society of Civil Engineers' Minimum Design Loads for Buildings and Other Structures), UrbanFootprint presents the 1-minute wind speeds to better align with the Saffir-Simpson scale which customers might be more familiar with.

---

[1] Bloemendaal, Nadia, et al. "Generation of a global synthetic tropical cyclone hazard dataset using STORM." *Scientific data* 7.1 (2020): 40.
[2] Bloemendaal, Nadia, et al. "A globally consistent local-scale assessment of future tropical cyclone risk." *Science advances* 8.17 (2022): eabm8438.

The table below shows the conversion factors we use in converting between wind speeds.

Source wind speed	**Target wind speed**		
	3-second	1-minute	10-minute
10-minute	1.38	1.14	1.0
1-minute	1.23	1.0	–
3-second	1.0	–	–

We present the rates of exceedance for wind gusts of 33 m/s (~74 mph) to 70 m/s (~156 mph) in 1 m/s intervals. This range corresponds roughly to that between the lower bound of Category 1 hurricanes to the lower bound of Category 5 hurricanes.

Spatial Resolution

Our results are presented on a 0.1 degree latitude/longitude grid.

Spatial Extent

We present the risk related to hurricanes from the North Atlantic (which make landfall along the Eastern Coast, including the Gulf of Mexico), and the Eastern Pacific (which make landfall in Hawaii and in rare cases along the West Coast of the United States). While we attempt to estimate wind speed rates in all of these locations, in practice for some time horizons or models, there are not enough high-intensity events to properly estimate the rates with high confidence. In particular, while there are synthetic tropical cyclone tracks off the United States West Coast, no location on land had enough events to actually predict risk.

For these locations of low risk, identified by not having at least 300 wind speed events greater than 18 m/s, we simply denote those as "low risk."

Time Horizons

We model two time horizons, in line with the two from Bloemendaal et al. The first is a "present-day conditions" time horizon, representing the risk under current climate conditions. These conditions and their effect on hurricane formation are derived from the historical record of hurricane tracks (called the IBTrACs dataset) from 1980 to 2017.

The second is a “future” time horizon, representing the risk under future climate conditions. These are defined as the “average climate conditions from 2015-2050”, under an SSP5-8.5 GHG emission pathway. Given that how the climate will respond to such GHG emissions is unclear, we perform the same analysis for four high-resolution climate models (CMCC, CNRM, EC-Earth, HadGEM3).

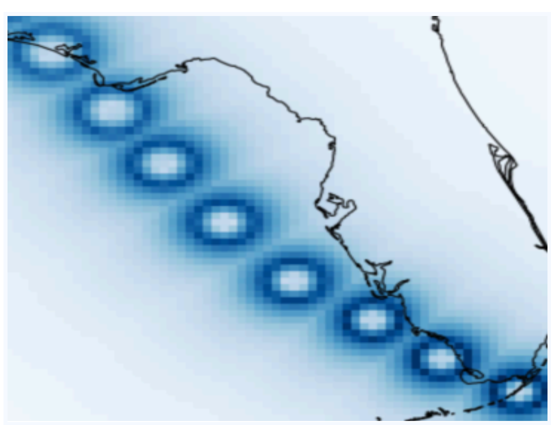
We extrapolate the output from the two time horizons to provide estimates for other time horizons and climate scenarios.

Methodology

UrbanFootprint uses published synthetic tropical cyclone tracts, both under current climate conditions and under future climate change scenarios, to generate synthetic wind fields on a 0.1-degree grid. We use a Generalized Pareto Distribution for each location on the 0.1-degree grid to model the probability distribution of maximum wind speeds given that they exceed a given threshold. The probability of exceedance for that threshold is then converted into an overall rate of exceedance to produce our final output.

Wind Field Modeling

We first convert each timestep in the Bloemendaal dataset into a wind field, where at each location, we have the 3-second wind speed at that time for that synthetic tropical cyclone. To do so, we use a Rankine vortex, a simple model that uses the maximum wind speed, radius to the maximum wind speed, and distance from the center of the tropical cyclone to the target location as inputs. In this model, wind speed increases linearly up until the radius to the maximum wind speed, and then decreases as 1/r. An example of what this looks like is shown in the figure below.



We make a modification to the Rankine vortex in our implementation. Specifically, we let the wind speed be the maximum wind speed from the center of the cyclone until the radius to maximum wind speed. Our final model is defined below:

$$W(r)=\begin{cases}W_{\max} & \text{for } r\le R_{\max}\\ W_{\max}\left(\frac{R_{\max}}{r}\right) & \text{for } r>R_{\max}\end{cases}$$

where r is the radius from the center of the cyclone, $W(r)$ is the wind speed as a function of the radius, and R_{max} is the radius to the maximum wind speed. While it is the case that at any instant the center of the cyclone has the lowest wind speed, the cyclone eventually moves so that the location that used to be at the center will eventually be hit with high winds. This approach ensures that we do not underestimate the maximum wind speed that is felt for locations directly on the path of the cyclone.

We also make some modifications to the tracks themselves. While the source data publishes timesteps in 3-hour intervals, we interpolate those timesteps so that the maximum distance between successive timesteps does not exceed 20 km. In addition, because we are focused on the impact of cyclonic winds on land, we exclude all timesteps that are far removed from land. For the purposes of this work, we are excluding any timesteps that are a distance of more than 100 times its radius from land. Finally, we remove timesteps that correspond to low maximum wind speeds, where the maximum 10-minute wind speed is less than 20 m/s.

Calculating the Rate of Exceedance

We record the maximum wind speed experienced at each location on the latitude/longitude grid for each tropical cyclone. For every location, we attempt to fit a probability distribution for the maximum wind speed for a given tropical cyclone. We follow the Peaks-Over-Threshold (POT) approach, derived from Extreme Value Theory (EVT). In this approach, we attempt to model the distribution of wind speeds exceeding a certain threshold.

Selecting the threshold is itself challenging because it involves a tradeoff between variance and bias. Choosing a lower threshold can include more data points, but it might also include values that do not truly represent the distribution of the most extreme values, leading to increased bias. On the other hand, while setting a higher threshold might filter out those lower values, because we have fewer data points the estimates of parameters become less stable and more sensitive to sampling fluctuations, thereby increasing variance.

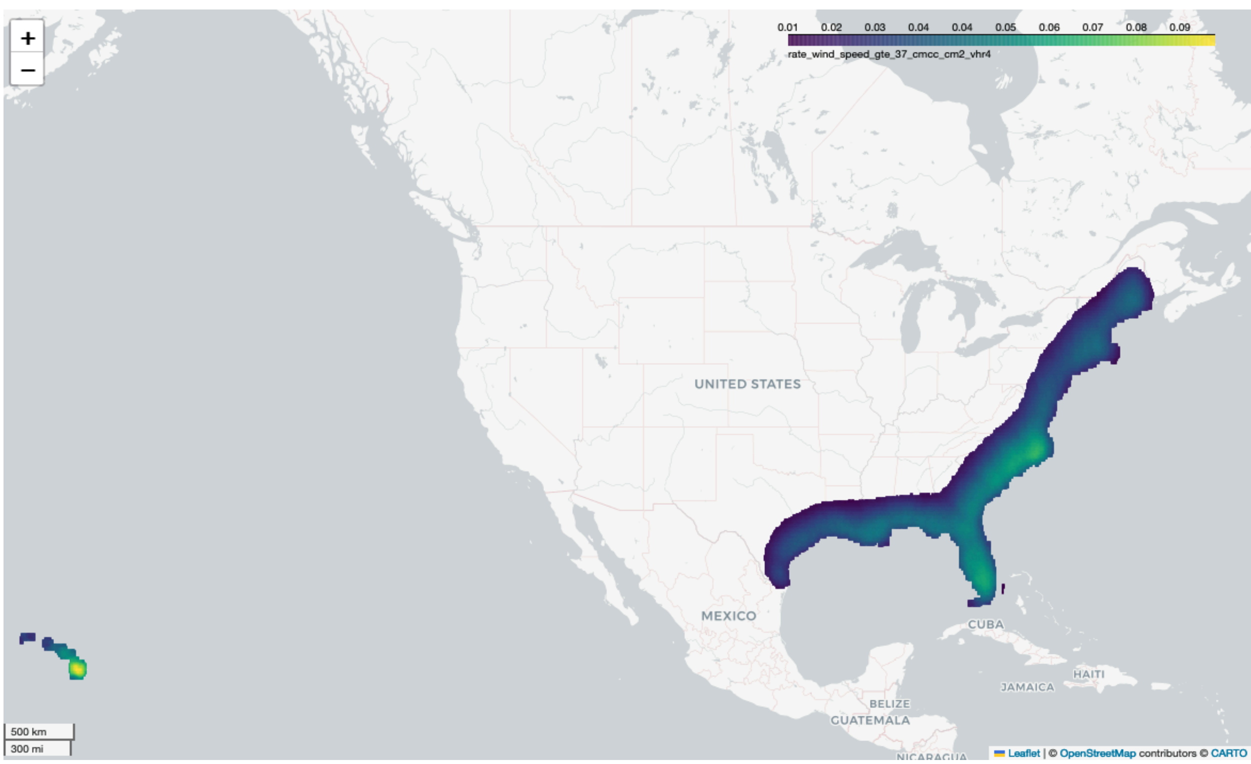
Our approach was informed by constraints from our context area as well as some empirical testing. We needed to model the rates of Category 1 hurricanes, and so our threshold could not be higher than 33 m/s. We therefore iteratively check wind speeds between 33 and 18 m/s (which is the lower threshold for a tropical storm) until there are at least 300 tropical cyclones with a wind speed higher than the threshold. If there are not at least 300 tropical cyclones with wind speeds greater than 18 m/s, we do not attempt to model the distribution. This minimum number of tropical cyclones was determined empirically to be enough to model the most high-risk areas of the United States.

For the locations with enough data, we fit a Generalized Pareto Distribution (GPD) to the wind speeds greater than the threshold. The GPD is a common distribution used in EVT because of its flexibility in modeling different tail behaviors. After the distribution is fit, we calculate the survival function for the distribution at each of the wind speeds of interest (33 m/s-70 m/s), multiply it times the total number of tropical cyclone with wind speeds greater than the threshold (to obtain the expected number of tropical cyclones that would happen in 10,000 years), and divide by 10,000 years to get the rate of wind speed exceedances. Finally, the rates of wind speed exceedances are converted to annual probabilities of exceedance by applying the Poisson assumption:

$$\text{Annual probability of exceedance} = 1 - e^{-\text{rate of exceedance}}$$

Combining the Outputs of Different Climate Models

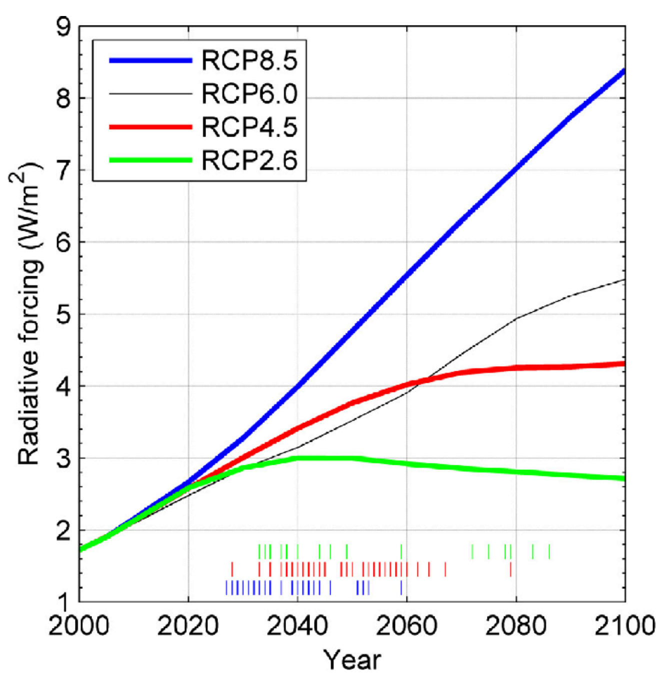
For the future-looking implementation, we follow the methodology above independently for all four climate models. To obtain a "middle of the road" estimate, we also present the median rate of wind speed exceedance across all four models, as shown in the figure below.



Extrapolating to different time horizons and climate scenarios

The approach outlined above gives us current and future estimates under SSP5-8.5 conditions for average climate conditions between the years 2015 and 2050. We assume that these then correspond to the conditions of the year 2030.

Using the modeled output described above, we also provide probabilities of exceedance for the year 2050 under SSP5-8.5 (equivalent to RCP 8.5) conditions, as well as 2030 and 2050 under SSP2-4.5 (equivalent to RCP 4.5) conditions. We interpolate an intermediate SSP scenario (SSP2-4.5) and extrapolate temporally to 2050 based on radiative forcing (RF). Radiative forcing describes the energy balance across the boundary of the earth's atmosphere. Higher levels of radiative forcing mean that there is more net radiation coming into the earth's atmosphere than being emitted. RF is the value described when talking about Representative Concentration Pathways (RCPs), which specifically refer to what the RF value is forecast to be in the year 2100. The dominant pathways that are used for policy analysis and in our work are shown in the plot below:



Based on this, we will approximate the radiative forcing for the scenarios of interest as:

$RF_{current} = 2$

$RF_{8.5-2030} = 3.4$

$RF_{8.5-2050} = 4.6$

$RF_{4.5-2030} = 3$

$RF_{4.5-2050} = 3.7$

With these RF values in hand, we can produce estimates of annual probabilities of exceedance for the scenarios as follows:

$$f_{category,\,scenario} = f_{category,\,current} + \left(RF_{scenario} - RF_{current}\right) \frac{f_{category,\,8.5-2030} - f_{category,\,current}}{RF_{8.5-2030} - RF_{current}}$$

Where $f_{category,\,scenario}$ is the estimated annual probability of exceedance for wind speeds corresponding to a given hurricane category under a given scenario. In essence, we are assuming there is a linear relationship between the probability of exceedance and the radiative forcing, and using the two points we have already estimated from models to fit that relationship.