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Borja G. Reguero
Pelayo Menéndez Fernández
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Modeling Tropical Cyclone Risk While Accounting for Climate Change and Natural Infrastructure in the Caribbean

Borja G. Reguero[e]
Pelayo Menéndez Fernandez[*]
Allison Bailey[b]
Katie Arkema[c]
Roberto Guerrero Compeán[d]

Abstract

This chapter describes tools and a methodology to model wind and flood risks from tropical storms under present and future climate accounting for natural infrastructure. Wind forcing provide a crucial link to hydrodynamic models that can be used in risk assessments to estimate extent of and damages from flooding and erosion. Further, such flood risk models can then include the effects of ecosystems, such as mangroves, to model the effects on risk of conservation and restoration outcomes but also individual nature-based projects to reduce risks. The chapter describes hazard modeling techniques and presents simple applications to (1) assess the effect of climate change in the Caribbean, by estimating wind fields for tropical cyclones for present and future climate scenarios, (2) address the limited observations in hurricane data by using existing tools to derive synthetic storms and readily use them in coastal models, and (3) compare modeling approaches and datasets to provide recommendations for assessing flood attenuation of mangroves. The results

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[*] Institute of Marine Sciences. University of California Santa Cruz, Santa Cruz, CA, 95060, USA.

[b] Natural Capital Project, Stanford University c/o School of Environmental and Forest Sciences, University of Washington, Seattle, WA, USA.

[c] Corresponding author. Pacific Northwest National Laboratory; Natural Capital Project, Stanford University c/o School of Environmental and Forest Sciences, University of Washington, Seattle, WA, USA.

[d] Inter-American Development Bank, 1300 New York Ave NW, Washington, DC, 20577, USA.

and data developed in these applications is available with this chapter to be used in other local applications, or to infer damages from wind or in flood hazard models.

Keywords: Disaster risk assessment, tropical cyclones, flood hazard modeling, mangroves.

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Introduction

Storms, floods, droughts and other extreme weather events increasingly threaten cities, regions and entire nations. Economic losses from such events are increasing, driven by a combination of development in the world's most exposed regions, such as coastal areas, and a changing climate (Emanuel 2005; Estrada et al. 2015; Guerrero Compeán and Lacambra Ayuso 2020, Reguero et al. 2020). Hurricanes, typhoons and cyclones are among the costliest natural hazards globally and represent one of the largest risks to tropical coastal nations, posing a significant challenge to sustainable economic growth goals for many countries (Munich Re 2013).

Hurricanes represent a major threat across all Caribbean shorelines. Hurricane Katrina, which hit New Orleans in 2005, was the costliest natural disaster of all time for the insurance sector, with losses totaling more than US$ 60bn. Hurricane Dorian (2019) was one of the strongest Atlantic hurricanes on record - and the strongest hurricane to have ever hit The Bahamas (Image). According to the Inter-American Development Bank, Dorian caused $3.4 billion in damages (Avila et al. 2020, Bello et al. 2020), an amount equal to one-quarter of The Bahamas' Gross Domestic Product (GDP). In 2020, Hurricanes Eta made landfall in Nicaragua as a Category 4 storm and led to the deaths of at least 175 people and caused $8.3 billion in damage. Days later, Hurricane Iota rapidly intensified into a high-end Category 4 hurricane and made landfall in the same general area of Nicaragua that Eta, scaling the catastrophic damage. These two storms made the year 2020 the only recorded season with two major hurricanes in November. In 2021, the Atlantic hurricane season was the third-most active Atlantic hurricane season on record. Hurricane Ida became the deadliest and most destructive tropical cyclone in 2021 after striking southeastern Louisiana at Category-4 strength, 16 years after Hurricane Katrina decimated that same region. After devastating Louisiana and moving farther inland, Ida caused catastrophic flooding and spawned several destructive tornadoes across the Northeastern United States. Damage estimates from the storm exceeded $75 billion, contributing to over 93% of the total damage done in 2021 season.

Extremely active Atlantic hurricane seasons are now twice as likely as they were in the 1980s due to global warming, threatening life and property in coastal areas (Pfleiderer et al., 2022). Under future climate scenarios, expected loss as a proportion of GDP could rise to between 2% and 9% by 2030 (CCRIF 2010). In absolute terms, expected losses may triple between now and 2030; and hurricane induced wind damage has the largest damage potential, accounting for up to 90% of the overall damage.

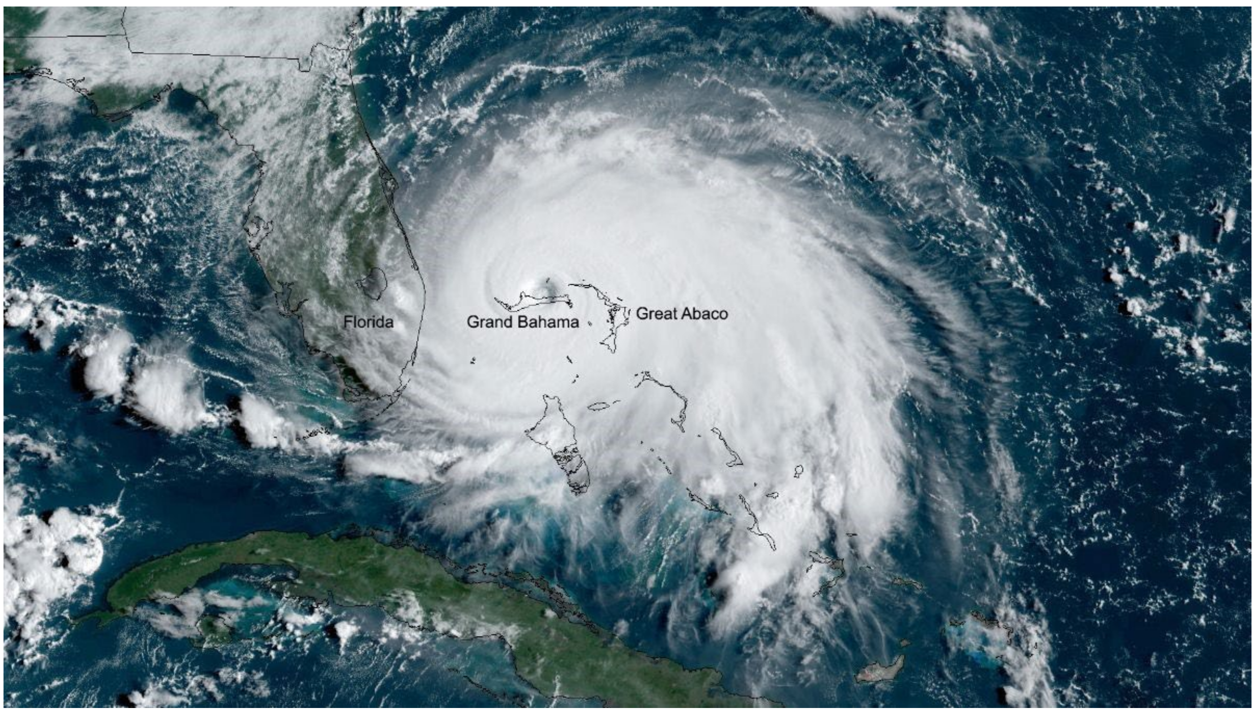

Image. Satellite View of Hurricane Dorian over The Bahamas, September 2, 2019. Source: NOAA.

In this Technical Note, we describe available tools and a methodology to model present and future risks using wind fields from individual storms under future climate, which can be used to model the role of natural infrastructure in coastal adaptation. Wind field information provides a crucial link to hydrodynamic models that can be used in a risk assessment framework to estimate extent of and damages from flooding and erosion. There are tools that can facilitate the analyses of damages and risk reduction such as historic hurricane observations, synthetic generation of storms, and numerical coastal models that can include the effects of ecosystems, such as mangroves, on overall risk. To illustrate such capacities, we provide simple examples of applications in parts of the Caribbean, as an example for detailed studies.

Current status of research and practice

Tropical cyclones usually develop from the large-scale clusters of thunderstorm cells over tropical oceans, generated from the evaporation of surface waters with temperatures higher than 26–27°C. When they reach hurricane force (>118 km/h), they are named "hurricanes" in the Atlantic and north-east Pacific regions, "cyclones" in the Indian Ocean and South Pacific, and "typhoons" in the northwest Pacific. Tropical cyclones can be active for several weeks and can stretch across large areas, reaching wind speeds of more than 250 km/h and in some cases exceeding 300 km/h. They mainly affect coastal regions and islands between 10N° and 40S° latitudes. In developing and emerging countries, especially in small island states, extreme tropical cyclones can trigger humanitarian disasters with loss of human life and macroeconomic impacts that can hinder socio-economic development (Munich Re 2013).

Tropical cyclones not only drive damaging winds, they also drive coastal flooding through storm surges, wave action, and intense rainfall. Rising mean sea levels combined with normal tides create hurricane storm tides, which can increase average water levels by up to 15 feet (4.5 m) or more . Wind driven waves from storms can thus be superimposed on the storm tide. Waves generate runup on the shoreline that produces additional increases in water levels and can cause severe flooding in coastal areas, particularly when storm tides coincide with normal high tides (Losada et al 2013). Furthermore, as waves can reach higher and further inland, the potential for erosion and structural damage is greatly increased during storm conditions. In addition to coastal flooding and high winds, tropical cyclones also cause torrential rains that produce flash floods and riverine and urban flooding (e.g., WMO, n.d.). Wind and flood models are used to characterize these storm impacts and assess damages (Emanuel, 2004; Knutson et al., 2010; Resio and Irish, 2015).

Cyclone activity is affected by natural climatic cycles, such as warm and cold phases affecting the surface temperatures of tropical oceans, but climate change is also playing a role. The latest scientific studies indicate that the number of tropical cyclones will remain virtually unchanged in most ocean regions through the end of the 21st century. However, some models project that major storms (Categories-4 and -5 on the Saffir-Simpson scale [e]) will occur more frequently in most regions of the Caribbean (Knutson et al., 2020). Precipitation around storm centers will likely increase, due to higher water vapor content in a warmer atmosphere associated with warmer ocean temperatures. Research indicates that climate change has already significantly increased the probability of extreme precipitation such as that seen in 2017 in the Houston area during Hurricane Harvey (Knutson et al., 2019). A recent study has also demonstrated that the historic increase in Atlantic tropical cyclone activity since the 1980s (Emanuel, 2005; Estrada et al., 2015) can be ascribed to changes in atmospheric circulation and sea surface temperature increase (Pfleiderer et al., 2022). Finally, years with exceptional hurricane activity, such as 2004, 2005 (Katrina), 2017 (Harvey, Irma, Maria), and 2020 may become more common in future due to warmer temperatures, although uncertainties about future changes in the risk of such seasons remains high. While future coastal risk will be determined by both sea-level rise and changes in tropical and extratropical storms, it is notable that sea level rise will increase the risk of coastal flooding from storms even if the other characteristics of the storms (frequency, intensity, rainfall, etc.) do not change with climate warming.

To manage these risks and prepare for the future, many governments and coastal communities require precise information on the economics of climate change and how to incorporate nature-based approaches in risk reduction strategies. Some of the key questions posed by stakeholders are (ECA, 2019):

1) What is the potential climate-related damage to coastal regions over the coming decades?
2) How much risk can be averted by proactive adaptation, including through nature-based approaches?
3) What investments will be necessary to support adaptation, and would the benefits outweigh the costs?

[e] https://www.nhc.noaa.gov/aboutsshws.php

Since tropical cyclones are one of the main drivers of climate risks in the Caribbean, this chapter provides an introductory description of some methods for modeling tropical cyclone-related risks to answer the first of these questions accounting for ecosystems and nature-based infrastructure.

A risk modeling framework to account for adaptation benefits and natural infrastructure

One risk management framework that aims to address the three key questions above was first introduced by the Economics of Climate Adaptation Working Group – a group comprised of experts from Climate Works, the European Commission, the Global Environmental Facility, McKinsey, Swiss Re, the Rockefeller Foundation, UNEP, and the Standard Chartered Bank, among other partners. The proposed evaluation framework helps inform climate-resilient development and decision making by considering present and future total climate risks, evaluate adaptation strategies, and inform decision-making under uncertainty comparing costs and benefits (ECA 2009). The approach follows several key steps (SwissRe 2011; Souvignet et al. 2016):

1) Conduct rigorous assessment of climate risks through scenario analysis, including present and future hazards, to inform and manage uncertainty about future climate and socioeconomic pathways.
2) Understand and characterize the inventory of local adaptation measures available to address those risks (present and future), and the cost and benefits of each. These interventions can include hazard mitigation measures and other policy, or socioeconomic investments designed to reduce total risk.
3) Prioritize the most effective measures and integrate them in socioeconomic development strategies.

Climate-related risk in its most simple form is a function of three components —hazard, exposure, and vulnerability (IPCC, 2012). New data sources and technologies are available for modeling and estimating hazard, exposure, and vulnerability (see Technical Appendix). These three components drive the scale and impacts of any disaster (GFDRR 2014):

- Hazard refers to the likelihood and intensity of a potentially destructive natural phenomenon, such as ground shaking from an earthquake or wind speed associated with a tropical cyclone.

- Exposure refers to the location, attributes, and value of the assets, such as people, buildings, businesses or infrastructure.
- Vulnerability relates the degree or extent the assets get impacted when exposed to the forces produced by a hazard event. For example, a building's vulnerability to floods increases with the velocity and flood water depths but decreases for elevated or reinforced buildings. Similarly, socioeconomic contexts can make responding to a hazard impact more or less difficult. Therefore, structural, physical, and socioeconomic vulnerability are relevant to risk assessment.

This framework can be used to assess present and future risk (by incorporating in the risk modeling the future changes in hazards, e.g., sea level rise or changing storms) and assess the costs and benefits of adaptation options. The role of adaptation is visualized in Figure 1 (e.g., Reguero et al. 2018): first, through attenuation of hazards, such as through implementation of nature-based solutions; second, the distribution or influence in assets and people such as relocation policies or planning development outside from flood prone areas; and third, influencing the vulnerability, for example by reinforcing or flood proofing buildings or designing new building codes. Such 'benefits' of implementing adaptation investments to reduce present and future risks can be represented in net present values and used in costs and benefit analysis by ranking strategies.

Cost effectiveness and, preferably, cost-benefit analyses can use these inputs to inform what is the present value of current and future adaptation actions to reduce risk, decide between what measures should be implemented or when to implement them. For example, resilience investments can be expressed in benefit to cost ratios (e.g., cost benefit waterfall in lower row in Figure 1) that can reflect the reduction of risk potentially achieved (width of bars in Figure 1) and the cost-benefit ratio (i.e., height of bars in the Figure).

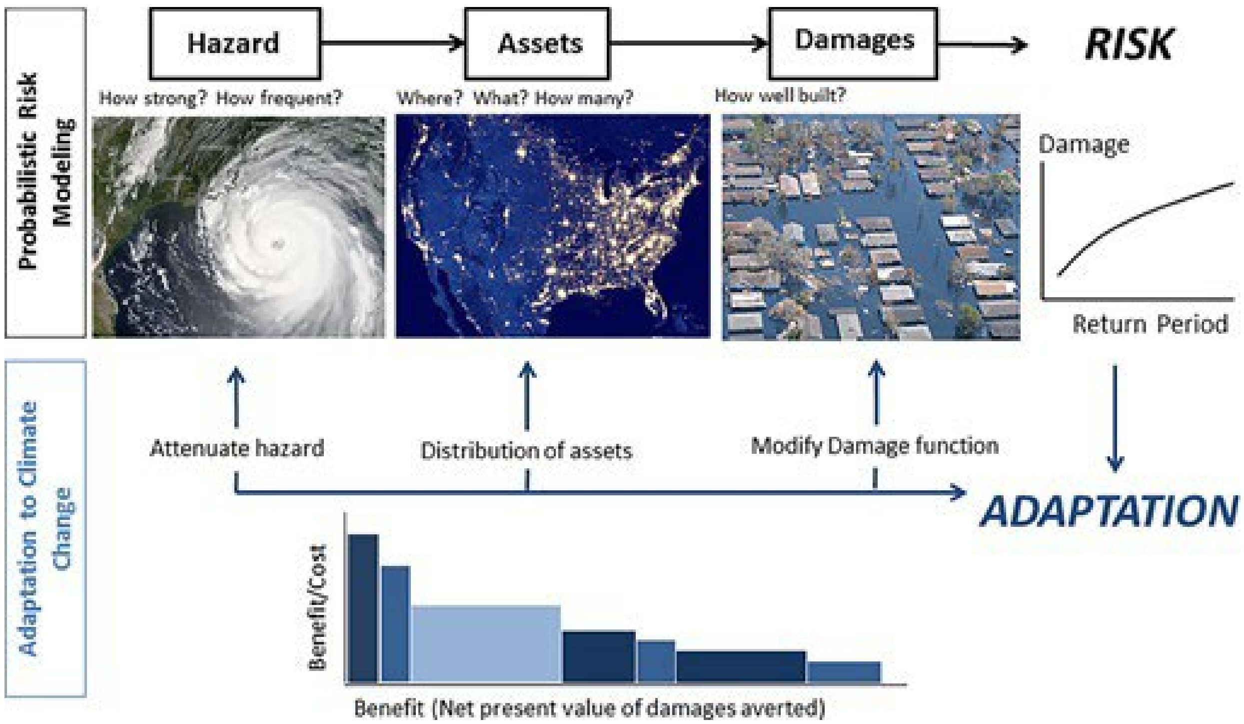

Figure 1. Risk assessment framework and the role of adaptation. Source: Reguero et al. (2018)

Integrated probabilistic risk modeling tools

Several tools and datasets are publicly available to assess climate-related risks (The Review 2008) to use the framework described above. Although the scope of this document is not providing a comprehensive overview of risk models and relevant datasets, some examples are outlined below for illustrative purposes:

(1) CLIMADA - https://wcr.ethz.ch/research/climada.html

Using state-of-the-art probabilistic modelling, CLIMADA allows to estimate the expected economic damage as a measure of risk today, the incremental increase from economic growth and the further incremental increase due to climate change. The economics of climate adaptation methodology as implemented in CLIMADA provides decision makers with a fact base to understand the impact of weather and climate on their economies, including cost/benefit perspectives on specific risk reduction measures. The model is well suited to provide an open and independent view on physical risk, in line with the TCFD (Task Force for Climate-related Financial Disclosure) and underpins the Economics of Climate Adaptation (ECA) approach.

As of today, CLIMADA provides global coverage of major climate-related extreme-weather hazards, namely: (i) tropical cyclones, (ii) river flood, (iii) agro-drought and (iv) winter storms. For these hazards, historic and probabilistic event sets exist, for some also under select climate forcing scenarios (RCPs) at distinct time horizons. CLIMADA also estimates risk using Asset information, which are characterized by the geographical distribution of people, houses, activities, public infrastructure; Damage functions, that relate impact to the economic consequence - or any other pertinent metric, like people affected; and (4) Risk reduction and Adaptation measures, such as improved building codes, seawalls, sandbags, and nature-based approaches (e.g. Reguero et al 2018).

(2) CAPRA - https://ecapra.org/

The CAPRA (Probabilistic Risk Assessment) Platform is an initiative that aims to strengthen the institutional capacity for assessing, understanding and communicating disaster risk, with the ultimate goal of integrating disaster risk information into development policies and programs. Under the CAPRA platform, government, institutions, private companies and other agencies address specific development challenges and meet disaster risk information needs through specialized software applications, extensive documentation, consultancy and advisory services, hands-on practical training and other complementary services.

Models like CLIMADA and CAPRA can facilitate deriving damages from tropical cyclones winds and flooding. Alternative models also exist in the risk industry, while others are often built on a per case basis by private, public and academic entities. However, they all work on the principles outlined above. Although CLIMADA and CAPRA include modules for deriving tropical cyclone hazards (wind), other approaches exist to assess the effect of climate change in tropical activity or derive hazards with more granularity.

Characterizing cyclone risks under climate change

Changes in tropical cyclone (TC) activity are among the most potentially consequential results of global climate change in the Caribbean, and it is therefore of considerable interest to understand how anthropogenic climate change may affect them. Global climate models are currently used to estimate future climate change, but the current generation of models lacks the spatial resolution necessary to resolve the processes occurring within tropical cyclones. Wind speeds are especially important contributors to damage, but they also generate storm surges and waves that drive flooding and erosion. Below, we provide a simplified approach for projecting future hurricane tracks and wind speeds for use in subsequent steps of risk assessments in the Caribbean.

First, using a handful of observed TCs in recent history has severe limitations when estimating extreme wind, storm surge and wave conditions for defining risks. Therefore, assessing wind or flooding risk from TC first requires generation of synthetic TC. Two different types of models are generally available for this: statistical and simple track models and dynamic and empirical track models. Simple track models generate synthetic tracks using observed characteristics of cyclones (e.g., wind speed, central pressure, radius of maximum winds, heading, translation speed) and sampling from probability distributions that may involve autoregressive processes and Monte Carlo simulations. These models are characterized by their simplicity but provide an efficient way to derive TC activity. Coupled statistical-dynamical models, however, use autoregressive processes for simulating the tracks and dynamic models for simulating the intensity and other properties of the cyclones (Emanuel, 2017, 2004).

In the recent literature, several synthetic TC databases and/or methods have been published for track generation. For example, the synthetic algorithm Synthetic Tropical cyclOne geneRation Model (STORM) provides a global dataset representative of 10,000 years of TC activity under present climate conditions (Bloemendaal et al., 2020). Other simulations have also been developed for the North Atlantic and the Caribbean (Emanuel et al., 2006; Hojjat Ansari et al., 2021; Nederhoff et al., 2021; Vickery et al., 2000). Such synthetic storms can be used to derive wind fields and inputs for other models. For example, among these models, the open-source Tropical Cyclone Wind Statistical Estimation Tool (TCWiSE) uses an empirical track model based on Markov chains to simulate synthetic TC tracks and wind fields in a format that can be directly used in hydrodynamic models such as Delft3D to simulate coastal processes (Nederhoff et al., 2021). An application using the models for flooding in mangrove areas is provided in the next section.

One of the challenges of existing models have been to derive the effects of climate change in frequency and intensity of cyclones. Theory and high-resolution dynamical modeling studies indicate that greenhouse warming will cause a global shift towards stronger tropical storms, with intensity increases of 2–11% by 2100. Existing modelling studies also consistently project decreases in the globally averaged frequency of tropical cyclones, by 6–34%. Dynamic projections of tropical cyclones (Bender et al., 2010; Knutson et al., 2020, 2019, 2013) show that the simulated frequency response of very intense tropical cyclones to climate warming may vary from that of weaker tropical cyclones: the intense tropical cyclones tend to increase in frequency whereas the weaker tropical cyclones tend to decrease in frequency in the future. As dynamic simulations of tropical cyclones under global warming are complex, changes in frequency and intensity can be captured in synthetic generation of storms to simulate, as a first order of magnitude, the effects of climate change for risk assessments. The general approach includes the following sequence of steps:

1) Obtain publicly available historic storm information and generate a synthetic set of storms that increases the amount of information of TC action to infer basic statistics (e.g., historic TC landings for a certain coastline).
2) Generate future storms using expected changes in location, intensity, and frequency, based on previous ensemble of hurricanes for the basin (e.g. Knutson et al., 2020).
3) Generate wind fields for each storm (historic and future) using wind models.
4) Interpolate wind speeds at specific output locations, so they can be analyzed and used to calculate statistics, for example, the 100-year return period of wind speeds.
5) Use wind and pressure fields to force hydrodynamic models (e.g. ADCIRC, Delft3D) to derive coastal hazards information.

We provide below an example of a simple assessment of present and future wind action in the Caribbean following steps 1-4, building from routines applied in CLIMADA-tropical cyclones (Aznar-Siguan and Bresch, 2019). Although the dataset is a first approximation to the effects of climate change in the wind hazard in the Caribbean, the data is shared with this chapter so it can be used in other applications and frameworks (similarly to the application for mangrove flood attenuation in this chapter).

Example 1. Climate change effects on TC winds in the Caribbean.

To showcase how these tools and datasets can be applied at regional scale, this section presents a case study for deriving wind action across the Caribbean basin. Based on the original CLIMADA's open-source hurricane model [f], this section provides a concrete example of how to develop region-wide information on coastal hazards, with an application for wind hazards. The example uses readily available information on historic storms, climate change projections and open tools to understand hurricane risk in the Caribbean. The result is an updated dataset of historic and future TC activity in the region, which can be used to infer the effects of climate change on projects and identify adaptation options. The wind speed statistics are then available to apply in hydrodynamic models, wind impact assessments or for informing actions to address future changes in wind damage risk.

The first step involves using historical information on storms to derive statistically consistent information across the Caribbean basin (see Historic TC activity captured by historic observations in Figure 2). TC track data since the year 1980 is available from the International Best Track Archive for Climate Stewardship (IBTrACS, version v04r00) (Knapp et al., 2018). https://www.ncdc.noaa.gov/ibtracs/) that provides global tropical cyclone tracks information worldwide.

[f] https://climada-python.readthedocs.io/en/latest/tutorial/climada_hazard_TropCyclone.html

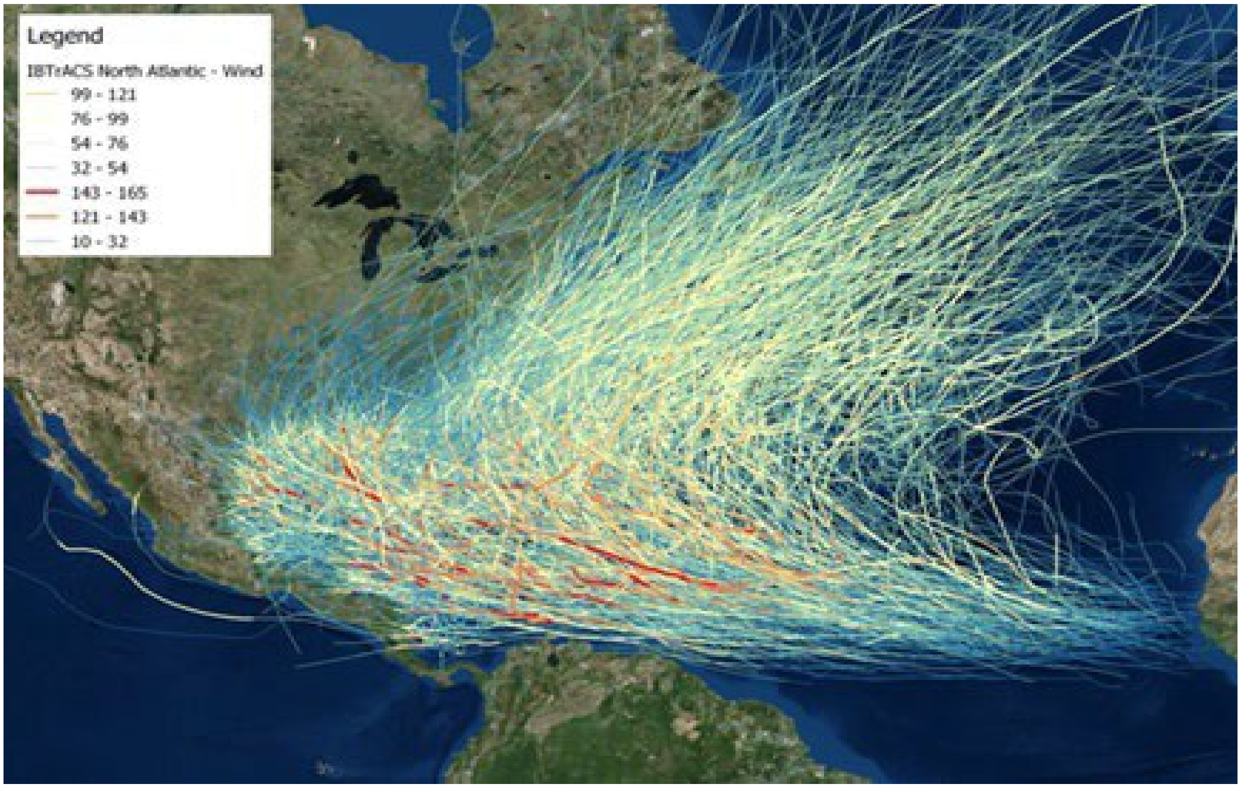

Figure 2. Historical storms in the North Atlantic. The lines represent location and wind speed of tropical cyclones in the North Atlantic basin since the year 1980. Source of data: https://www.ncdc.noaa.gov/ibtracs/.

Second, the historic information can be used to derive a stochastic set of storms for statistical wind intensity-probability analysis. The methods are detailed in (Aznar-Siguan and Bresch, 2019), and summarized below. Synthetic tracks were obtained from historical ones by a direct random-walk process, starting at slightly perturbed initial locations of the tracks (Emanuel et al., 2006). The model framework for this application generates probabilistic tracks based on five components:

(1) A storm track model bootstraps synthetic tracks from each historic storm using a gaussian generation area, which is controlled by a parameter $\delta\delta$ within a radius of the original initial point of the track[g].

(2) A random track evolution model generates a new track, which is controlled by a maximum heading allowance $\delta\delta\delta\delta$ and translation speed (i.e. how new track points deviate from the previous position).

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[g] Other models use Markov processes and historic information on sea surface temperature to create the generation areas, e.g. (Nederhoff et al., 2021).

(3) A statistical intensity model adjusts the original track wind speed (w) at each time step based on a gaussian distributions of intensities (e.g. $ww \pm \delta\delta ww$).
(4) Decay of wind intensities after landfall is taking into account by building an exponential decay coefficient of the wind speeds (and corresponding increasing pressure) and applying it to the synthetic tracks after landfall.
(5) A parametric wind field model estimates the time-varying two-dimensional surface wind fields along each time step of the storm.

The specific configuration for this example included a generation of 20 new synthetic tracks from each historic track. The random walk process was limited to a maximum random starting point of 1.5 degrees radius from the original location; a maximum heading allowance $\delta\delta\delta\delta$= 5 degrees; 0.1 degrees maximum possible distance from the previous position; and wind intensities drawn from a probability distribution based on historic differences in wind speeds between track points. The model is based on routines originally implemented in the CLIMADA tropical cyclone model (Aznar-Siguan and Bresch, 2019). The storm origins and percentage occurrence of storms in the probabilistically generated set is similar to the historical occurrence. The storm is associated a certain frequency of occurrence, based on the total number of events simulated.

To account for the effects of climate change, the model included an average change in the frequency and maximum wind speed for each category of storm, based on existing ensembles of dynamic studies. Given the considerable heterogeneity in projected change in frequency and intensity of future cyclones, we modeled two scenarios for future storm activity: (1) average estimates from a recent dynamic study for the Caribbean basin, presented in (Knutson et al., 2022); and (2) the mean estimates for the North Atlantic from the global ensemble of projected responses to anthropogenic warming in (Knutson et al., 2020). The changes in wind intensity and frequency were applied to the simulated tracks linearly and depending on the storm category, according to Table 1. For example, considering the first scenario, the wind in track categorized as a category-3 hurricane was affected by an increase in the intensity by 4.7% and the frequency of occurrence by -43.4% by the end of the century, following Table 1.

	Tropical Storms	Category 1	Category 2	Category 3	Category 4	Category 5
Scenario 1. Average estimates in (Knutson et al., 2022) for the North Atlantic						
Change in maximum wind speed (%)	+4.7	+4.7	+4.7	+4.7	+4.7	+4.7
Change in frequency (%)	-10.2	-41.7	-45.4	-43.4	-9.3	95.5
Scenario 2. Mean estimates from the ensemble in (Knutson et al., 2020) for the North Atlantic (*)						
Change in maximum wind speed (%)	+2.94	+2.94	+2.94	+2.94	+2.94	+2.94
Change in frequency (%)	-14.1	-14.1	-14.1	-14.1	+9.9	+9.9

Table 1: Scenarios considered to simulate the effects of climate change. (*) Scenario is considered for comparison purposes, since the most recent estimates in Knutson et 2022 do not provide changes in maximum wind speeds between different storms.

Third, for each storm track, the wind fields can be calculated at hourly time steps using different wind models. Most parametric wind field models are symmetric, i.e., wind velocities are assumed to be equal at equidistant locations from the storm center (Chavas et al., 2015; Emanuel, 2004; Holland, 1980) whereas models can account for wind variability with respect to both radial distance and azimuthal angle (Chang et al., 2020; Holland et al., 2010; Yan and Zhang, 2022). Here we used the revised Holland parametric model (Holland et al., 2010) to estimate wind fields at each location (Figure 1). The model was also compared with wind field estimates from other two parametric models: (Emanuel, 2004) and (Emanuel and Rotunno, 2011), with equivalent results. The maximum wind speed and the duration of each TC is registered at each coral reef location globally. The model also estimates change in wind intensities after landfall using an exponential decay in wind speed (and increase in pressure) to the tracks after landfall (Aznar-Siguan and Bresch 2019). The simulated historic and future wind speeds were recorded in a 0.1-degree hexagonal grid across the Caribbean and are available with this chapter for other risk analysis applications.

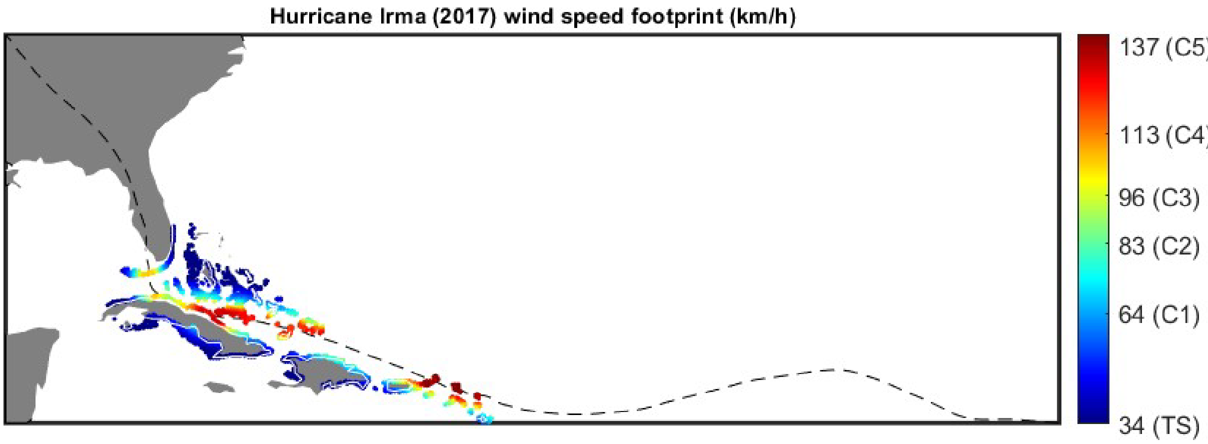

Figure 3. Wind footprint of Hurricane Irma (2017).

Fourth, the results for each point across the Caribbean are used to infer the probability of occurrence by ordering all the storms in descending order (a total of 14,784 storms) and fitting a linear model in a semi logarithmic scale. Figure 5 represents the spatial distribution of the probability of exceeding wind speeds of a major hurricane, a category-3, in each location of the Caribbean. A Category-3 hurricane in the Saffir Simpson scale is considered a 'major hurricane' that can produce devastating damage [h]: well-built framed homes may incur major damage or removal of roof decking and gable ends; trees will be snapped or uprooted, blocking roads; electricity and water will be unavailable for several days to weeks after the storm passes. The resulting percentage change in wind speed between present-day and future tropical cyclone activity are shown in Figures 6 and Figure 7 for each climate scenario. The differences between climate scenarios, despite being derived from different ensembles, is not large. The results show that the central Caribbean have high probability of experiencing damaging hurricane winds locally[i] (Figure 5), while the expected change through the century will increase between 20 to 40%, with the larges expected changes in the northern part of the basin (Figures 6 and 7).

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[h] https://www.nhc.noaa.gov/aboutsshws.php

[i] Note that the caterogy-3 winds are calculated here locally, based on local time series of wind speeds. The results may differ from an analysis of the probability of being affected by a category-3 hurricane because such category is defined by the maximum wind speed through the storm track, not locally (i.e., a category-3 will present wind speeds below the maximum speed in many areas within its area of affection).

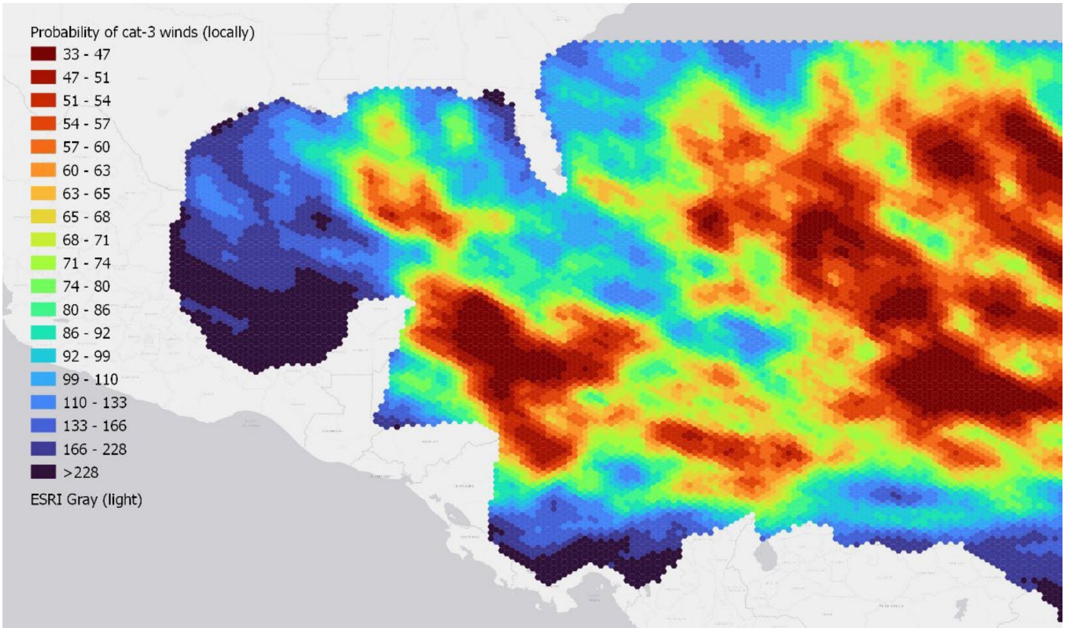

Figure 4. Present-day probability, expressed as a return period (years), of having winds at least exceeding 96 kts in in each location of the Caribbean. These winds correspond to local wind speeds of a category-3 according to the Saffir-Simpson scale, which are associated to major hurricanes that can produce devastating damage.

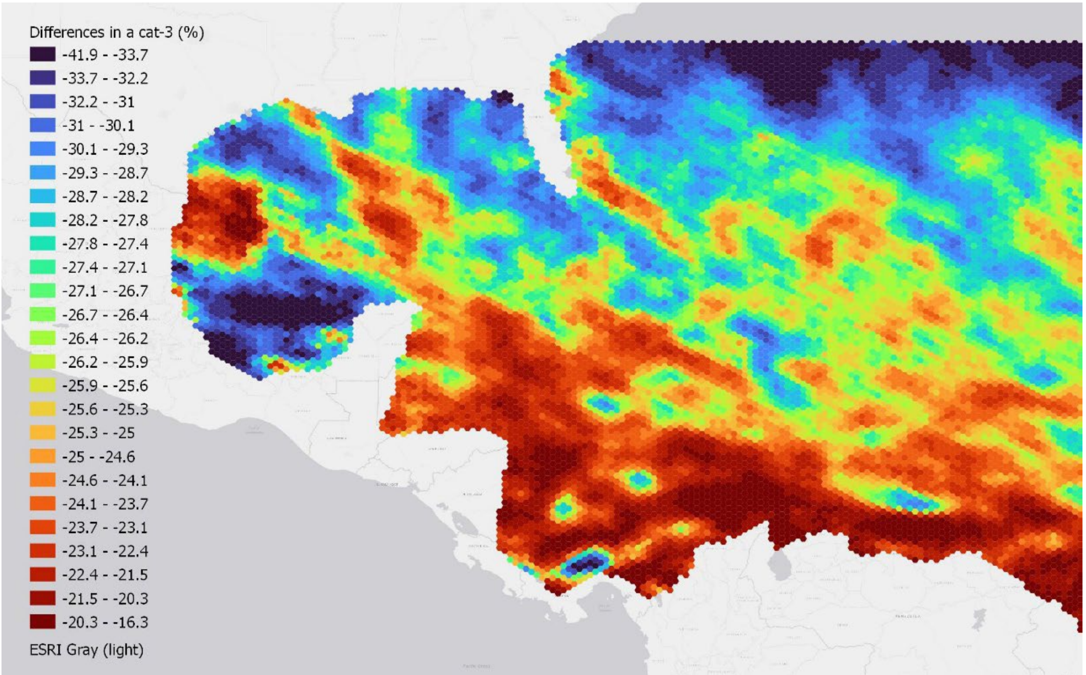

Figure 5. Percentage change in the probability of a category-3 hurricane between present-day and the end of the century, for the average climate change scenario in Knutson et al 2022.

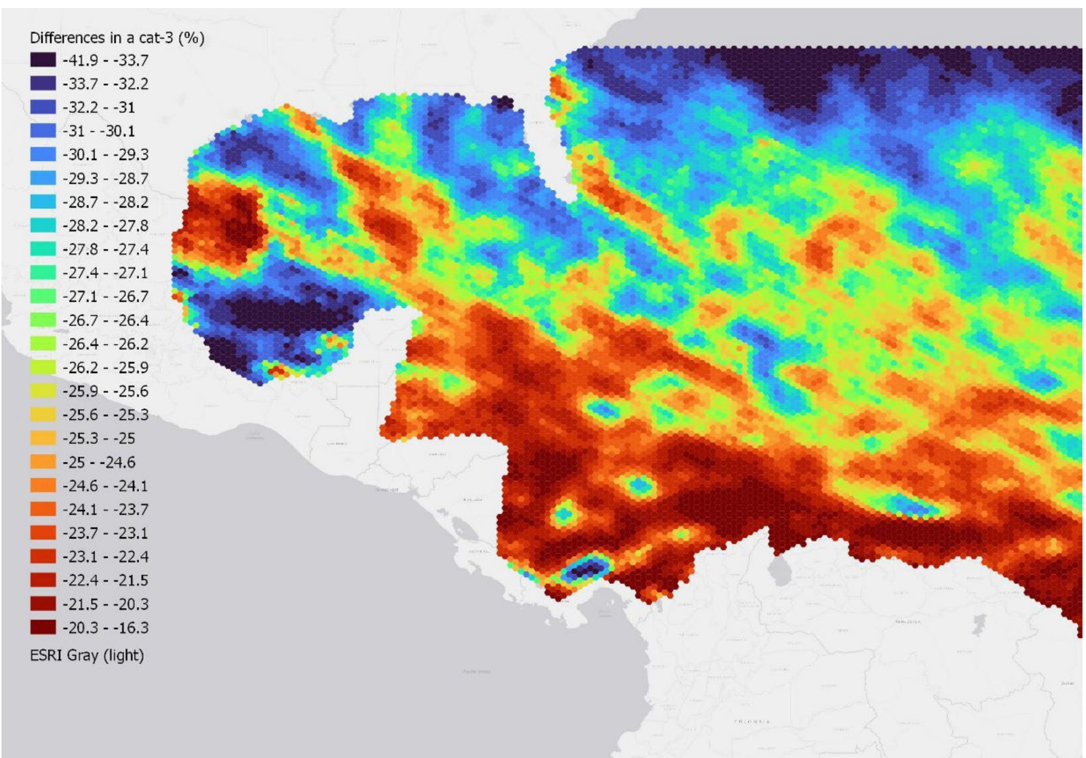

Figure 6. Percentage change in the probability of a category-3 hurricane between present-day and the end of the century, for the high climate change scenario, based on the ensemble for the North Atlantic in Knutson et al 2020.

Deriving adaptation benefits and including the role of natural infrastructure in coastal risk

The effects of nature-based projects can be included in these risk modeling frameworks and tools at different levels of granularity. Applications for conservation and/or restoration of ecosystems have been increasing across spatial scales, which have informed adaptation investments but also innovative risk financing solutions. Some examples that follow these approaches include a global assessment of the flood mitigation benefits of coral reefs (Beck et al., 2018); a similar assessment of flood risk reduction from mangroves (Menéndez et al., 2020); and most recently, a high-resolution, national assessment in the US coral reef-lined coasts (Reguero et al., 2021). The latter example for the U.S. coral reefs provides detailed flood maps that quantify in a spatially explicit form how and where coral reefs provide over US$ 1.8 billion in annual coastal flooding risk reduction across the U.S. Many of these reefs present annual conservation benefits of US$ 1 million per kilometer and year, but they also provide critical protection to the most vulnerable communities in islands Territories [j]. Examples also exist for specific storms. For example, one assessment estimated that coastal wetlands reduced $625 million worth of property damage during Hurricane Sandy in 2012. In more than half the zip codes along the East Coast, wetlands helped reduce the cost of damages by 22 percent (Narayan et al., 2017).

To illustrate how hurricane wind results can be used for assessing flooding, with and without ecosystems, an example below provides an application in the Bahamas. Using information from hurricanes in the previous section, it models flooding and develops a sensitivity analysis of the effects of using different mangrove layers in flood risk models, to provide recommendations on datasets and modeling approaches for local risk assessments.

Example 2. Flood attenuation by mangroves in the Bahamas.

The Bahamas, in particular, is highly dependent on coastal ecosystem's services provided by coral reefs, mangroves and seagrass beds, among others. Around 25% of the Bahamas population have some income from fisheries and 75% of the country´s GDP comes from the tourism activity (Arkema et al. 2015, 2019). Mangroves are also critical for providing other ecosystem services

[j] https://sustainabilitycommunity.springernature.com/posts/new-opportunities-for-the-natural-coastal-infrastructure

that are important to coastal communities in Latin America and have been effectively accounted, such as carbon storage and sequestration.

The risk reduction benefits of mangrove forests have been recently assessed at the global and national scales (Menéndez et al., 2020, 2018), but the use of global datasets can result in large variations in local flood risk applications (Menéndez et al., 2019). There is also a general lack of high-resolution information about vegetation parameters such as canopy height, density, and biomass that can all influence the capacity of mangroves to attenuate waves and reduce the risk of coastal flooding and erosion (Liu et al., 2013; Maza et al., 2022; Mendez and Losada, 2004). This spatial data is rarely available over large enough areas to meaningfully inform disaster risk management. The improvement of resolutions of satellite-derived information, however, is helping address many of these information gaps (e.g. Ruckelshaus et al., 2020).

Here, we conduct a pilot analysis that explores the value of new data technologies to quantify the effect of mangrove distribution and effects on coastal flooding estimates based on a case study on Andros Island in The Bahamas. Through a sensitivity analysis, we provide recommendations on modeling approaches for flood risk assessments in mangrove protected coastlines, by identifying sensitivity to different mangrove datasets, spatial resolution grids and habitat modeling strategies. The different steps are explained below.

First, we selected 15 historic hurricanes[k] that have affected the island and calculated wind fields in a spider web format, as provided by the TC Wise tool (see previous sections). Second, we compare four mangrove datasets available for the Caribbean, with different resolutions (Table 2): Global Mangrove Forest (GMF), Global Mangrove Watch (GMW), the World Atlas of Mangroves (WAM), and a local dataset derived by The Nature Conservancy (TNC) for Andros Island (Silver et al., 2019). This dataset is considered as the benchmark as it was derived from distribution of

[k] The hurricanes correspond to historic category 4 and 5 storms that have affected the island: The Bahamas Hurricane (1929), Betsy (1965), Inez (1966) David (1979), Andrew (1992), Gordon (1994), Floyd (1999), Katrina (1999), Michelle (2001), Wilma (2005), Irene (2011), Irene (2011), Sandy (2012), Matthew (2016), Dorian (2019) and Isaias (2020).

mangrove forests using RapidEye (2009, 5 m) and Landsat 5 and 7 (2005, 30 m) satellite imagery classified for Andros Island. The differences between datasets are represented in Figure 7.

Data Title	**Source**	**Extent**	**Scale / Resolution**	**Source Data Time Period**	**Sensor(s)**	**Data Access**
Global Mangrove Forests v.1 (GMF)	Giri et al. (2011)	global	30m pixel	1997-2000	Landsat	https://sedac.ciesin.columbia.edu/data/set/lulc-global-mangrove-forests-distribution-2000
Global Mangrove Watch v.2 (GMW)	Bunting et al (2018)	global	25m pixel / 100 m^2 minimum mapping unit	1996, 2007-2010, 2015, 2016	Landsat, ALOS PALSAR, PALSAR-2, JERS-1	https://data.unep-wcmc.org/datasets/45
World Atlas of Mangroves v.3 (WAM)	Spalding et al (2010)	global	varies	1999-2003	Landsat, IKONOS	https://data.unep-wcmc.org/datasets/5
Regional Landsat-derived Mangrove cover	TNC	Andros Island	30m pixel	2002	Landsat	The Nature Conservancy

Table 2: Details about all mangrove layers included in the analysis

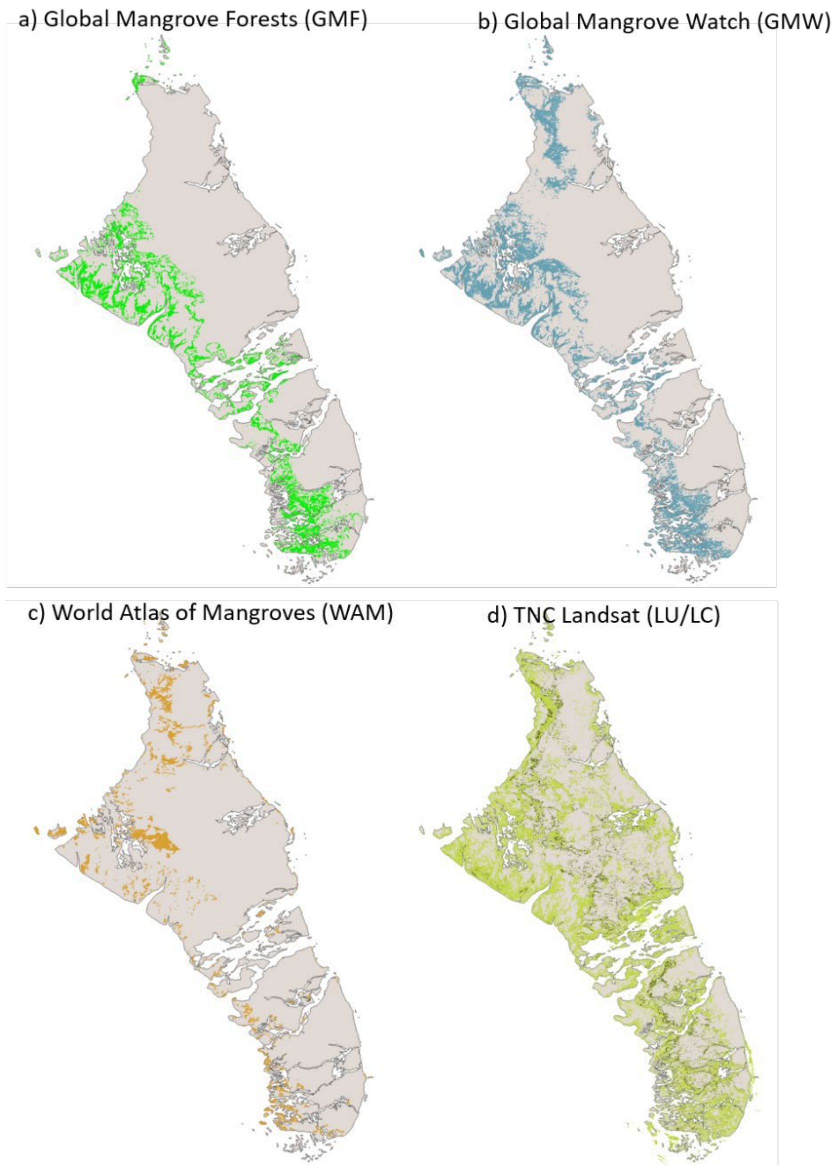

Figure 7. Differences in mangrove cover between four mangrove datasets.

Third, using the model Delft3D, storm surge and waves were modeled at three spatial scales for comparing the effects of different mangrove covers on flooding and factoring in the effects of vegetation. Each tropical cyclone was run individually over an unstructured numerical grid of approximately 1-km horizontal resolution that covers the northeastern Caribbean (see Supplementary Figure 1). The effect of mangroves was not considered at this stage. A second grid (Level 2) was nested to model coastal flooding across the entire island of Andros at a 100 m horizontal resolution. At this level, the influence of mangroves was included as a drag force to the flows via the Manning coefficient (0.14 for mangroves) based on bed friction force (Liu et al., 2013; Zhang et al., 2012). This scale and approach are often used at national projects where data availability is limited (bathymetry, topography, habitat distribution). Three high resolution grids with 10 m horizontal resolution were also nested to the intermediate grid to compare the effects locally, covering small areas at the Northwest, Southwest and East coast of the island. This level of scale corresponds to the highest modeling resolution consistent with the digital elevation model and mangrove information data accuracy (~10m).

For the simulated hurricanes, the average across storms shows up to 80% differences in flood extent between mangrove layers (Figure 8) in areas with more than 50% of the surface covered by mangroves (West of the island). However, in areas with disperse mangrove patches (East) differences of considering different mangrove layers were reduced to 7%-12%. The results also show differences of about 15% in flood extent between using a high resolution (10-m) and larger resolution flood model (100-m) (Figure 9).

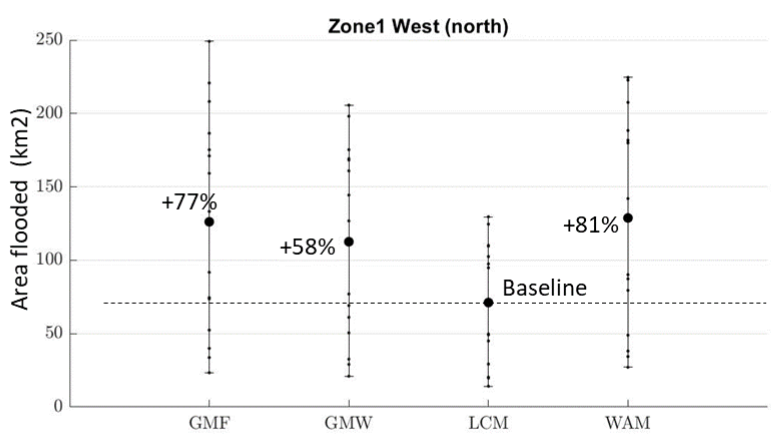

Figure 8. Differences in area flooded between the four mangrove datasets. The Landsat based Cover Map (LCM) derviced locally for Andros is chosen as a baseline for comparison with the other global mangrove datasets.

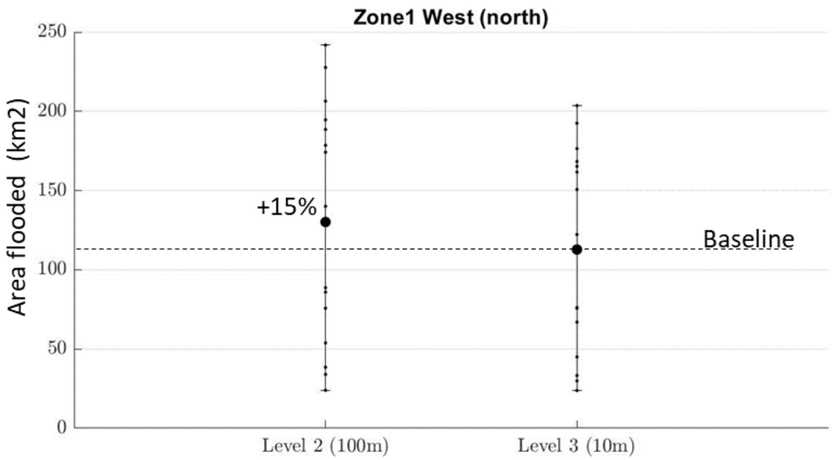

Figure 9. Differences in mangrove cover between four mangrove datasets.

Implications

The modeling presented here shows that coastlines across the northeastern Caribbean are the most exposed to high hurricane winds. The central Caribbean and the U.S. Gulf Coast are also areas where high wind speeds are more frequent. Studies of tropical cyclones for the Atlantic basin indicate that the simulations of very intense tropical cyclones respond differently to climate warming than do weaker tropical cyclones. Intense tropical cyclones tend to increase in frequency whereas weaker tropical cyclones tend to decrease in frequency in these simulations. The results in Figures 4-6 show that wind speeds associated to major hurricanes are relatively frequent at present and would become between 20-40% more frequent in many locations by the end of the century. The Southern Caribbean sees the smallest decreases, while the central Caribbean will see more cyclone activity.

The second example involves an application of historic wind fields in a hydrodynamic model to assess flooding with different mangrove layers in Andros Island in the Bahamas. Results from simulations of 15 major hurricanes affecting the island were compared with alternative mangrove cover datasets to show that differences in flood extent can vary up to 80% in areas with high cover of mangrove forests. The results of improving the resolution of the model, however, are less substantial and only improved the flood extent by 15% after considering a 10-m flood model versus a 100-m one. This suggests that special attention should be paid to local data of ecosystem distribution in local applications as flooding effects could be largely overestimated. As a recommendation, future flood risk assessments with mangrove cover should use as local specific data as possible.

These types of valuations have been demonstrated useful in the past to enable pioneering risk financing options such as resilience insurance for natural infrastructure (e.g., Mexico, TNC, 2019; Reguero et al 2019; TNC, 2021). For example, the coastal protection value of reefs in Mexico led to the first insurance for an ecosystem to date: a reef insurance policy that protects a section of the Mesoamerican reef from major hurricanes. This parametric solution was implemented in 2019 and triggered in 2020 by Hurricane Dorian(Reguero et al., 2019; Mexico, TNC, 2019), representing the first time ever that an ecosystem has benefited from an insurance payout to be repaired after the damage sustained from a storm. The application and the case used similar tools to the models presented here.

This technical note fills a key gap in hazard modeling by estimating wind fields for tropical cyclones for present and future climate scenarios, under limited data; and provides a first analysis on the sensitivity of other factors such as mangrove cover. Other models exist that use dynamic behavior of hurricanes under climate change, but the approach shown here provides easily replicable estimates that could be updated as other information becomes available for future storms. These results can be used to infer damages from wind or in flood hazard models. Damages from wind are a significant hazard, representing by far the greatest contributor to economic losses due to hurricanes (CCRIF 2010). Wind fields from individual storms are crucial inputs to hydrodynamic models for estimating flooding and erosion damages and the impact of ecosystems on the overall hazard, as demonstrated for mangroves in the application for Andros Island . Finally, wind field information can also be used in the future for deriving damage estimates on ecosystems (e.g. on coral reefs or mangroves), as well as damages on built assets (see an example in Box 1).

Next steps and opportunities for future work

Historic and future information on hurricanes can be used to evaluate risk in flood models (see Arkema et al. (2021c)), damage assessments, and to assess different adaptation strategies. Pilot work in the Caribbean (CCRIF, 2010) showed that different adaptation strategies can be compared to each other through cost-benefit analyses using information on present and future risks, and the wind/flood mitigation effect of the different interventions. However, assessing adaptation effectiveness at the local scale requires detailed models on wind and flood damage. Future advances could collect information on the effectiveness of adaptation projects to inform estimates at regional scales and allow larger scale comparisons of adaptation strategies.

While wind and flood damages of hurricanes are increasingly being assessed at high resolutions and with greater precision, other effects of hurricanes remain to be characterized. For example, long lasting sea water inundation during hurricane Dorian in The Bahamas contaminated an aquifer that sourced over 200 wells used for water supply. With the islands inundated for long periods, clean drinking water became a critical priority. Recent research shows that future increases in enhanced wave-driven flooding in Pacific islands could drive significant salinization problems in underground freshwater sources (Storlazzi et al., 2018). As the impacts of climate change continue to add to existing risks, compound effects like these will grow in intensity and frequency - and they will particularly affect vulnerable communities. Furthermore, very little information or methodologies exist for assessing social impacts or estimating vulnerability curves that quantify the impact of storms on natural assets such as ecosystems, as well as their recovery. These are key limitations for assessing the role of nature-based solutions in climate resilience strategies.

Appendix. Technical details

Hazard information

Hazard information can include historic data on storms and flood levels, or be derived from wind and flood modeling (see applications in chapters below). Numerical models can be used to derive wind fields, and surge and wave fields that can be used to infer damages and losses in coastal areas. More recent applications include the effects of ecosystems in these hydrodynamic models, such as reefs (Reguero et al. 2019, 2021), or coastal wetlands (Narayan et al. 2017; Menéndez et al. 2020).

Satellite imagery is increasingly becoming available for use in assessing and understanding risk. Satellite-derived imagery can be used to derive meteorological data, for example, and these increasingly are being used to quantify flood and drought risks at global and national scales, including for buildings, roads, and other infrastructure (e.g. GFDRR, 2014). Satellite-derived imagery also now allows historic tracking of changes in land use, ecosystems and built infrastructure. For example, the European Joint Research Center developed a global high-resolution mapping of global surface water (https://global-surface-water.appspot.com/#) and its change over time. This model can provide flood extent and thus inform estimates of flooded area (Pekel et al. 2016).

Exposure data

Efforts to develop exposure data for global application are gaining in momentum, and new information from global to local scales for socioeconomic exposure are now available for use in risk modeling tools. Greater availability of global data sets on population extent, building types, etc. from satellite imagery is typified through some of the resources below:

- Population distribution is available from different sources. One example is WorldPop that provides global information on - https://www.worldpop.org/ , and includes an R package that provides API access to the WorldPop Open Population Repository. (https://wopr.worldpop.org/)
- Multitemporal urban features/human built-settlement datasets have also become increasingly available from remotely-sensed imagery (Nieves et al. 2020). One global example is the Global Human Settlement Layer that provides historic information on built up area and population (https://ec.europa.eu/jrc/en/global-human-settlement-layer)
- Nightlight data is often used to characterize urban changes but also economic exposure in risk modeling. Data derived from nighttime satellite imagery have helped develop various globally consistent proxy measures of human well-being at the gridded, sub-national, and national level such as socioeconomic variables, energy use, urban built-in expansion, and carbon emissions - see a review in (Ghosh et al. 2013).
- The Global Assessment Report (UNDRR 2015) also developed built capital exposure

Other relevant information includes land use (and change) and distribution and built-up areas, which can be related with economic value depending on the use and building typology for risk assessment purposes (e.g. see Huizinga et al. 2017).

- At national and subnational levels, data and information from governments (such as statistics authorities, transportation and infrastructure departments, or education and health departments) are also increasingly available and can be used to characterize hazard risks.

- Volunteer geospatial initiatives (e.g., OpenStreetMap) is also increasingly seen as a way to engage communities in the collection of data but also in the planning and management of disaster risk.

Vulnerability

Determining direct flood damage is commonly done using depth-damage curves, which relate the flood damage that would occur at specific water depths per asset or per land-use class. Many countries have developed flood damage models using depth-damage curves based on past flood events and expert judgement. However, damage curves are not available for all regions, which is one key limitation for risk damage assessments. The European Commission has made available a set of global flood depth-damage curves based on a collection of sources, as well as guidelines for flood risk estimation, including in developing countries. The dataset contains damage curves that provide fractional damage as a function of water depth, as well as maximum damage values for a variety of assets and land use classes. The dataset was created based on an extensive literature survey for each continent. The guidelines also differentiate flood damage between countries, estimated by determining maximum damage values at the country scale. For Central and South America, the dataset used information available from literature in: Argentina, Bolivia, Brazil, Colombia, El Salvador, Guatemala, Haiti, Mexico, St. Maarten (https://publications.jrc.ec.europa.eu/repository/handle/JRC105688).

Box 1. Example: Wind damages from Hurricane Irma in the Caribbean.

Following a similar approach, CLIMADA was used to assess wind damages from Hurricane Irma in (Aznar-Siguan & Bresch 2019) across the Caribbean. Similar analyses were combined with coral reef hydrodynamic models to generate the spatial distribution of flood damages and the resulting risk reduction benefits of coral reefs in the Meso American Reef (MAR) in Mexico (Reguero et al. 2019). The economic value of exposed assets was obtained in (Aznar-Siguan and Bresch 2019) by downscaling national gross domestic product (GDP) information with nighttime lights data (indicating location and intensity of development and human activity, from NASA's Black Marble 2016 annual composite Visible Infrared Imaging Radiometer Suite (VIIRS) day–night band) at 500 m resolution (Román et al. 2018)). The application for the reefs in MAR used instead data on built capital from the Global Assessment

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