Open-Source Tropical Cyclone Risk Modeling for New York State

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Open-Source Tropical Cyclone Risk Modeling for New York State

Final Report

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Notice

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Abstract

This project developed and implemented an open-source model for estimating New York State hurricane (or tropical cyclone, the generic term for hurricane) risk under present and future climate conditions. The Columbia HAZard model (CHAZ) is a statistical-dynamical downscaling model that generates large numbers of synthetic hurricanes given large-scale environmental conditions derived from global climate models or observation-based reanalysis data sets. When downscaled from ERA-Interim reanalysis data, CHAZ successfully reproduces many aspects of observed tropical cyclone (TC) characteristics, including rapid intensification. When downscaled from global climate models from phase 5 of the Coupled Model Intercomparison Project (CMIP5) for a future scenario under the representative concentration pathway 8.5, CHAZ showed that the projections of individual global and basin TC frequency depend sensitively on the choice of moisture variable used in the genesis component. Simulations using column-integrated relative humidity show an increasing trend in the future, while simulations using saturation deficit show a decreasing trend. Both sets of simulations give similar results in the historical period. Changes in TC frequency directly affect the projected TC tracks and the frequency of strong storms, which leads to large uncertainty in assessing regional and local storm hazards. At the NYS level, the projected landfall storm frequency indeed follows the projected annual Atlantic basin-wide frequency and thus is also sensitive to the choice of the moisture variable used in CHAZ. That is, when the model projects an overall reduction of Atlantic hurricane frequency, NYS landfall storm frequency decreases and vice versa. Changes in other aspects of NYS storms are insensitive to the choice of the moisture variables in TCGI. Increases in NYS storm intensity due to climate change are not statistically significant in the near future (next 30 years), but the team sees a clear increase in the relative frequency of the most intense storms by the late 21st century. Similarly, there is no clear change in the speeds of NYS storms from the historical period to the near future (next 30 years), but there is an increase in the frequency of slow moving storms and a reduction in the frequency of fast moving storms by the late 21st century. The scientific uncertainty in the frequency projections adds an additional layer of challenge for assessing NYS hurricane risk in a changing climate. While the climate change signal is clearer by the late 21st century, the uncertainty in the frequency projection remains. Such uncertainty is fundamental and epistemic in nature and should be further addressed in future work.

Keywords

statistical-dynamical downscaling model, hurricane, tropical cyclone, climate change, risk assessment

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Acronyms and Abbreviations

CCSM4	National Center for Atmospheric Research (NCAR) Community Climate System Model 4
CMIP5	Phase 5 of the Coupled Model Intercomparison Project
ERA-Interim	European Centre for Medium-Range Weather Forecasts interim reanalysis
GFDL CM3	Geophysical Fluid Dynamics Laboratory Climate Model, version 3
HadGEM2-ES	UK Met Office Hadley Center Global Environment Model, version 2, Earth System
Hist	1951–2005 historical period of CMIP5 models
Ibtracs	International Best Track Archive for Climate Stewardship
MIROC5	Model for Interdisciplinary Research on Climate, version 5
MPI-ESM-MR	Max Planck Institution Earth System Model with medium resolution
MRI-CGCM3	University of Tokyo Center for Climate System Research, the National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology Frontier Research Center for Global Change; and the Meteorological Research Institute of Japan's Climate General Circulation Model 3
PI	Potential Intensity
rcp85	representative concentration pathway 8.5
rcp85late	Late 21st century, 2070–2099, warming climate scenario under rcp85
rcp85nf	2005–2040 near future warming climate scenario under rcp85
TC	Tropical cyclone
TCGI	Tropical cyclone genesis index
TCGI_CRH	CHAZ experiment with TCGI using Column Integrated relative Humidity
TCGI_SD	CHAZ experiment with TCGI using Saturation Deficit

Executive Summary

Hurricanes, or more generally tropical cyclones (TC), are one of the worst natural hazards. Historically, relatively few hurricanes have made landfall in New York State. The State, however, is extremely vulnerable to these storms because of its geographic location and well-developed coastal regions. A single catastrophic storm (making landfall or not) can cause enormous damage, exemplified by Hurricane Sandy in 2012 and Tropical Storms Irene and Lee in 2011. The first step toward mitigating the threat of TC is a rigorous risk assessment. Because of the rarity of hurricanes, historical records are not sufficient to provide guidance. Furthermore, our climate has changed since the pre-industrial era, which makes the present different from the past, and the future different from the present. The team's interest in hurricane risk under future climate conditions means that not only information from past storms must be use—but in addition, an understanding of the physics of weather and climate must be used.

This four-year (2017–2020) project aimed to develop a statistical-dynamical downscaling hazard model for estimating NYS hurricane risk under present and future climate conditions. Throughout the project, three tasks were conducted: (1) development of a statistical-dynamical downscaling TC risk model, the Columbia HAZard model (CHAZ), (2) Global TC projection from CHAZ downscaling under climate change scenarios, and (3) CHAZ-based NYS hurricane risk assessment in the current and future climate.

The development of CHAZ (Version 1.0) was completed at the beginning of 2018, and the model was introduced to the scientific community in Lee et al. (2018). A brief description of CHAZ and its performance when downscaled from a reanalysis data set for a historical period will be reported in section 1.1. In 2018 and 2019, the project team performed the climate change experiments by downscaling CHAZ from six global climate models from phase 5 of the Coupled Model Intercomparison Project (CMIP5) for a historical and a future scenario under the representative concentration pathway 8.5 (rcp8.5). The most robust finding is a 4–5% increase in the relative number of intense storms and 1–5% increase in the ratio of storms that undergo rapid intensification by the end of the 21st century. An intriguing finding is that CHAZ proposes two diverging future scenarios for global and basin-wide annual TC frequency, one in which frequencies increase and one which frequencies decrease. The divergence comes from a seemingly small assumption on the moisture variables used in the CHAZ for TC seeds (i.e., storm precursors). While this result is unsatisfying,[1] it is consistent with the projections of state of science, in which some models suggest an increase in annual TC frequency while others suggest a decrease. Research results from the climate change experiment were published in 2020 June (Lee et al. 2020a) and are discussed in section 1.2.

The project team is organizing results from the NYS hurricane risk assessment for publication (Lee et al. 2020b). In section 1.3, the team shows that the CHAZ captures the observed NYS storm characteristics in terms of their intensity, forward speed, and impacting angles. The model generates more northward (coming from south) storms than the observations. The team focuses on two periods under rcp8.5, the near future (up to 2040) and late 21st century. The ratio of the strong impacting storm increases, but the annual frequency of landfall storms is sensitive to the overall Atlantic hurricane frequency projection. Other aspects of NYS storm climatology are not sensitive to the projected frequency. NYS storm intensity increases as the climate warms; this signal is clear by the late 21st century. Changes in storm forward speed and impacting angle are statistically insignificant in the near future. In the late 21st century, there will be fewer extremely slow as well as fast moving storms in the State.

The deliverables of the project include (1) a large set of synthetic NYS hurricanes and (2) landfall and hurricane wind return levels for NYS with specific thresholds. These deliverables are described in detail in section 1.4.

In addition to the scientific results, this NYSERDA project stimulated several research projects within the academia and with the private sectors. As a result, there are three additional publications using results from this project and more to come. These academic and broader impacts of this NYSERDA project are reported in section 2.

1 Project Research Results

1.1 An Environmentally Forced Tropical Cyclone Hazard Model

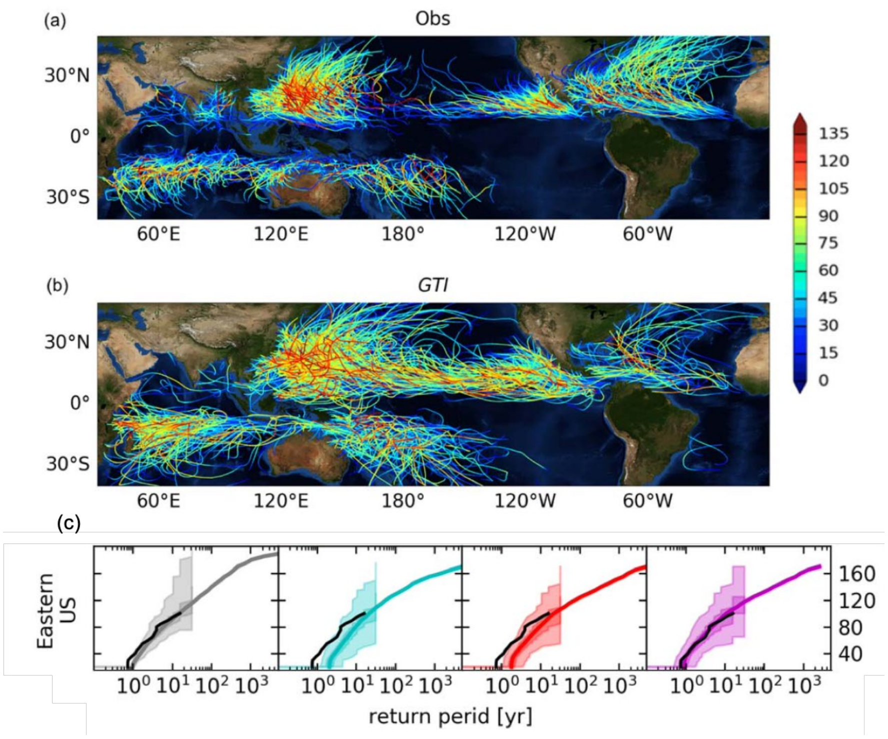
The first step of the project was to develop a new statistical-dynamical model. Since a working prototype of the intensity (Lee et al. 2015, 2016) and wind models (Chavas et al. 2015) already existed at the time the project started, the primary work here was to (1) develop the genesis and track models, (2) further improve the intensity model, and (3) couple all the components. The genesis model was developed using a TC genesis index (TCGI, Tippett et al. 2011), and a beta-advection track model was developed following Emanuel et al. (2006).

The developed statistical-dynamical model is called the Columbia HAZard model (CHAZ[2]). In short, CHAZ initializes weak vortices randomly, with a global formation rate and local probabilities at each location that depend on environmental conditions through TCGI. Several versions of the genesis index have been developed (Camargo et al. 2014), using slightly different predictors. Here the team used the original Tippett el al. (2011) version of the genesis index. The track model then moves storms forward by advection of the environmental steering wind plus a "beta drift" component accounting for the Earth's curvature and rotation. The evolution of the storms' intensity is then determined by the intensity model using the surrounding large-scale environment via an empirical multiple linear regression model, plus a stochastic component. The stochastic component accounts for the internal storm dynamics and does not depend explicitly on the environment. Ambient environmental variables required by the CHAZ model are potential intensity (PI), deep-layer (850 millibars [mb] to 250 mb) vertical wind shear, the moisture variables—column integral relative humidity (CRH), the absolute vorticity at 850 mb, and the steering flow.

In the 2018 Journal of Advances in Earth Modeling System publication (Lee et al. 2018), the team introduced and evaluated CHAZ performance on global TC climatology, estimating the long-term hazard of rare, high-impact tropical cyclones events globally, and generating 400 realizations of a 32-year period (approximately 3,000 storms per realization) with environmental conditions from European Centre for Medium-Range Weather Forecasts interim reanalysis (ERA-Interim, Dee et al., 2011). Figures 1a and 1b show that the CHAZ model captures many aspects of tropical cyclone statistics, such as genesis and track density distribution. Of particular note, it simulates the observed number of rapidly intensifying (defined as when storms intensify more than 30–35 knots [kt] per 24-hour period) storms, a challenging issue in tropical cyclone modeling and prediction. Using the return period curve of landfall intensity as a measure of local tropical cyclone hazard, the model reasonably simulates the hazard in some regions (such as western north Pacific and the Caribbean islands). In other regions, such as the Northeastern United States coast (Figure 1c), the observed return period curve can be captured after a local landfall frequency adjustment that forces the total number of landfalls to be the same as that observed, while allowing the model to freely simulate the distribution of intensities at landfall.

Figure 1. CHAZ Simulated Global Tropical Cyclones

Simulation (a) historically tracks (2000–2012) and color-codes by intensity. Simulation (b) is similar to (a) but from a randomly selected member (out of 400 realizations) from CHAZ and (c) reflects return period curves of landfall intensity in the Eastern U.S. Colors gray, blue, red, and magenta show return periods generated by intensity model only (along best-track storm trajectories) by intensity and track models (using observed genesis location) by CHAZ and by CHAZ with local bias correction applied, respectively.



1.2 Statistical–Dynamical Downscaling Projections of Tropical Cyclone Activity in a Warming Climate: Two Diverging Genesis Scenarios

The next step of the project was to conduct the climate change downscaling experiments. As Earth's climate warms due to increasing concentrations of greenhouse gases, TC properties are expected to change. Among the more confident expectations are that TC precipitation and wind speeds will increase, and that the impact of storm surge will increase due to rising sea levels. There is much less confidence in projections of changes in TC frequency or in the spatial distributions of storm genesis, track patterns, and translation speeds. The uncertainties are, in general, even larger at the scale of individual basins than at the global scale, and larger still at sub-basin scales. Changes in frequency and track patterns influence all other aspects of the hazard at any specific location, making hazard assessment challenging. In the 2020 Journal of Climate publication (Lee et al. 2020), the team studied projections of various measures of TC climatology on both global and basin-wide scales under warming.

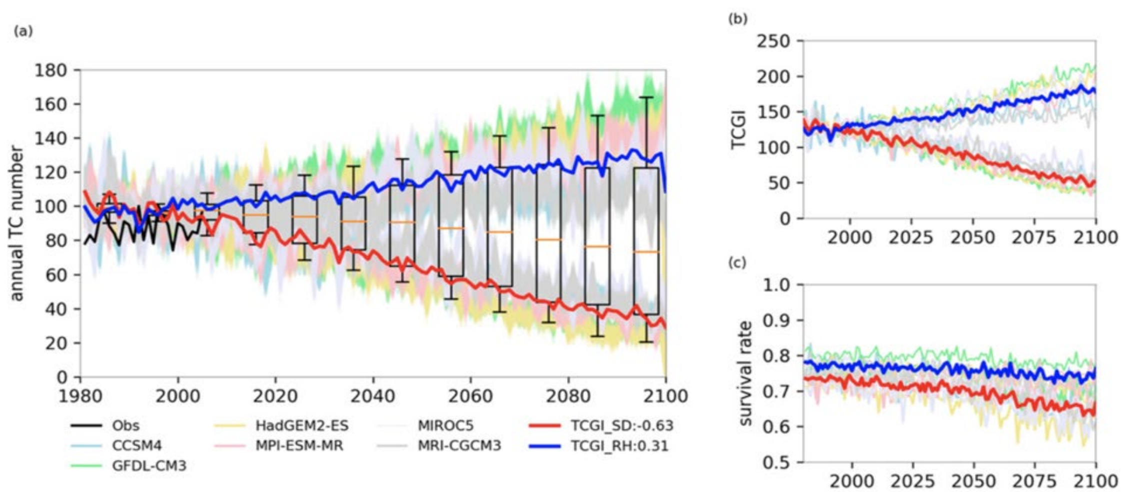
The team downscaled the CHAZ model using environmental conditions derived from six models taken from phase 5 of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012). They are the NCAR CCSM4 (Gent et al. 2011); the GFDL CM3 (Donner et al. 2011); the UK HadGEM2-ES (Jones et al. 2011), the Max Planck Institution Earth System Model with medium resolution (MPI-ESM-MR; Zanchettin et al. 2012); the Model for Interdisciplinary Research on Climate, version 5 (MIROC5; Watanabe et al. 2010), from the University of Tokyo Center for Climate System Research, the National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology Frontier Research Center for Global Change; and the Meteorological Research Institute of Japan's Climate General Circulation Model 3 (MRI- CGCM3; Yukimoto et al. 2012).

The most intriguing result was that the greatest uncertainty in the results was not driven by the particular model downscaled but by the choice of moisture variable used in TCGI. Simulations using column relative humidity (CRH, the original form of TCGI developed by Tippett et al. 2011) show an increasing trend in TC frequency in the future, while those using saturation deficit (SD, a version developed by Camargo et al. 2014) show a decreasing trend, although both give similar results in the historical period. CRH and SD both describe how far the atmosphere is from saturation, and they have very similar spatial patterns in the present climate. They are different in that SD is the difference between the column integrated water vapor and the same quantity at saturation, while CRH is the ratio of the same two quantities. In the current climate, the two TCGI versions yield similar results for the historical period, so that historical evidence is inadequate to determine which of the two is more realistic. The theoretical argument for using SD is that it better reflects the increase in the thermodynamic inhibition of TC formation in a warming climate. At larger SD, greater surface fluxes are required to saturate the column on mesoscale, a prerequisite to genesis (Emanuel, 2013, 2018). However, this argument has not been articulated in detail nor tested in any demanding way, so that in the team's judgment, it does not settle the argument conclusively in favor of SD over RH.[1]

Changes in TC frequency directly affect the projected TCs' track density and the frequencies of strong storms on both basin and regional scales. This leads to large uncertainty in assessing regional and local storm hazards. Increases in the fraction of major TCs, rapid intensification rate, and decreases in forward speed are insensitive to TC frequency and choice of genesis index, however. The present results are also consistent with prior studies in indicating that those TC events that do occur will, on average, be more destructive in the future because of the robustly projected increases in intensity.

Figure 2. The CHAZ Projected Annual Tropical Cyclone Frequency

Time series of (a) the CHAZ-simulated annual global TC frequency, (b) the TCGI-estimated seeding rate, and (c) the survival rate of the synthetic storms. Thin lines show downscaling results from each of the CMIP5 models, indicated by color. The box-and-whisker diagram in (a) shows the median (orange) and the 5th, 25th, 75th, and 95th percentiles. The thick blue and red lines show the ensemble mean from the TCGI_CRH and TCGI_SD experiments, respectively.



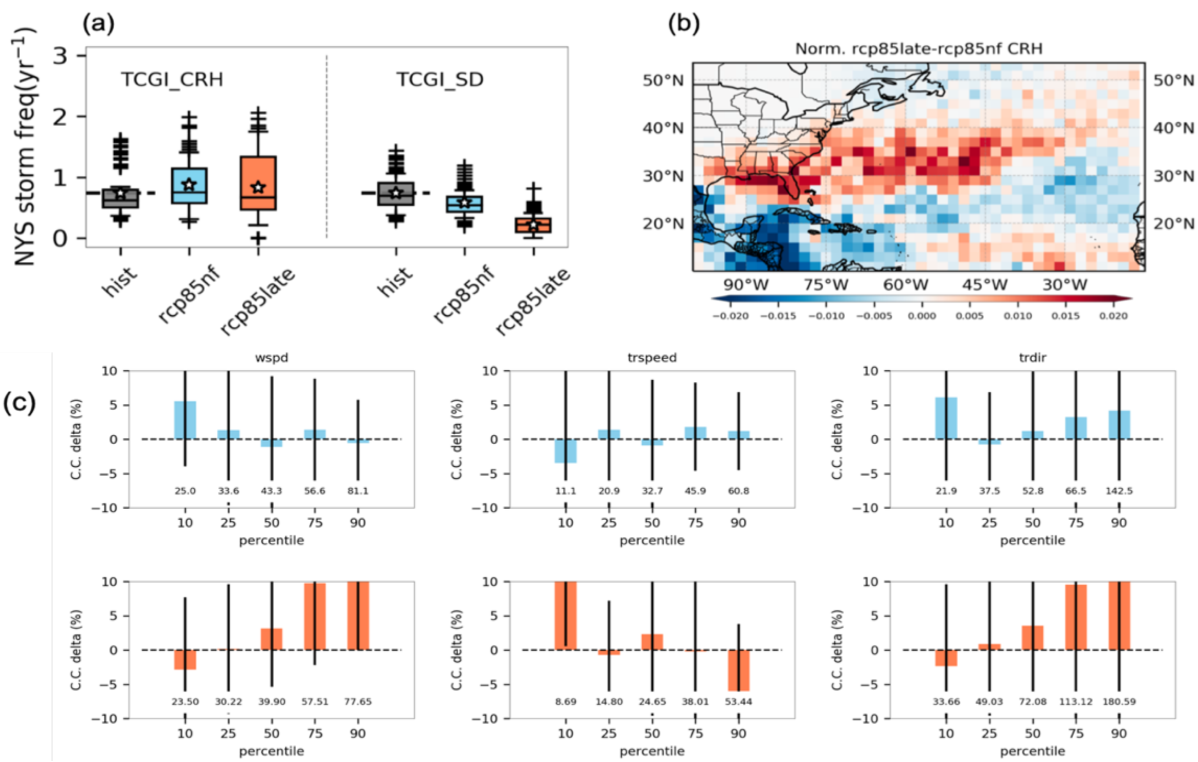
1.3 Climate Change Impacts on New York State Hurricane Risk in Near and Distance Future

The final step of this project was to assess the climate change impact on NYS storms and the associated risk assessment. The NYS storms were defined as those that impact the area whether they make landfall in the State or not. The team again used environmental conditions from the CMIP5 models. Following Lee et al. (2020a), the team showed a range of possible changes in tropical cyclone hazards, which is determined by both the climate model forcing and the structural uncertainty related to certain key modeling assumptions—the choice of the moisture variable in the TCGI—in the CHAZ model. To detect hurricane wind risk, a machine-learning wind reconstruction model (Yang et al. 2020a) using an empirical parametric wind model (Willoughby et al. 2006) was applied to the synthetic NYS tropical cyclone tracks.

Figure 3a shows that the projections of NYS storm frequency are similar to those for Atlantic hurricanes. In the simulations using TCGI_CRH, there is an increasing trend in NYS storm frequency while those using TCGI_SD show a decreasing trend. The normalized spatial distribution of hurricane activity (i.e., regardless of the changes in the absolute TC numbers) suggests that the relative probability of storm activity in subtropical to midlatitudes increases (Figure 3b). The distribution of NYS storm intensity also shows a small shift towards higher values (not shown). Percentile analysis suggests a 5% increase in the lowest 10-percentile State storms from the historical period to near future. From near future to the late 21st century the 75-percentile and 90-percentile of storm intensities increase by more than 10% (Figure 3c), and the ensemble spread of the changes of the 90-percentile storm intensity does not include 0, indicating a higher confidence of the change. We further conduct a statistical hypothesis test on the distribution of the NYS storm impacting intensity, which suggests the distributions from the historical period to near future to late 21st century are distinguishable (not shown). The increase in the NYS storm intensity changes can be attributed to the increase in PI (Sobel et al. 2016) and the decrease in the vertical wind shear (Ting et al. 2019). The percentile analysis of storm motion suggests an increase in the low-percentile values and a decrease in high-percentile values in the late 21st century, which suggests that there will be less extremely slow- and fast-moving storms.

Figure 3. Climate Change Impacts in New York State Hurricane Characteristics

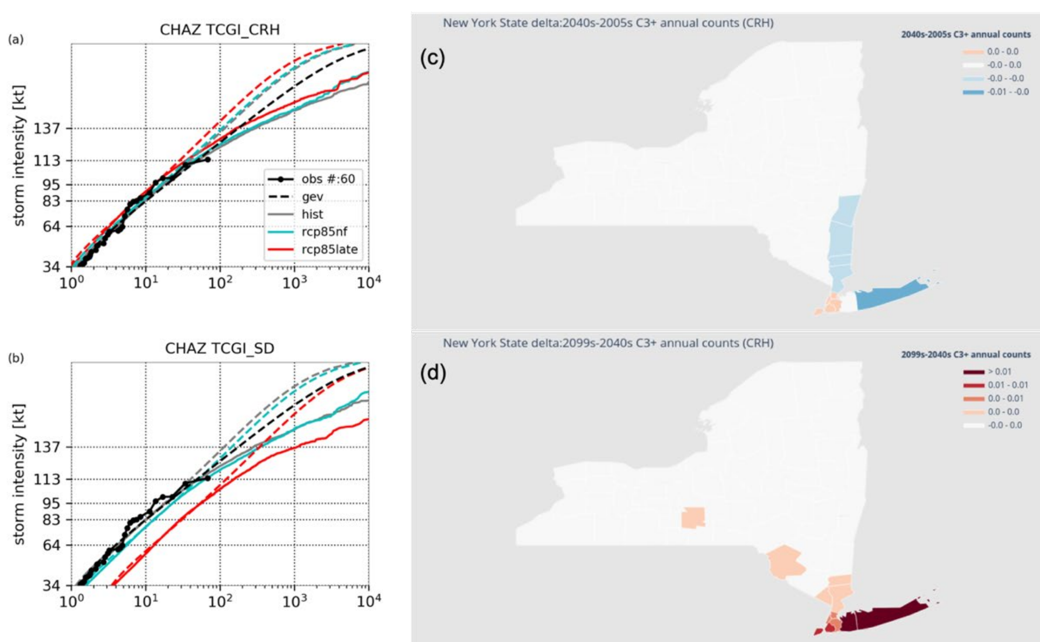
Simulation (a): the CHAZ-simulated annual NYS TC frequency in hist, rcp85nf, and rcp85late periods from TCGI_CRH and TCGI_SD experiments. The black dash lines indicate the observed frequency from 1951 to 2019 IBTrACS data. Simulation (b): the normalized track density difference between rcp85nf and rcp85late periods, and simulation (c): changes (in %) in the values of NYS storm intensity, translation speed, and impacting angle from hist to rcp85nf (blue) and from rcp85nf to rcp85late (orange) at 10, 25, 50, 75, 95 percentiles. The black line shows the 95% confidence interval. The numbers showing at the bottom of each panel are the observed values in kt, kilometers per hour (km/hr), and degree from east (increase counterclockwise) for intensity, translation speed, and impacting angle, respectively.



NYS landfalling hurricane risk is then assessed using the annual frequency and return period curve of the landfall intensity and the impacting wind speed. The latter is an average recurrence interval. Figures 4a and 4b show the return periods of impacting intensity within 300 km from the center of Long Island. In the CHAZ TCGI_CRH projections, the return periods shorten (increasing risk) while they become longer (decreasing risk) in the TCGI_SD projections as the climate warms. This again reflects the influence of the projected Atlantic hurricane frequency on the regional risk. Another important feature in Figures 4a and 4b is that the landfall intensity distribution does not follow the generalized extreme value (GEV) distribution (dashed line), which challenges the use of GEV with observations to estimate long-term risk, a common practice in hurricane risk assessment. Next, the annual exceeding frequency of the regional impacting wind is calculated at the county level. Figures 4c and 4b show the climate change delta (differences between the two climate periods) of the exceeding frequency of the major hurricane wind strength in the TCGI_CRH simulations. There is an increase in the New York area from historical to near future and an overall increase in the wind risk in New York City, Long Island, and Hudson Valley regions in the late 21st century. Details of the exceedance frequency for each county are provided in the next section.

Figure 4. The Return Period of Landfalling Storms and the Changes in the Impacting Frequency of the Storm Wind

Simulation (a): the return period computed from observations (black-dotted line) and CHAZ TCGI_CRH experiments in hist (gray), rcp85nf (blue), and rcp85late (red) periods. The dashed lines show the return period curve estimated using generalized extreme value theory. Simulation (b) is the same as (a) but for CHAZ TCGI_SD experiments. Simulation (c) is the climate change delta in annual frequency of NYS counties experiencing Saffir-Simpson Category 3+ surface wind from hist to rcp85nf periods. Simulation (d) is the same as (c) but for the difference between rcp85nf and rcp85late.



1.4 Deliverables

The deliverables of the project include a large set of synthetic NYS hurricanes, landfall return levels for the State, and spatial maps of landfall wind probability with specific thresholds.

1.4.1 CHAZ Event Sets

There are 30 files in total in the CHAZ generated NYS storms, and the event sets are organized by the climate models, the climate periods, and the experiments (indicated by the file name).[3] For example, CCSM4NYS_2005_SD.nc contains CHAZ synthetic storm tracks using TCGI_SD, downscaled from CCSM4 in the historical period (1951–2005). The files are in the netcdf format, a self-describing data format that is commonly used in atmospheric and climate sciences. Here the team provides an example showing how to read the data in python:

```
In [1]: import xarray as xr

In [2]: ds = xr.open_dataset('GFDL_CM3NYS_2005_CRH.nc')

In [3]: ds
Out[3]:
<xarray.Dataset>
Dimensions: (ensembleNum: 40, lifelength: 125, stormID: 929)
Dimensions without coordinates: ensembleNum, lifelength, stormID
Data variables:
 time (lifelength, stormID) float64 620.0 1.69e+03 ... -5.479e+04
 longitude (lifelength, stormID) float64 299.0 278.8 280.2 ... nan nan nan
 latitude (lifelength, stormID) float64 15.81 24.75 22.92 ... nan nan nan
 Mwspd (ensembleNum, lifelength, stormID) float64 25.0 30.0 ... nan nan
 year (stormID) int32 1951 1954 1954 1955 1955 ... 2000 2003 2005 2005
```

1.4.2 Landfall Storm Return Level

Figures 4a and 4b show the return levels of NYS storms. Specifically, the State storms are defined as storms passing through a circle centered at 73.13ºE and 40.79ºN with a radius of 300 km. The CSV files of the return periods can be located at Columbia University.[4,5] The data are also shown in Table 1.

Table 1. Return Level of Landfalling Hurricanes

The landfall NYS storm return period from 1951–2019 observations, CHAZ-CMIP5 historical (1951–2005), rcp85nf (2006–2040) and rcp85late (2070–2099) periods at Saffir-Simpson scale.

SS_SCALE	OBS	HIST	RCP85NF	RCP85LATE
		TCGI_CRH		
34	1.317948718	1.256097755	1.122103437	1.006994631
64	4.868941585	4.265498486	3.798319641	3.267150051
83	7.593333333	9.802383098	8.791696546	7.186958656
96	13.39851852	18.52230987	17.34387632	13.3505182
113	61.2	50.14844857	44.88919594	35.2051862
137	68	297.2837427	263.789182	165.6607599
		TCGI_SD		
34	1.317948718	1.243036329	1.594275022	3.744348063
64	4.868941585	4.354123273	5.61004447	13.01956617
83	7.593333333	9.925108575	12.8420455	29.4434138
96	13.39851852	19.27542443	24.1345924	58.46148859
113	61.2	51.92871898	63.06271243	153.907733
137	68	280.3517646	346.0519825	1088.314188

1.4.3 Annual Exceeding Frequency of Storm Impact Wind at County Level

Figures 4c and 4d are examples showing the changes in the annual exceeding frequency of storm impact wind in NYS counties CHAZ TCGI_CRH experiments. This deliverable includes both figures similar to Figures 4c and 4d and tables of the frequency at each period for each NYS county (e.g., Table 2).[6]

Table 2. Annual Frequency of Hurricane Wind at Albany and Bronx

An example showing the .csv files of annual frequency of NYS hurricane impact wind at Saffir-Simpson scale. In the headings, the year indicates the period: 2005, 2040, and 2099 are hist, rcp85nf and rcp85late respectively, and the county is labeled at the right end of the table.

2005_TS+	2005_C1+	2005_C2+	2005_C3+	2005_C4+	2005_C5+	2040_TS+	2040_C1+	2040_C2+	2040_C3+	2040_C4+	2040_C5+	2099_TS+	2099_C1+	2099_C2+	2099_C3+	2099_C4+	2099_C5+	county
0.233075023	0.007683906	0.00044826	0.000104879	6.24E-06	0	0.275465456	0.007677578	0.00044642	5.62E-05	0	0	0.32982502	0.009815577	0.00050998	3.86E-05	0	0	Albany
0.725285893	0.033334169	0.002791754	0.000499833	5.35E-05	0	0.784661834	0.036095753	0.002655329	0.000548363	2.57E-05	0	1.063659139	0.050447454	0.004692249	0.000851286	7.17E-05	0	Bronx

1.4.4 The Open-Source CHAZ Model

As indicated by the project title, the CHAZ model is designed to be an open-source tool. The proposal team is currently working with a Columbia University graduate student, Emma Schetcher, to document the CHAZ model and make it user friendly and machine-independent.[7]

1.5 Key Points

- The confidence in the CHAZ model stems from its underlying physics-informed statistical machinery, which allows CHAZ not only to capture the statistics of the historical TCs but also to simulate the climate change impact on global TCs.
- CHAZ is shown to be a suitable tool for assessing TC risk at regional scale.
- Changes in the global and basin-wide TC frequency are epistemically uncertain—due to the lack of theoretical knowledge of tropical cyclone genesis, the team is not confident whether there will be more or less tropical cyclone genesis as the climate warms. However, it is noteworthy that an ongoing work led by the research team suggested that at least for North Atlantic hurricanes in the recent history, the observed annual frequency from 1951 to 2019 is more consistent to the CHAZ simulations using CRH in the TCGI, the one suggests an upward (increasing) trend in the frequency.
- The most confident climate change impact on global TCs is the increase in the global and basin-wide ratio of extreme storms. In the State, the upward trend in TC intensity is less confident in the next 30 years, but it is confident by the end of 21st century.
- There is no clear signal in climate change impact on the storm motion globally, at individual basins, and in the NYS area.
- NYS hurricane wind risk largely depends on the projected Atlantic hurricane frequency. However, regardless of the frequency, if a hurricane hit NYS in a warming climate, the consequence is likely to be more severe due to the increased intensity.

2 Academia and Other Broader Impacts

This NYSERDA project supported the foundational development of the CHAZ model, which enables many academia research activities and collaborations, especially on the topic of climate change impacts on hurricane activity. Its usage for seasonal and sub-seasonal hurricane activity has been explored recently as well. As the main goal of the CHAZ model development is to assess regional risk in a changing climate, the research results from this project also increase the collaborations between the research team and private sectors, such as catastrophic modeling groups, insurance and reinsurance companies, investment firms, etc. The openness of the CHAZ model will bring the state-of-art academia research results to the commercial catastrophic modeling. In sections 2.1 and 2.2, the team briefly describes the research activities and collaborations enabled by this NYSERDA project.

2.1 Past and Ongoing Research Activity

2.1.1 Columbia Climate and Life Fellowship: Asymmetrical Tropical Cyclone Wind

In 2018, Lee received the Columbia Climate and Life (CCL) fellowship to study Asymmetrical Tropical Cyclone Wind Fields in Risk Assessment. The project, similar to this project, aims to develop a parametric wind component of the CHAZ model. The wind component was developed by Qidong Yang, a Columbia University undergraduate student, advised by Lee and Tippett. Yang, Lee and Tippett are currently working on submitting the fellowship study to the Journal of Weather and Forecasting (Yang et al. 2020a).

2.1.2 Tropical Cyclone Hazard to Mumbai

In 2019, Sobel led a research project using CHAZ to study tropical cyclone hazards to Mumbai, India. Mumbai is a low-lying coastal city that is highly vulnerable to storm surge. Located on the west coast of India facing the Arabian Sea, Mumbai has not experienced extreme tropical cyclones in recent history. In other words, when using historical data, the estimated TC risk for Mumbai is zero. Using CHAZ's reanalysis simulations from Lee et al. (2018) and Sobel et al. (2019) showed that while the probability is low, it is possible for Mumbai to experience major hurricane strength tropical cyclones in the current climate.

2.1.3 Swiss Reinsurance Company Ltd: Climate Change Signal in Hurricanes Today

In 2019, Sobel was awarded a research grant from Swiss Reinsurance Company Ltd (commonly known as Swiss Re). The project aimed to detect climate change signals in hurricanes today using the CHAZ model. Specifically, the proposal team used CHAZ-CMIP5 downscaled synthetic events from Lee et al. (2020a) along with a new downscaling experiment using CMIP5 pre-industrial control forcing. One of the project results is that the observational data is more consistent with the CHAZ TCGI_CRH simulations than with the TCGI_SD simulations, adding weight to the possibility of increasing Atlantic hurricane activity as the Earth's climate warms. The project results are current in preparation for publication (Lee et al. 2020c).

2.1.4 A Long Short-Term Memory Model for Global Rapid Intensification Prediction

Qidong Yang worked with Lee and Tippett and developed a machine-learning based rapid intensification prediction model. The CHAZ development data used in Lee et al. (2018) were used in this project. The project result was published in Journal of Weather and Forecasting in 2020 (Yang et al. 2020b).

2.1.5 Effects of Climate Change on the Movement of Future Landfalling Texas Tropical Cyclones

This is a National Science Foundation (NSF)-funded project led by Dr. Pedram Hassanzadeh at Rice University. Lee and Camargo contributed to this study by using the CHAZ-CMIP5 downscaled synthetic storms to examine the climate change impact on Houston hurricane storm translation speed. The research result was published by Nature Communication in 2020 (Hassanzadeh et al. 2020).

2.1.6 Using Large-Eddy Simulations to Estimate the Risk of Extreme Wind Gusts in Tropical Cyclones

Lee is working with Dr. Daniel Stern at Naval Research Laboratory, Monterey CA, to study a possible way of using tropical cyclone track event sets (such as those from NHC best-track data and those generated by CHAZ) to estimate extreme wind gusts. Lee is currently working with Stern on publishing this work in the Journal of Monthly Weather Review (Stern et al. 2020).

2.1.7 Willis Reinsurance: Obtain Climate Change Conditioned Atlantic Tropical Cyclone Landfall Rates for a Number of Gates

Lee and Tippett were funded by Willis Reinsurance (Willis Re) to provide estimates of climate change impacts on Atlantic hurricane landfall rates and forward motion for several U.S. coastal gates.

2.1.8 Applying CHAZ to Sub-Seasonal Time Scale TC Activity

Dr. Shuguang Wang at Columbia University is currently using CHAZ to study contributions of the instraseasonal and synoptical steering flows on typhoon tracks and landfall locations in the Western Pacific.

2.1.9 The Vulnerability Curve Component of the CHAZ Model

A Lamont postdoc fellow, Dr. Jane Baldwin (mentored by Sobel and Camargo) is currently working with the World Bank (Dr. Brian Walsh) to use CHAZ for estimating the impacts of typhoons on the well-being behaviors in the Philippines. To conduct this research, she is developing a vulnerability curve component for the CHAZ model. Dr. Baldwin will present the project results Assessment of Tropical Cyclone Wind-Related Risks to Wellbeing in the Philippines at the 2020 American Geophysical Union conference.

2.1.10 OASIS Collaboration

The research team is collaborating with OASIS Loss Modeling Framework, an open-source catastrophe modelling platform, to provide open data to the risk community. The team has released the CHAZ-reanalysis runs to the OASIS.

2.1.11 Aon Collaboration

Sobel is leading a pending proposal submitted to Aon on Quantification of Climate Change Scenarios Risk Using Catastrophe Models.

2.2 Four Pending Research Grants

The following pending research proposals use the CHAZ model:

- Sobel is developing a Columbia Work Project Disaster Risk Reduction and Climate Adaptation.
- Lee is participating in a collaborative NSF Coastlines and People (CoPe) proposal (led by Rice University) on Focused CoPe: Hub for Adaptive Resilience of Coastal Industrial Community.
- Camargo and Lee are participating in an NSF proposal (led by University of Hawaii) using CHAZ to study how climate change induced changes in ENSO diversity impact hurricane activity.
- Lee is participating in a National Geographic grant (led by California Polytechnic State University [Cal Poly]): The Social Consequences of Disasters and Storms.

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Appendix A. The CHAZ Model

The CHAZ model contains three modules. The TCGI genesis model, the beta-advection track model and an autoregressive intensity model. There are two types of **TCGI** used here. In the first one, CRH is used as the moisture variable:

$$\boldsymbol{\mu = \exp\left(b + b_{\eta}\eta_{850,c} + b_{CRH}CRH + b_{PI}PI + b_{SHR}SHR\right).}$$

In the second one, SD is used:

$$\boldsymbol{\mu = \exp\left(b + b_{\eta}\eta_{850,c} + b_{SD}SD + b_{PI}PI + b_{SHR}SHR\right).}$$

Here μ is the estimated seeding rate, and b is the intercept and $b_x$represents the coefficient of parameter *X*. The subscript 'c' in $\eta_{850,c}$ indicates that TCGI uses absolute vorticity clipped at 3.7×10^{-5} (Tippett et al. 2011). The team calls these two sets of experiments CHAZ-CRH and CHAZ-SD.

The **beta-advection track model** defines the steering flow as weighted large-scale winds at 850 hPa and 250 hPa plus a "beta drift" component:

$$\mathrm{V}_{\boldsymbol{advection}} = \boldsymbol{0.8 \times V_{850hPa} + 0.2 \times V_{250hPa} + \beta.}$$

Lastly, the **autoregressive intensity model** can be expressed as

$$\boldsymbol{V_{t+12h} - V_t = L(V_t, V_t - V_{t-12h}, X_t, X_{t+12h}) + \epsilon_{t+12h}}$$

Where $V_t$is the storm intensity at time t and X are environmental variables related to TC intensification. The deterministic component, $L(V_t, V_t - V_{t-12h}, X_t, X_{t+12h})$, has the form of a second-order vector autoregressive linear model with environmental variables as exogenous inputs. ϵ_{t+12h} here is the stochastic component accounts for the internal storm dynamics and does not depend explicitly on the environment.

Endnotes

1 In an ongoing, follow-up work (Lee et al. 2020c), Lee, Sobel, Camargo, and Tippett conduct a set of in-depth statistical analyses and suggest the observed Atlantic hurricane activity from 1951–2019 is more consistent with CHAZ-CMIP5 downscaling simulations using column integrated relative humidity. Thus, at the time when the report was written, the team placed more confidence in the scenarios of increasing global TC frequency as the climate warms.

2 The mathematical formula of CHAZ is described in the Appendix A.

3 "Index of Final Report".https://iri.columbia.edu/~clee/test/NYS/finalreport/1.4.1/

4 https://iri.columbia.edu/~clee/test/NYS/1.4.2/CRH_NYS_rp.csv

5 https://iri.columbia.edu/~clee/test/NYS/1.4.2/SD_NYS_rp.csv

6 All figures and csv files are at https://iri.columbia.edu/~clee/test/NYS/finalreport/1.4.3

8 A working-version of the public release is at https://cl3225.github.io/CHAZ.github.io/

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